# AGENT BASED APPROACH TO LAND USE MIX

By

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## Abstract

Modelling and simulating the dynamics of crowd movement within the complex built environment such as a city centre is an evolutionary, processing research task. Recent methodological and theoretical advances have provided the opportunity to explore and provide answers to various crucial problems on land use mix. Daily in our urban settlements we seek for resources and attractions. Our search behaviour is complex and emergent, related to urban morphology and land use patterns as this is generated by our daily movement and activities. This report discusses a pedestrian movement study which examines the ways pedestrian behaviour and flows affect and are affected by the formation of the built environment and the land uses. The focus is in retailing uses and especially shopping. For the formulation of the model, an agent based simulation approach is adapted based on object oriented analysis and programming. Agents are given long distance vision and direct their movement and behaviour in response to the information retreat from their vision field, morphology of the local environment, and their individual desire for retail or exploration of the area. The simulations are used to extract meaningful conclusions on the pedestrian behaviour and factors that have an impact on it. Various formations of retail location patterns in a 7 x 7 grid are explored and three different approaches of agents' behaviour are used in order to get meaningful conclusions.

**Keywords:**

Agent-based system, retail, pedestrian movement, synthetics

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## Introduction

Today, urban growth and change processes are still issues extremely complex to fully understand and resolve. Urban systems are highly complex systems, emerging from different social, economic and physical systems with different set of rules. Various interactions between different factors, like actors and agencies determine the growth of these systems. Changes happen continuously but it is extremely hard, even impossible, to predict the effects and the overall change, that an alteration or an intervention will have in the urban system. Especially in our days where the areas that require a change are restricted by the current infrastructure, networks, building form and economics like the cost of land. Now we all acknowledge how extremely vital is to fully understand all that, how different interacting systems influence the growth process, in order to be able to intervene and guide the 'distributed' decision taking process and so control urban development for a better future. [Penn, A., and Turner, A., 2003]

The biggest interest lies on the dense central areas. These are the areas where planning is challenged to deliver change today but where intervention is restricted by 'untouchable' historical and cultural values (cities with rich historical centre and strict regulations that control interventions), dense building environment and networks and thus high expenses and retail values. City centres are playing a leading role internationally and are competing each other for investment that will lead to growth and development. Growth and development will improve their aesthetics and functionality as it will give the opportunity to bring new architecture in and alter dysfunctional, problematic functional elements of the city. Investment will bring as well posterity with an increase of capital and thus new working places, retail opportunities and an increase of tourism and visitors numbers in the centre. Unfortunately or not, the extreme cost and difficulties due to the reasons described, pushes interventions to focus in delivering change through the dynamic aspects of urban systems and thus networks and distribution of flows [Zachariadis, V., 2005]. Distribution of flows in urban networks is becoming more and more important in planning process and out of them, in central and highly dense areas the essential, most important networks are those of transport and movement. That makes the study of pedestrian movement and the interaction with activities and uses, an essential part of spatial analysis in order to understand and be able to project and control the side effects of such interventions in the urban system, an area that research until recently was limited and problematic. Now the need for pedestrian movement research and modelling rises, and although in few cases conventional approaches in pedestrian modelling are appropriate, in many cases characterised by highly dynamic systems it is analysis in the finer scale that is important and leads to meaningful conclusions and estimates. Thus actor modelling and agent based simulation is the appropriate solution and that's the approach taken in this thesis.

This report will analyse the role of pedestrian flows on land use and buildings and vice versa with a series of experiments focusing on the effects of spatial configuration, location of facilities-shops and attraction as a population of agents with different profiles move in the models environment aiming to satisfy their goal. In the first part of the paper there will be a theoretical analysis of pedestrian movement-complexity theory influenced by retail theory experts, shopping behaviour analysts, surveyors and planners. The report and thus the model will be mainly based on the space syntax and agent simulation research currently undertaken at University College of London. In the second part of the report there will be a technical description of the model, the experiments that were performed and the results-conclusions that these generated.

# Part I: Theoretical background

## 1.1 Research opportunity

Urban growth and change processes are still issues extremely complex to fully understand and resolve. Cities are complex systems with many dynamically changing parameters and sub-systems that operate interactively at different scales and big numbers of actors. Analysis and understanding of the complex urban system was until recently problematic and inadequate as many gaps in knowledge by numerous factors didn't allow a coherent understanding of the processes especially at the very fine spatial scale. The complexity of the interactions involved made unclear where to focus or what exactly to observe or measure, and particularly what factors might be considered to be prior to others or more influential. Urban life is diverse, making impossible to reach explanation of localised problems by attributing to them a portion of the city-wide outcomes. Especially if we consider that cities grow organically and as they grow their complexity grows as well in a totally distinguished and unique way from each other, making comparisons hard to make. Urban life is not a 'fractal'[1] (in opposition to cities themselves that posses complexity characteristics of fractals like self-similarity in different scales), to suggest that the complexity of a city's life derives as an appropriate sized equivalence of a small town. In addition to that, existing datasets are rare and of low resolution that ignore the fine scale morphological variables, as data gathering was really expensive [Penn, A., and Turner, A., 2003]. The detailed studies that were undertaken tended to focus on particular aspects (according to their interest) of the field rather than a more coherent approach on the interactions between systems.

We as designers, we need to focus on the individual-pedestrian or agent in the actor modelling. We need to investigate the dynamics of distributed decision taking of the individuals in these complex systems of the built environment and their coherent outcomes, if we are willing to try and control urban development in order to produce cities that are vital and viable. It is known and accepted for example that urban spatial morphology has a powerful effect on pedestrian movement patterns [Hillier, B., Penn, A., Hanson, J., Grajewski, T., Xu, J., 1993]. Less is though fully acknowledged to what

[1] Most cities are formed by a mixture of organically or naturally growth, characterized by random-chaotic disorder and Euclidean order created from the planners. Fractal geometry offers a good field for application on cities as even the planned cities contains some organic growth and irregularity. If cities belong to fractal geometry, then elements like city boundaries, networks, hierarchies, urban texture and the density of population will be found on different scales, 'self-similarity'.

degree specific land uses act as attractors of pedestrians or pedestrian movement is an attractor of land uses and even less is understood about the process that forms the land use patterns and clustering and the manner in which these patterns affect pedestrian movement as the pedestrians search to satisfy their goal. And all that in our days that there is a strong commercial imperative for predictive models which are able to simulate how attractive different locations are to consumers and vice versa. The purpose of this thesis is to investigate all these issues.

Furthermore there is always the problem that the investigation undertaken remains theoretical since intervention in a real urban system and generally real life scenarios are expensive and long term to study which makes computer simulations an ideal solution. Especially now that as very recent events manifested (terrorism), there are still urban phenomena, issues and scenarios that have to be analysed and investigated prior to their appearance. Everything remains in order as long as there is a balance between all agencies and actors, crucial in complex systems such as an urban system. Radical changes like extreme phenomena (natural or not) or just events like concerts, carnivals, open markets, great openings and public protests cause a change in balance like an increase of pedestrian flow that in most of the cases will test and prove current infrastructures and networks problematic and not functional. Simulations and models will have to be made for every possible case and scenario to be able to predict and avoid unpleasant events and results.

Now many theoretical and methodological advances have made it possible to start gaining the understanding that is required. These are the understanding of the mathematics of complexity and synthetics, research on the local movement in built and urban space through theories like space syntax and the development of powerful computing and agent based simulations. All that will be analytically described in the next chapters and influence and form the theoretical framework to which the model is based.

## 1.2 Theoretical framework-complexity theory

### 1.2.1 Emergent systems

Urban reality is partially formed as a combination of co-dependent emergent systems. Pedestrians are interacting in many ways, through crowding, flocking and other mimic tensions. They behave in complex ways as they search their environment to satisfy their goals and they seem always to express preference to spaces occupied by other pedestrians. Pedestrian movement is a complex system that just recent methodological and theoretical advances may have made it possible to understand.

The idea of complexity hinges on the notion of emergence.[2] Emergence is an idea inherent to complexity theory and closely related to self-organization. In emergent systems, a small number of rules or laws, applied at a local level and among many objects or agents[3], are capable of generating surprising unexpected levels of complexity in aggregate forms. These patterns manifest themselves in such a way that the actions of the parts (units-agents in our case) at local scale do not simply sum to the activity of the whole in order to extract estimates for the meso and macro scales. Essentially, this means that there is lot of complexity and many things going on in the dynamics of the system than simply aggregating little pieces into larger units. Although often ordered in their structure, the complex systems that are generated are not always just random or chaotic but recognizable and ordered features usually emerge. Furthermore, these systems are dynamic (generated from the interactivity among their constituent parts) and change over time and the dynamics often operate without the direction of a centralized executive and in many cases not affecting the aggregate superficial equilibrium of the system [Torrens, P. M., 2000]. The factor that determines whether a system demonstrates emergent behaviour is the interaction of its agents. Ignoring the interacting functions among the agents of the system makes it impossible to forecast the attributes of the macro-scale just based on knowledge of the agent. The reverse is also true, as in emergent systems it's not possible to develop understanding of the actor's behaviour by investigating the aggregate outcomes at the macro scale [Zachariadis, V., 2005].

### 1.2.2 Synthetics versus reductionism

Synthetics is a relatively new way of approaching scientific inquiry, in an innovative approach to define complexity. It is a bottom up approach to complex systems such as cities. Much research in urban studies and the social sciences in general, and particularly in geography, is challenged by a dichotomy between the individual (household, person-agent, and independent objects in general) and the aggregate (populations, collectives, and regions). In urban studies, search for detailed analysis leads closer and closer to the individual-local level. But in a spatial sense, researchers

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[2] This is to such an extent that complexity studies has been termed as the science of emergence [Krugman, P. R., 1996]

[3] Here an agent is defined as the basic actor of the system or otherwise the minimum independent unit detected. The models are based on that approach.

face the dilemma of reconciling patterns and processes that operate and manifest at local scales and lay the possibility of understanding the driving forces behind urban phenomena, with those at larger scales that guaranty inclusion of the needed elements of the analysis and offer meaningful conclusions. This can be considered as a problem of ecological fallacy. An ecological fallacy occurs when it is inferred that results based on aggregate data cannot be applied to the individuals who form the aggregated group [Torrens, P. M., 2000].

There are many examples in which aggregate forms may be extrapolated from the individual. However, care has to be taken when reconciling the two, particularly when processes that operates at the local level are interdependent (actions of one individual-agent depend on another). In these cases, an understanding of the interactive dynamics that link local-scale and larger-scale phenomena is needed as understanding of the processes that generate macro-scale patterns may not be easily gleaned by simply aggregating up from the individual.

Reductionism on the other hand, analyzes problems by breaking them down to their constituent component, reducing them to manageable pieces and gaining understanding of them in process. It may be appropriate in cases like centrally controlled and hierarchical (vertically laid out) systems but certainly cannot be implemented when confronted with systems formed by multiple horizontal interactions of individual, independent actors-agents. Reductionism is not appropriate for such systems as it fails to consider the emergent properties of a system, those that come as a by-product of the interactive dynamics of individual elements [Zachariadis, V., 2005].

### 1.2.3 Cities as complex systems

Treating cities as complex adaptive systems is a relative new and innovative approach to urban studies. Many urban systems may be regarded as emergent in their behaviour and complex in their organization. Cities are excellent examples of complex emergent systems. From local-scale interactions such as individual-agents movement habits and actions, the geomarketing strategies of individual or grouped retail establishments, and social differentiations and phenomena, large-scale and ordered patterns emerge in the aggregate. These are for example peak-hour congestion, economies of agglomeration, and social segregation. These aggregate patterns often emerge independently of the dynamics driving the individual components of the system [Batty, M., Torrens, P. M., 2001]. In general, complex urban systems also display many traits common to complex systems in the biological, physical, and chemical worlds.

Complexity approach to urban studies also parallels closely with postmodern schools of thought in urban geography, particularly ideas about deconstruction and the representation of multiple perspectives [Torrens, P. M., 2000]. The complexity approach focuses on the seeds-initial state of the system, emphasizing the interaction among elements, without sacrificing a holistic perspective. The complexity approach also focuses model development on important issues such as the importance of historical (seed-initial) conditions, feedback between subsystems, interaction, dynamics, noise and perturbations and others.

To understand cities' problems we need to adapt a bottom up approach to urban systems, to research and understand the individual decision taking process. Synthetics study phenomena by applying a range of behavioural rules on a system's agents and allowing their interactions until macro-scale pattern can be detected which can be then examined and related to real world cases. Thus synthetics is the appropriate approach and solution for this kind of problems and analysis. Mathematics of complexity offer hope that systems as apparently complex and chaotic as urban growth and change, and the distributed decision making that underlie them, may become tractable to theory. By using computational models with this approach, small variations in the initial conditions (according to what the user wants to study, in our case spatial configuration and retail) can lead to widely divergent end results. By that is easily to isolate and study the effect of individual factors-elements or agents in the urban environment-system in each case.

## 1.3 Local movement

### 1.3.1 Pedestrian movement as a complex system

It has been analyzed already, that urban reality and cities are complex systems partially formed as a combination of co-dependent emergent systems. Out of them one system that can be described as a complex system, generated from local scale interactions and associated to emergent systems with its own interdependent factors, is pedestrian movement which is the focus of this thesis. Pedestrian movement flows and their impact although never challenged or disputed, was not a mainstream part of spatial analysis until the early 1990's. That's in contrast to the link between vehicular movement-traffic and land use that was well acknowledged and studied since 1950's.

An urban critic and writer, Jane Jacobs, suggest that the answer to the demanding nature of urban problems is hidden into city's streets and their interdependent factors. To understand the complexity of the cities and their problems we need a bottom up approach. According to Jacobs, pedestrian pathways and the other components that form the public space network of a city are the stage on which ordered complexity is fabricated. Pedestrian spaces are important because they allow random interactions between people-pedestrians on the streets, enabling cities to create emergent systems. These systems have the ability to self-organize and adjust themselves, in order to produce the best possible solutions to given problems. Jacobs also claims that these adjustments despite their complex outcomes are not centrally driven and in most cases the individuals-agents are not even aware of them [Jacobs, J., 1961]. In case that there is urban chaos and disorder, in cities that had equilibrium and used to work perfectly, this is the result of emerging outcomes of an underlining sequence of various actions in the micro level (that can be related to the individuals-agents).

### 1.3.2 Space syntax

One other useful and rather recent theoretical and methodological tool, useful for this thesis is space syntax. Space syntax theory, expound at UCL, has developed techniques for analysis of urban and built space, combined with theories of society where spatial morphology has an active role in built environment. Space syntax methods represent and quantify the pattern properties of built space in order to control for morphological variations in studies of other aspects of urban function like movement and retailing. Space syntax is a first order generalisation of accessibility or connectivity of streets where streets are treated as nodes and network measures computed, if streets are related to one another in various physical ways such as through their intersection [Batty, M., Jiang, B., Thurstain-Goodwin, M., 1998].

Research using these techniques has found that spatial configuration has a pervasive effect on many aspects of social function. The main finding is that up to 80% of the variance in pedestrian and vehicular movement from space to space in urban areas can be explained by simple measures of the degree of integration of the street segment. Secondary important factors affecting pedestrian flows are the density of development of land indexed by building height and the predominant ground level property use [Penn, A., and Turner, A., 2003].

Space syntax suggests that markets in retail and commercial property may be affected by the spatial configuration of the city more directly and at a finer-micro scale than central place and gravitational theories of location have indicated. This is due to the fact that movement is the driver force for many urban phenomena, like retail land use locations, depending on people passing by. Retailing is highly sensitively to pedestrian traffic and therefore the rent rates can vary substantially even down to the lower scales (from building to building). Dynamics of urban land use and its relationship to configuration is characterised by feedback and may well exhibit non linear behaviour both in time and space. Movements imply processes of interaction over different time scales at different speeds from slow in years to fast in minutes and seconds. In many urban environments there are clear evidence for different location strategies emerging for prime market attractor functions and other sensitive functions. Certain uses in the urban fabric can be categorised as trip generators and have the power to alter the flow distribution across pedestrian network.  [Penn, A., and Turner, A., 2003].

Other urban phenomena (apart from land use and retail) have been found as well to be related to movement-configuration. These are: variations in property crime which is negatively related to pedestrian and vehicular movement rates [Hillier, B., 2004], variations in atmospheric pollution at head height which is related to vehicular flows and urban morphology [Penn, A., Croxford, B., 1998], spatial segregation in inner city patterns which is related to the degree of separation between different age groups use patterns [Penn, A., and Turner, A., 2003], and finally the continual rebuilding of urban structures and the changing economy of property [Batty, M., Desyllas, J., Duxbury, E., 2002].

### 1.3.3 Pedestrian movement and retail

Apart from space syntax theory, the influential socio-economic role of pedestrian flows on land use and land value and vice versa, has been approached and acknowledged by a big range of theorists and experts, including retail theory experts, shopping behaviour analysts, planners and psychologists. There is also a significant analysis and data of characteristics and factors that affect pedestrian behaviour while the individual-pedestrian performs a defined task, varying from shopping to just simple tourism.

Movement choices are governed by cost of movement and visual stimuli. At the human scale, interactions occur over different sized areas, each implying a different dynamics, purpose, and goal. Where interactions between people take place in very small spaces of the order of $10m^2$, then the dynamics of movement is dominated by density considerations such as crowding whereas over wider areas of $100m^2$ or even $10km^2$, movement is less characterized by geometry, more by cost and purpose. Cost of movement is determined by the distance and so the effort required reaching the end destination and the condition-width of the walking surface. Parameters like street furniture, localised congestion, generally obstacles, decision making with respect to what is immediately attractive and existence of green space along the route affect cost of movement. Knowledge of the environment and so ability to mentally reconstruct the layout of the city (mental maps or place legibility as it was phrased by the urban analyser, Kevin Lynch[4] [Lynch, K., 1960]) also affects cost of movement as it enables pedestrians to take the best and fastest possible decisions in their routes, reducing destination stress (mental stress created when pedestrian cannot reach destination in the way and time that he imagined). Visibility of the environment and its content is important too as what we see influence the way we move. Interesting spaces are those from which new spaces are visible [Turner, A., 2001a], while when a space is beyond the field of vision the promise of new information is a positive inducement to exploration. Three dimensional forms are also important and building components for example have been found to be important factors in preference for urban scenes. Kaplan and Kaplan suggested that spatial configuration may be more important than content in preference. Environmental preference tends to be associated with meaningfulness as we tend to like environments that make sense and offer opportunities for meaningful engagement. Environmental design has a significant impact on the path choices of visitors who are unfamiliar with the layout and content of the larger environment. The configuration of the street is important in arousing anticipation as some elements arouse curiosity, like for example partially revealed scenes with complex configuration in a shopping centre. Zacharias concluded that routes with a variety of shops are most likely to be chosen by pedestrians. Presence of people, signs, awnings and potted plants in front of stores had a significant effect on the path choices made by these groups of individuals. Their presence increases motivation to venture into the scene while their removal decreases motivation [Zacharias, J., 2001].

The other most important parameter influencing movement cost is the role of other pedestrians. People passing in a street reveal important characteristics of the local environment by their numbers, visible identity and comportment. If the presence of people and their activities is a major motivator for other pedestrians, then first path choices will tend to favour those already selected by others. This is more dominant in the case that the pedestrian is unfamiliar with the urban environment (visitor) as studies

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[4] According to Lynch [Lynch, K., 1960] mental representations, along with the actual city, contain many unique elements, which are defined as a network of paths, edges, districts, nodes, and landmarks.

have shown that in this case individuals tend to go to streets containing signs of human activity and mainly other persons. In urban settings, the absence of people often triggers feelings of insecurity (in contrast to fields-forest where visitors may be attracted by scenery without humans), which can be justified by the increased level of the perceived safety risks in the empty streets of modern cities [Zacharias, J., 2001]. On the other hand, increased numbers of pedestrians-crowding has negative effects and is undesirable as it decreases walking speed and may cause problems of discomfort (P-stress named from pedestrian) or even agoraphobia to some individuals. Thus apart from the direct interaction between individuals, pedestrians affect each other's decision in the meso scale by including other pedestrians activity into the process of calculating movement cost and choosing their trajectories [Zachariadis, V., 2005]. This is indication of a complex system with emergent phenomena.

In addition to all that it is worth to mention, as this will be used in the modelling strategy, that there is a variety of pedestrians-retailers circulating in the streets of a town centre each with a different agenda to perform and behaviour characteristics. These might be individuals that are familiar or not with the environment, goal-oriented shoppers with a strict shopping agenda, leisure shoppers that will visit many shops and tourists attracted by desirability of the area. The behaviours range from movements which are well defined and completely purposive to those which are more random and exploratory. Usually people unfamiliar with the environment, tourists, will tend to follow the movement stream of the 'locals'. As for motivational state, there are distinguished differences in estimated parameters between goal-oriented and leisure-tourist behaviour. At longer distances, there is no significantly a difference between these two, suggesting that pedestrian fields are dominated at this distance by distance only. At shorter distances, the probability of a store being included in a pedestrian's perceptual field is higher if the pedestrian is involved in leisure shopping. Goal-oriented pedestrians seem more focused in their perception and less open to signals of stores they don't plan to visit [Dijkstra, J., Timmermans, H., deVries, B., 2005].

## 1.4 Case for agent based approach

### 1.4.1 Reasons for using agent based modelling

From everything that has been stated until now, it is quite clear that agent based modelling is the most appropriate way to represent and model pedestrian movement. Especially now that recent development of powerful computing have made it possible to develop urban simulation experiments, with a variety of objectives and characteristics according to the needs of the researcher, that enable the detailed investigation of the dynamic interactions between different complex systems that control the processes of urban function, growth and change. Agent based modelling has many methodological and practical advantages compare to other methods of analysis and theory as it can be object-oriented and can deal with dynamic and emergent aspects of complex urban systems at the level of individual and with a bottom up approach.

At the meso and macro scales of urban environment, methods like pedestrian counting for pedestrians passing through the study area in order to explain and predict the impact of layout and visual stimuli on the movement patterns seems to be appropriate approach for urban simulation. However below a certain scale (micro scale), such as in town centres and shopping areas, particularly where spatial representation is more appropriate in terms of the built form (building blocks and public spaces) rather than territorial subdivision, aggregative approaches to explain and predict urban phenomena begin to lose their meaning. As we approach the human scale, relationships begin to articulate between objects rather than aggregates. In town centres and in shopping malls, location and movement is best described in terms of the individuals who use such spaces rather than in terms of their aggregation by social or any other attribute. Predicting local movements and the individual usage of urban facilities (as well as if it's required from the user, patterns of crime and deprivation), require an object oriented approach and simulation which will treat the populations involved as distinct objects or otherwise agents-individuals.  At these scales where all aspects of environment like buildings, public spaces, and streets must be represented as distinct objects, the associated behaviour patterns of individual users must be directly and explicitly simulated if impacts of changes to the geometry and formation of the local environment or changes of programmed agents behaviours-actions are to be understood [Batty, M., Jiang, B., Thurstain-Goodwin, M., 1998]. To develop models of such local behaviour, individuals must be represented and modelled explicitly too as distinct objects and from this comes the idea of 'agent-based' modelling. Retail uses can be extremely sensitive to location factors (related to rent rates as privileged locations equal to high rents) such as pedestrian flows, which makes modelling at this scale crucial to be as detailed as possible, bringing analysis down to individual detailed level. Thus agent based modelling is the ideal solution to imitate and understand issues related to the interaction between pedestrians and land use. This is entirely consistent with complexity theory where the complexity of the system emerges in global and structural terms from actions, each of which are simple in themselves, of relatively autonomous agents, acting with their own self-interest in mind, without appeal to any grand design or response to any overall global rationality or utility. Of course many systems cannot be characterised in this way but local movement patterns and behaviours in small-scale built environments appear to fit the approach rather well. [Batty, M., Jiang, B., Thurstain-Goodwin, M., 1998]

Space syntax theory has formed a useful unifying framework to enable research on the interactions between the different independent but interactive systems that are representative of urban environment and its functions. That is related to the fact that many aspects of socio-economic life are part of the space pattern defined by the built environment and thus to configuration of space methods of analysis. However these methods despite that they can help us to understand and analyse empirical data, they cannot deal with the dynamic and emergent aspects of urban systems at the level of individual. Space syntax as well is based on integration of space and street connectivity. These accessibility measures although providing indices associated with forecasting trip volumes, are not based on models which simulate processes of movement and thus do not provide methods for predicting the impact of locational changes on patterns of pedestrian flow. In short although these indices can show changes in flow due to changes in the geometry and location of entire streets, they are unable to account for comprehensive movement patterns which link facilities at different locations to one another. Although space syntax deals with movement economies, it has not yet been possible to link such indices to the socio-economic structure of the city at the local scale [Batty, M., Jiang, B., Thurstain-Goodwin, M., 1998]. The socio-economic function of the built environment can be viewed in terms of the interactions between various actors and agencies and thus agent based modelling is the way to achieve that.

Agent based modelling is beneficial as well for modelling local movement, as local movements must account for different varieties of behaviour ranging from movements which are well-defined and completely purposive to those which are more random and exploratory, based on walkers who are familiar and know the environment completely to those who do not know the local geometry and attractions of the environment at all. An agent-based approach is the only way in which we might account for such diversity and design models which can be tuned to quite different walker situations. To imitate real life phenomena, agents might be required to be programmed with intelligence capable of activity scheduling and rescheduling behaviour, learning the environment and adjusting to it and many other complex behaviours according to users needs [Batty, M., Desyllas, J., Duxbury, E., 2002]. Active and passive (end of trip, decision to return to gateway and exit the system) stages on the agents behavioural movement may also been adopted but in the pedestrian systems, good origin and destination data for each individual is never enough as it is the actual movement through the street system that is important.

### 1.4.2 Related work

There have been many approaches and explorations on agent based modelling. Simulation methods have shown considerable success in other complex social and economic domains thanks to the number of their attributes. Simulation methods are separated into two areas. The first is the use of restricted random aggregation processes to generate urban form by using different random, Lindenmeyer system and fractal growth processes. Examples are work by White and Engelen (1993), Batty and Longley (1994) and Erickson and Lloyd Jones (1998). The other area is in the simulation of patterns of movement and way finding through complex environments. The approaches range from those used for robotic navigation to the 'swarm intelligence' and flocking algorithms used to simulate animal behaviour in art forms. Penn and Dalton (1994) developed simulated automata and tested various rule sets governing way finding decisions to explore which resembles better pedestrian flows in cities [Penn, A., and Turner, A., 2003]. At Los Alamos, the TRANSIM model based on CA has been developed to model individual trip movements at the level of the automobile. An extensive research on the use of cellular automata to simulate pedestrian takes place as well in CASA (centre for advanced spatial analysis) at UCL. They have created CA agent based models to simulate local movement [Batty, M.,

**Figures 1, 2, 3: CA agent based models created in CASA at UCL.** Pedestrian flow in an idealised mall and pedestrian simulations for the Notting Hill Carnival.

Jiang, B., Thurstain-Goodwin, M., 1998], dynamics of small scale spatial events [Batty, M., Desyllas, J., Duxbury, E., 2002] and others.

Out of all them the most successful and the one adopted and used in this thesis (described analytically in the next chapter) is the use of agents that have vision and so can perceive their environment and other agents and act in response to that. This is a huge benefit in comparison to many CA systems where the agents are virtually blind as their view shed is restricted to their immediate neighbourhood of the grid only. CA systems are also problematic on cases where there are many local optima or where trip making is dominated by very specific destinations.

## 1.5 EVAS agents

EVAS (exosomatic[5] visual agent system) are agents with vision developed in the vr centre at UCL. The system allows large number of agents (released at any moment) to inhabit the same environment at the same time and move in real time on current PC computers. These agents have a visual field, which at any moment is defined by the boundary features of the environment and the agents' angle of vision and direction of

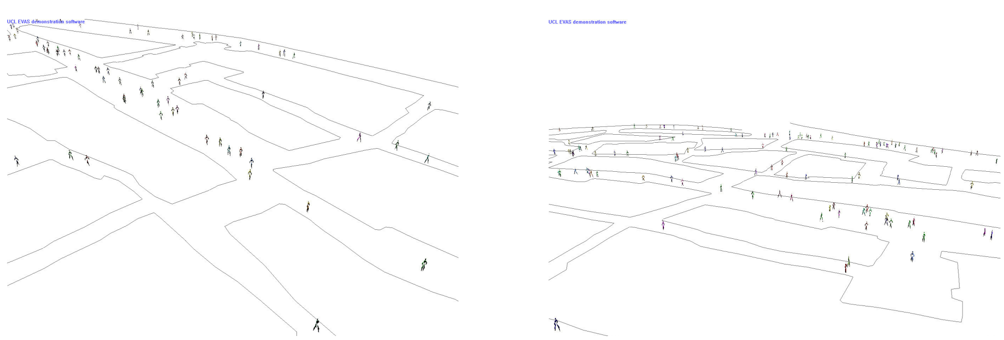


**Figure 4: UCL EVAS demonstration software.**

gaze. EVAS system gives agents simple visual perception of their environment using a dense grid visibility graph to guide agents. Solely by adding the ability to see we are led to an intuitively attractive model of human-pedestrian behavior: that the human moves in a direction that provides him  the potential for possible further movement. Gibson calls such interaction between human and environment 'natural vision'. Agents are given movement rules that depend on what they can see from where they are currently

[5] The visual architecture is called 'exosomatic' (outside the body) because the visual possibilities lie outside the agent, in the environment.

on the environment. Peponis attempt a categorization of a number of 'rules' of navigation: 1) avoid backtracking, 2) if all else is equal, continue in the same direction, 3) divert from the current heading when a new view allows you to see more spaces and/or activity ( that is other people) [Turner, A., Penn, A., 2002].

Agents with vision allow two types of interaction. The first is that agents can see and respond to each other which mean that they can be motivated-attracted by the presence of other agents and move towards that direction and that they are able to avoid each other without collision especially in cases of crowding. The second is that agents can see information on the boundary of the visual field and thus a block representing a building can be tagged with information to which an agent may be attracted to. That gives the opportunity to simulate complex behaviors like shopping, simply by giving selected parts of the boundary a 'taste' and each agent a 'hunger' (introduced by Mottram) which aims to satisfy by exploring the environment and trying to locate a 'taste' that suits his 'hunger'. 'Hunger' and 'taste' are encoded as random vectors that represent likes and dislikes [Penn, A., Turner, A., 2003]. When the vectors are aligned, then they appeal to each other, and the agent walks towards it. In the case of shopping behaviour, the agent can be programmed to enter the shop and stay there until its taste vector moves on and thus start looking for another 'taste'-shop.

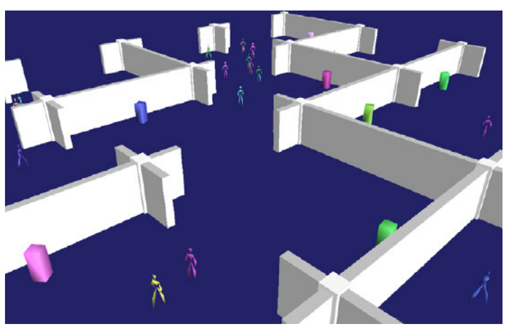


**Figure 5: Ecomorphic dialogues.** Viewers-agents and artworks (coloured blocks) within a 5 x 5 grid of rroms separated by columns. The colours represent the taste vectors of the agents.

Research has shown that programming the agents with the very simple movement rule: 'select a location at random from the entire plan area visible to you, turn and move in that direction, and repeat the process every three steps' leads to remarkably high correlations between aggregate agent movement flow and observed pedestrian movement in buildings [Penn, A., Turner, A., 2003]. This correlation is maximised when agents are given an angle of vision of 170˚, approximately that of normal human vision. Turner has proved that this agent rule correlates with observed pedestrian movement at least as well as space syntax ‘axial integration’ and better than visibility graph analysis [Turner, A., 2003]. This thesis accepts these facts and as a result coding of agents behaviour is based on those principles-rules.

EVAS agents are based on the biological concept of ecomorphology which examines the morphology of the organism in relation to the environment it inhabits. However, the organism itself is an active agent that shapes the environment that in turn shapes it. The two are linked through what autopoietic[6] theory calls structural coupling (in our case structural coupling between agent and the virtual urban environment), and thus the environment itself evolves as an ecomorphic entity. Active perception considers the natural possibilities of the environment as the motivator for action, indeed, for the process of perception as a whole [Turner, A., 2002].

[6] In Maturana and Varela's model of cell operation, each `unity' maintains itself as a distinct entity through a recurrent process called autopoiesis, which they regard as the defining attribute of living beings. If the unity is engaged with the environment, then the engagement occurs between their respective structures, which they call structural coupling [Turner, A., Mottram, C., Penn, A., 2004].

# Part II: Agent based simulation

## 2.1 Aims and objectives

The objective of the thesis is to develop an understanding of the dynamics of land use and its correlation to trip generation and flow distribution. The focus is on the investigation of the impact retail uses have on the movement flows of a number of pedestrian agents with various profiles and vice versa. A simplified shopping behaviour for the agents is modelled in order to get conclusions. The aim is to try to find solutions and answers about the relationship between spatial configuration of an idealised city centre, location of attractors-shops and the efficiency with which agents with long vision can search in a complex urban environment in order to satisfy their goals. The thesis concentrates on the agents' point of view, studying their behaviour and efficiency and how their visibility based programmed rules adapt and perform on the different spatial patterns, presence of open spaces or not, different initial origins-gateways, different agglomerations and dispersions of shops and how and whether all that and the different shopping behaviours affect patterns of agent movement as a whole.

In the first phase agents only with exploratory movement behaviour (not goal-oriented seeking to shop) are used. The purpose was at this stage to study the affects that spatial segregation and urban formation, of the chosen models settings, have on the agent's movement behaviour and the movement flows that they form. In the second stage, the environments are added with shops (defined information for the urban blocks) that the agents start to seek. The locations of shops (different at each case study) vary from total random distribution to aggregate clusters and streets but in almost all cases were influenced by the results in the first part (same urban formations and environments are used with the first phase as only agents behaviour and creation and relocation of shops change). The aim is to explore the differentiations that will provoke in the pedestrians flow and agents behaviour related to results from the first phase and between each case study-morphology in the same stage. By that it will be and practically (not only theoretically) proven, the significance-affect that retailing had in the experiments and so to pedestrian movement in an urban environment. Extreme case studies, i.e. crowding in the case of an event like open market or carnival, were also examined in the third phase for more coherent results which shows the broad range of possibilities and uses-studies that an agent-based model like that can have. In this stage, a third group of agents, goal-oriented, related and attracted by the 'big event' was added in the environment.

## 2.2 Modelling strategy

The model is visualised as a simple 7 x 7 urban grid, conceptualised as a city's centre. There are two main spatial configurations of the urban grid used for the experiments. The first is the ordered orthogonal grid, or otherwise the man-made city with the 'Euclidean' geometry, the case where man was allowed to create his urban environment[7]. The second is the random less ordered grid that uses a random factor to scale and misalign the blocks and the overall pattern. This spatial configuration represents the organic growth, the natural process of time in space with no man-made changes to spatial patterns. In all cases the heights of the blocks were kept low in contrast to how modern city's centre are, for visual reasons as the interest of the report and the analysis is generated from the agents paths-movement, which has to be kept visible. The area-surface of the model is considered to be a pedestrianised public space, easy to approach and walk able by all agents based on the fact that biggest percent of shopping and city's centres worldwide are now pedestrianised and free of vehicular circulation (with the exclusion in some cases of public transportation). Agents are allowed to move freely to any point across the environments surface in the x and y axes as long as the space is not occupied by another agent or urban block. The surface area of the system is modelled for easiness and better analysis with a grid of small squares. As the first agent steps on a square, the square changes its colour to red and then as other agents step on the same square the colour change its values with a small variation from to red to yellow in the colour range. The augmentation is on the values of red and green.

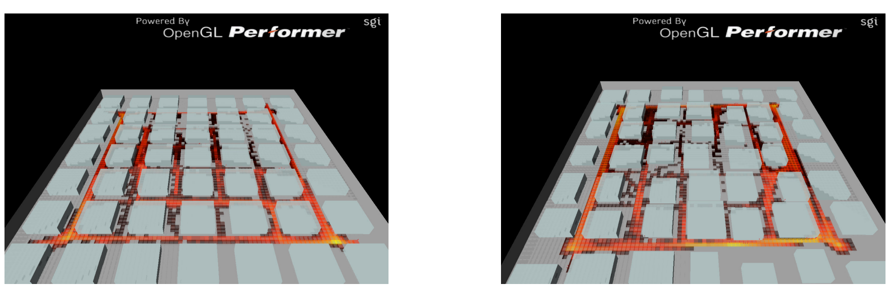


**Figure 6: The 7 x 7 grid of the environment.** The two spatial configurations of the orthogonal 'Euclidean' and random grid can be seen.

The code that changes the RGB values:

[7] With the first and most classical example the ancient Miletos by Hippodamos.

```
float r=0.2f, g=0.5f, b=0.2f;
mybox->getDiffuseColor(r,g,b);
mybox->setDiffuseColor(r+0.16,g+0.02,b);
```

There is the assumption that all the individuals who move within the model enter and leave the system at the same points, called ‘gateways’. These gateways will vary in the scenarios in order to obtain more completed coherent results. Gateways are either on the sides or the corners in a two-way or four-way system. A case where the gateway is in the centre (theoretical transport linkage, like an underground station) was also examined. That’s an abstract representation of the arrival points to the city’s pedestrianised centre in terms of infrastructure, i.e. underground stations, bus or tram stops, parking exits etc or even the gates of a walled-fenced historical city.

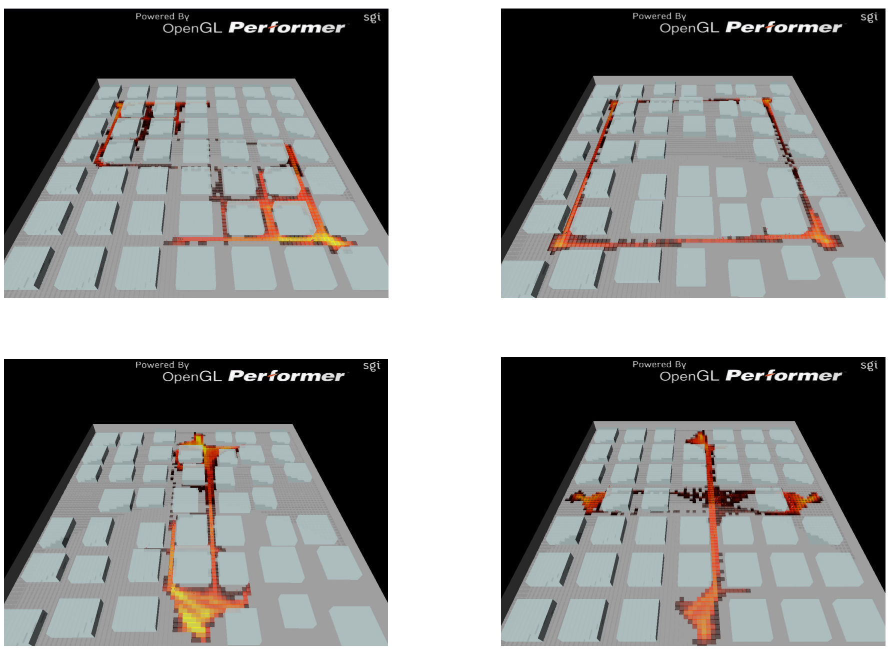


**Figure 7: Gateways of the system.** A 2-corner, a 4-corner, a 2-sides and a 4-sides system

The software agents are based on EVAS agents and have vision of their environment. This means that they have a visual field which at any moment is defined by the boundary features of the model’s environment and the agent’s angle of vision and direction of gaze. The agents are given movement rules (based on Peponis rules) that depend on what they can see from where their current location is in the environment. The rules are rather simple. The agents are programmed with three segments looking at three different locations, forward, left and right with a random angle value in the range of 0° to 90° to each side (that forms the total range of 180° which is that of a human vision[8]) and a maximum sight of 50 units that covers the biggest part of the 85 x 85 units environment. From the three values that will get, they will make a comparison of the lengths and choose the longest one. If there is a tie of the lengths, a random selection is made to move to a direction. That makes agents behave naturally and rationally as they are attracted and move towards open visible space. Agents are also attracted by the presence of other agents and will move towards their direction forming groups and recognizable movement flows. This is a significant social behavior.

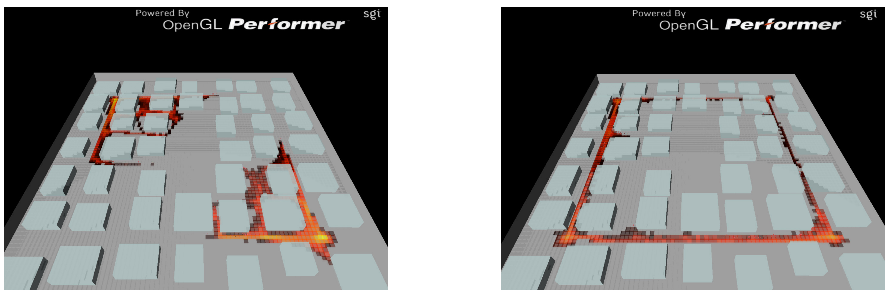



**Figure 8: Presence of agents as a motivator-attractor to other agents.** The photos show the difference in agents' movements and flows when they are visually connected to each other as those ones will move to that direction to meet the other instead of exploring the area

The matrix with the random angle value:

```
pfMatrix leftmat, rightmat,smat;
float angle = float(pfuRandomLong() % 90);
```

Segment looking left::

```
leftmat.makeRot(angle, 0.0f, 0.0f, 1.0f);
dirs[0].xformVec( dirs[2], leftmat );
dirs[0].normalize();
```

Comparison of lengths coding that if left length is the longest one then turn towards that direction:

```
if (lengths[0] > lengths[2] || lengths[1] > lengths[2]) {
    if (lengths[0] > lengths[1]) {
      mat.preMult(leftmat);
      m_speed = lengths[0] / 100.0f; }
```

The agents are aware of the environment only from their vision (not any extra scripted information) and so they don't acknowledge what is further than to what they can see

[8] Studies have shown that the average male has an angle of vision 170° and the average female 180°.

and especially where shops are located, and thus they have to search for them. If the agents never get a visual contact with a shop matching their taste-criteria they will never visit it. One of the purpose of this thesis is to study the efficiency of this search behavior of the agents and corelate with real persons search behavior. That provides more coherent results on the importance of spatial configuration and shop location as scripted knowledge of the environment would alter route choices (faster and easiest route to reach destination, cut ways instead of following the open, visible and crowded arteries of the system) and so diminish the importance of the parameters that are the focus of the study. Search behaviour is organized according to nearest destination strategy and thus agenda, and agents are seeking for their nearest located and not already executed-visited goal. Agents are connected to each other through location attractor-shopping and through congestion. In this way, various feedbacks are reinforced and the system can be self-organizing. To script the search behavior, the agents are separated to types according to their taste vector. The taste vectors are vectors with a defined color in precision of two decimals in RGB (red, gree and blue) values. Each store (agents' goal) has a prescribed color and so if the agent's taste vector is exactly that color (exact numerical precision is required in these experiments as no flexibility is provided), the moment that the agent will be visually connected to it, he will start walking towards it, enter it (pass through it) and exit it, starting the search for a new shop matching his taste. When the agent has fullfilled a visit, he adds the particular box number (each shop-box or urban block has a prescribed number) to his visited list to avoid visiting it again. The separation of agents to types, different color boxes, enables the separation of agents according to the objectives of their trip (goal-oriented, tourists etc) as in real life for the requirements of each experiment.

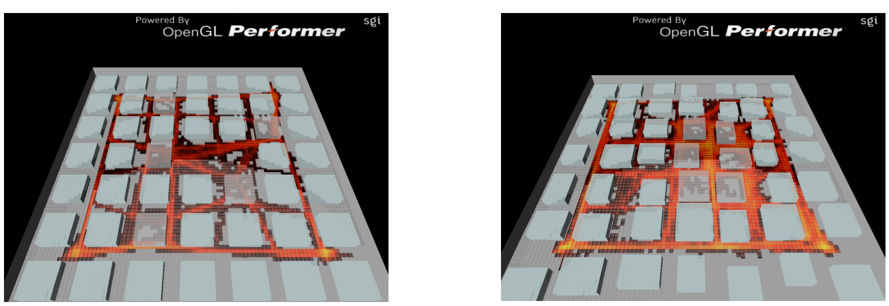



**Figure 9: Different shop locations and distribution.** A random distribution of five shops and an aggregate cluster of six shops.

Separation of agents to agents types according to what taste vector (colour of block) they have:

```
m_agent_type = agent_type;
```

```
if (m_agent_type == 1) {
   m_taste_vector = pfVec3(0.89f,0.90f,0.90f);}
```

The rules saying that if the agent has a visual contact with a shop matching his taste vector and has not visited already, to visit it and add it to his visited list:

```
if (!visited) {
        mb->getDiffuseColor(r,g,b);
        pfVec3 shop_taste_vector = pfVec3(r,g,b);
        shop_taste_vector.normalize();
        pfVec3 my_taste_vector = m_taste_vector;
        my_taste_vector.normalize();
            if(m_taste_vector == pfVec3(r,g,b)){
                m_target = boxnumber;
                m_visited_list.push_back(boxnumber);
                 tpoint = result.point;
                 tpoint.xformPt( tpoint, mat );
                 dir = j; }
```

Each agent enters the model-environment with a goal-aim or otherwise a set of spatial related tasks-objectives to satisfy. The agents are actors-shoppers with a shopping activities schedule. They are separated into three main categories according to their objectives and behavior-movement, related to their shopping behavior-desire. These are: 1) agents with no specific intention, tourists, attracted by desirability of spaces and aim to explore the environment (used in phase one and most of the experiments of phase two), 2) leisure shoppers with personal shopping and other activities agenda and thus agents attracted by more than one destination-shop (used in phase two and three) and 3) goal oriented agents with a fixed destination as one shop and strict time schedule (used only in phase of three as visitors of the special event, market). The first ones don’t have a taste vector and so their behavior is limited and ruled by their visibility, thus attracted by open space and other agents. The target is the investigation of the impact retail uses have on the route selection of this number of pedestrian agents with the various profiles. Studies of whether these groups affect each other in their movement and behavior are also done as characteristics of interaction and emergent behavior. It will be shown that to a certain extent they do, as the agents with taste vectors seeking for shops create new paths and so crowded flows towards the location of the stores, which the ‘tourists’ agents will be attracted to and follow as well. On the other hand, it will be shown as well that the presence of ‘tourists’, strong axial lines and so crowding distracts the shoppers from their goal and reaching directly their destination. This is a proof of  the significance of retailing to pedestrian flows.

One of the aims for the model was simplicity and control. The user by simply manipulating the code is able to control the frame and characteristics of the model as well as agents behavior in order to examine the case study-scenario that he desires. In the past, many models particularly large-scale land use and transport models were regarded as unnecessarily complicated and unwieldy. In many cases users did not understand how the models worked, a serious issue considering that the purpose of a model is to learn more about how a system functions [Torrens, P. M., 2000]. In this thesis the model was kept simple concentrated only to the defined issues to make it easily readable to everyone with a simple visual interaction. For this reason the area of the environment is only a 7 x 7 urban grid as it is time efficient, rather fast to run a simulation in real time, and walk able in real life terms (cost of movement).

## 2.3 Modelling platform

The model's software is scripted using C++ programming language with open GL Performer. Open GL Performer is a powerful and comprehensive programming interface for developers creating real-time visual simulation and other professional oriented 3D graphics applications. It is an object oriented language, based on the same ideas with agent based modelling and bottom up research approach. Therefore the use of it for agent modelling, offers many advantages like speed, existence of libraries and flexibility. It also enables the recreation in 3D form, a more realistic approach for coherent results especially in our case that the agents respond to their vision, in contrast to for example swarming methods and CA that are recreated in 2D. Also the use of classes in the script provides flexibility to deal with any aspect and behaviour of the agents' movements in the environment which are easily categorised and grouped for better control.

## 2.4 First phase

### 2.4.1 Orthogonal grid

In the first phase of the experiments, agents with no taste vectors are used. These agents don't have any attractors and so their only activity is exploration of the area as this is ruled by their visibility of open space and other agents. The purpose is to study various different settings of spatial configurations and the flows and rates of pedestrian movement that these will form.

In the very first stage and series of experiments a simple 7 x 7 ordered ‘Euclidean’ grid was used, a rather idealised economic city centre. This ordered uniformity is projected on the agents’ flows as well as the experiments show strong axial lines of equivalent movement rates in all experiments, the formation of long Haussmann like ‘boulevards’. The rates are only affected by the location of the gateways as in the experiments with gateways located on the sides; there is less movement on the corners of the environment and more on the central streets that link the gateways. This is reasonable as the agents’ groups entering from side gateways are visually connected and so attracted through the central streets of the system, increasing by that the movement rates towards the centre of the system.

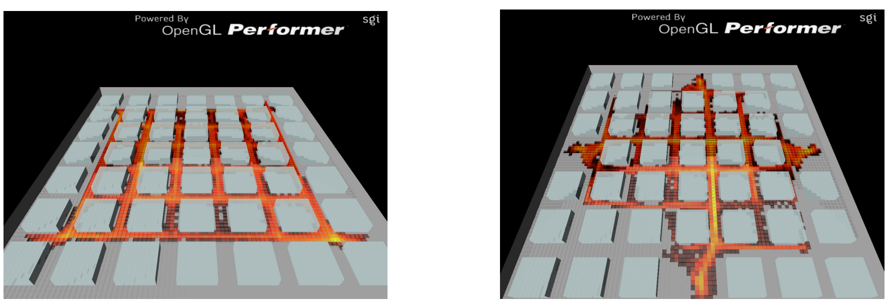
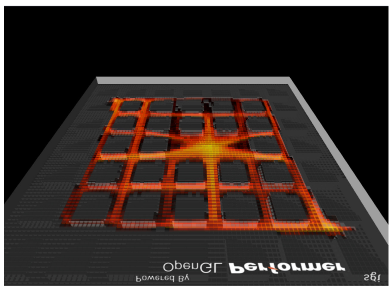



**Figure 10: Different rates from fifferent gateways.** A four corners and a two sides system.

The next stage-step in the experiments was the insertion of open space in the environment by keeping two or three urban blocks free-empty. These blocks which are centrally located are the same in all phases and stages of the experiments to enable comparisons and safer and easier conclusions to be made. The purpose was to study the affect of these spaces considering that the agents are programmed to be attracted by open visible spaces. This is an abstract idea-representation of openings in dense city environments in the form of ‘piazzas’ and squares or parks. For the needs of the experiments these areas were kept walk able for the agents and no parameters (trees and greenery or street furniture and cafeterias) that characterised these spaces and block or obstacle pedestrian movement were modelled. The experiments show that the open space affects the behaviour of the agents. The agents as they are attracted by open visible spaces concentrate in the open space making it the ‘centre’ of their action. Rather strong axial lines are formed with the streets, on the sides towards the directions from which the agents arrived from their gateways. The linearity appeared in the first experiments without open space, has been diminished and replaced by a more radial pattern of flows generated from the central open space. It can be seen as well that the geometrical centre of the open spaces is the cross by of all agents' movement spreaded radial, and that on the sides exactly in front of the blocks façade movement is minimum. It will be shown in the next phase how a presence of a shop at one of these locations alters the flow patterns.



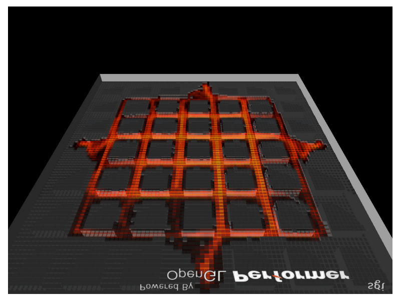


**Figure 11: Linear and radial patterns.** The radial patterns generated from the two blocks open space compare to the linearity, boulevard like, of the normal orthogonal grid.

### 2.4.2 Random grid

In this series of experiments the urban blocks of the 7 x 7 grid were slightly misaligned and scaled using randomness. The idea was to create by that different visibility conditions as the lines of sight are much smaller from the broken street alignments, to provide an alternative more organic distribution of urban blocks (as the ones someone experiences in the centres of historical, medieval cities) and create new more interesting places like squares and corners and all that by preserving the same 7 x 7 block alignment. The aim was to study how the agents will respond to these deformations. After all, organic growth 'fractal alike' through the history of time always created narrow pathways and interesting small open corners or squares that visually attract visitors-pedestrians and increase the curiosity for exploration of the area. This is a totally different result and affect compare to man made uniform grid with 'boulevard' like streets that are definitely more functional with clear open ways-flows but not visually pleasant and interesting in the way of the different and unexpected as the individual moves. On the other hand the orthogonal grid provides long line of sights and so a much easier pattern for the pedestrians to memorise and orientate[9] themselves which in our days that time factor is important for all the socio-economic reasons is a great advantage for a city centre. Reaching a destination in a uniform ordered urban grid is much easier and faster. After all cities structured with long and wide 'boulevards' have less traffic problems.

The experiments as it can be seen from the photos (appendix A10-14) show more organic patterns and different rates of circulation and axial lines integration. High movement rates are gathered where longer lines of sight are present either in the form of linear spaces or openings formed by small open spaces, square like areas. These small open spaces provide bigger walk able areas and direct links to other streets, and so attract the agents as they explore the environment making them their focus of attention. The misalignment and scale of blocks allows the agents to move directly to these spaces, even diagonally, not having to follow always straight lines and turns at right angles. This breaks the monotonous orthogonal geometry that was encountered in the first series of the experiments, and provides a more unequal and organic formation of patterns and flows. Another interesting detail is that in the experiments with the side gateways (especially in the 2-sides entrance system, appendix A13) patterns preserve the same organic form but the rates-flows present a stronger linearity as a result of the smaller distance to the centre of the system and thus the faster visual connection of the agents groups. It is also interesting that the number of agents-population doesn't affect the patterns and flows, only movement rates, as the experiment with only 20 agents (appendix A12) present the same results.

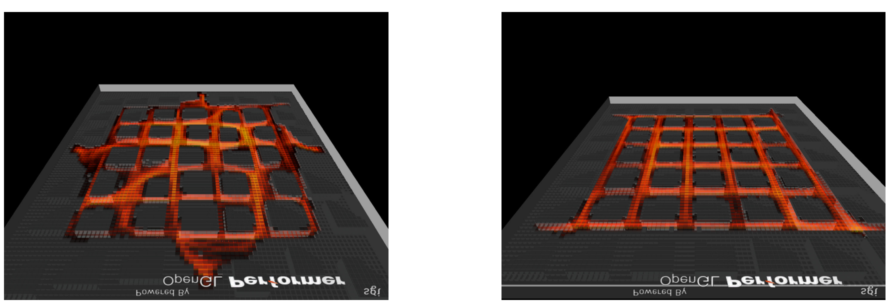


**Figure 12: Organic patterns.** The organic patterns and the different rates of flows and axial line integration in the random grid compare to the orthogonal grid.

[9] The most classical example is the area of Manhattan in New York City, an ordered orthogonal grid where streets (horizontal) and avenues (vertical) are named with numbers in sequence, i.e. Fifth Avenue and 23rd Street, making it extremely easy to orientate and memorize.

The next stage-step of this part of the experiments was again the insertion of open space in the random deformed grid. The agents and in this case, as in the experiments with the orthogonal grid, make the centre of the open space the epicentre of their action forming radial flow patterns generated from the centre. The difference is on the organic patterns presented in the surrounding streets as the agents search the environments. The experiments also presented a difference in time as the disordered spatial configuration delayed the agents from visual connect and reach the open space. It is also very interesting that in all cases the big open space has a strong line connections and present high rates with a small square on the bottom left corner of system created by the random factor. The experiments in most cases present a clear link that unifies these two open spaces (appendix A15-17). Other strong axial links are presented on the linear spaces to the directions of the gateways which especially in the experiment of the two corners gateways (appendix A18) are even stronger than the axial link connecting the open spaces. In the only case study (appendix A21) that the gateway was in the centre of the environment and so in the epicentre of the action, the agents remained in that area with extremely high movement rates not exploring the rest of the environment (for this reason this gateway system was not used again).

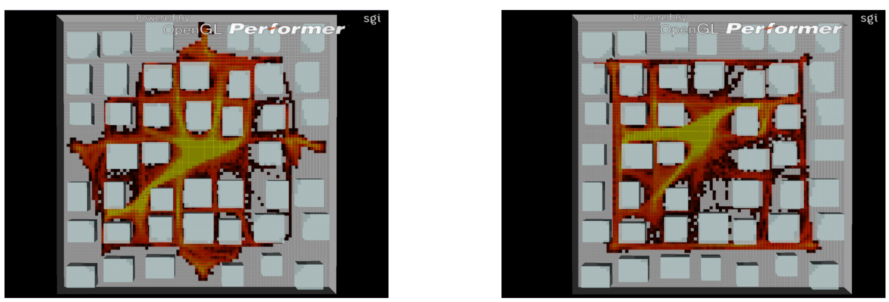



**Figure 13: Axial links of the open spaces.** The strong axial link that unifies the two open spaces and the axial links towards the directions of the gateways.

## 2.5 Second phase

### 2.5.1 Random distribution

In the second phase of the experiments agents with taste vectors are used in the environment. These are leisure shoppers with a personal shopping agenda, aiming to search and locate-visit the shop-urban block that has the colour and so matches their taste vector. Only one type of shopper agents and thus and one category of shops is used in this phase of the experiments. The purpose is to study how pedestrian rates and flows will be altered by the different spatial configurations and shops distribution in the environment, compare to the first phase. This will prove the significance of retailing in the environment and thus in real life as well. Efficiency of agents search behaviour will also be examined to prove efficiency of methodology in this kind of experiments. For more coherent results and safer conclusions, tourists-agents with no taste vectors are also added in most of the experiments in a percentage of 37.5% of the total population. The purpose is imitating real life's complexity and to study and understand the influence that these agents will have to the search behaviour of the shoppers and vice versa. This is a proof that the environment is an emergent system where alterations and different set up in the micro scale (agents) will affect and determine the end result of each experiment, analyzed with the method of synthetics. All the experiments in this phase use four corners gateway systems in order to study and compare at the same time the search behaviour of the agents starting from the most remote locations and arriving from all sides at a shop. Each shop considers being a whole urban block and so entry and exit is provided on all sides.

In the first stage of this part of the experiments a random distribution of five to six shops was examined (same distribution was tried to be used in all experiments of this stage which reduces the number of shops to five when an open space is inserted). The experiments show patterns rather similar and related to the ones seen in phase one but with higher rates in the areas surrounding the shops. The only difference in the patterns is that the axial lines are not straight along the length of the streets but break to two segments in each case aiming diagonally at the shop located on that street. In general the agents enter the environment and start their exploratory behaviour in order to locate

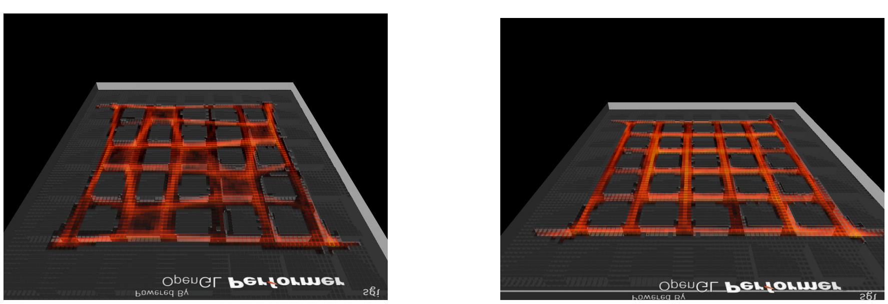


**Figure 14: Random distribution of shops.** The similarity of the patterns between the random distributed shops (left) and phase 1 (right). The only difference shown is the breaking of the axial line along the streets in two segments aiming each shop

and visit the shops. When the agents exit a shop they start searching again unaware of the location of the other shops. This behaviour is exactly the same when a shop is not visible (most of the times in these experiments) with that of the tourist agents which explains the similarity of the patterns and the rates. Spatial configuration is more important than shops location in these cases as single distributed shops don't have the strength on their own to affect the rates and patterns (it would make a difference only if the agents were aware of the location, a landmark shop, programmed to visit it from the beginning). Different but strong axial links and high pedestrian rates are presented in the cases where there is a clear visual and linear connection between two shops and searching effort is minimized. In these cases when the shoppers exit a shop they move directly in a straight line to the next visible one which proves and the efficiency of the methodology, to use vision agents. This is more clearly seen in the experiments where only shoppers are used (appendix B3) which present polygonal patterns, diagonal links from and to the other shops, especially when the shops are located in blocks surrounding an open space and thus visibility and ability to walk directly on the destination is higher.

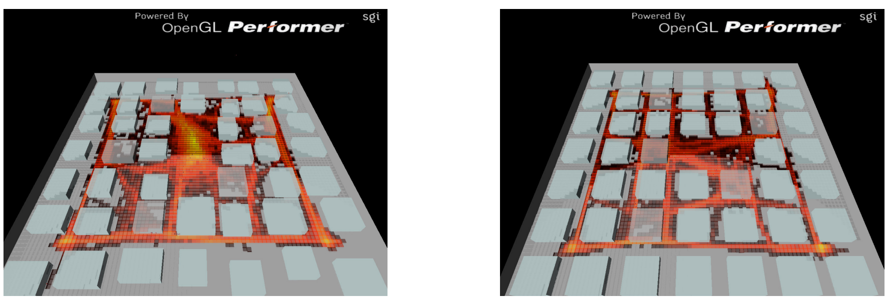



**Figure 15: Polygonal patterns in random distributed shops.** Strong axial links are presented where there is clear visual and linear connection between two shops, forming polygonal patterns.

The experiments prove as well the importance of the strategic location of a shop in an advantageous site. In all experiments the insertion of open space attracts the agents and provides higher visibility levels. The agents easily and quicker discover the shops that are located in the surrounding blocks, which in their terms benefit from that and present the highest rates of agents visits. The agents spend more time in the area of the open space in order to visit the visible shops and only after they visit all them, they continue their search for the more distributed shops which in their terms present the lowest rates. Although it is interesting that in all experiments, as 'the first you come to' rule is applied, the first visited shops (crucial in retailing) are the ones located near the gateways, the ones that the agents discover first as they exit the gateway and enter the system. This is a rational behaviour from the agent's point of view (start of their shopping journey and so greater anticipation and desirability) and the most advantageous location in terms of shop distribution for this type of systems which have controlled and defined entry points. An exit from an underground and especially train station provides an easily estimated number (by analysts with the method of pedestrian counting for example) of populations to attract. Especially if the area is characterised by a defined land use (specialised shopping type) and thus a percentage of agents with a well known and predicted agenda-goals to satisfy for the shopping analysts. Shops located in the surrounding blocks will aim to be the first to satisfy the agents' goal and benefit economically from that.

### 2.5.2 Street alignment

In this series of the experiments a total of ten shops are aligned on the two sides of the central street, the centre of the environment. This is an abstract representation of a central shopping street in a city's centre, especially in smaller towns where there is a separation of land uses, where every shop might benefit or not from the presence of competitors but all together will form a massive attractor, a sink for the population. This formation provides time efficiency and decrease of cost of movement as once the first shop is found, and so the street alignment, the rest will be found with little additional effort. In real life terms a similar formation will enable and increase the probability of a shopper that will satisfy his goal as he is provided with many choices in short distances, without having to search further in more distributed locations. It also provides the opportunity of selection, as the shopper can view all the shops aligned, count and acknowledge his choices and select the most preferable ones.

The experiments show that once the first shop has been found, the subsequent ones are found with minimal additional effort and lot of time saving. In the ordered orthogonal grid finding the first shop and the alignment is a fast procedure (as the spatial configuration enables at least one shop to be visible at all times from almost every angle of the environment) while in the random grid slightly more time is required for the agents that might get confused by the spatial configuration and the smaller length of their vision segments. In all cases as the agents enter the alignment and are visually connected to all the shops, they will remain in the street alignment until they satisfy their goal, neglecting and not searching the rest of the environment. The experiments shows that in this formation all the pedestrian flows and rates are gathered along the lengths of the shops sides especially in the case studies that only shoppers were used. In all cases the pattern created is a grid of strong axial lines around the shops and so the alignment (as all shops-blocks can be approached, entered and exited from all sides), connected on the edges with strong axial lines to the gateways as the edges which are visible are the shortest distances to the gateways.

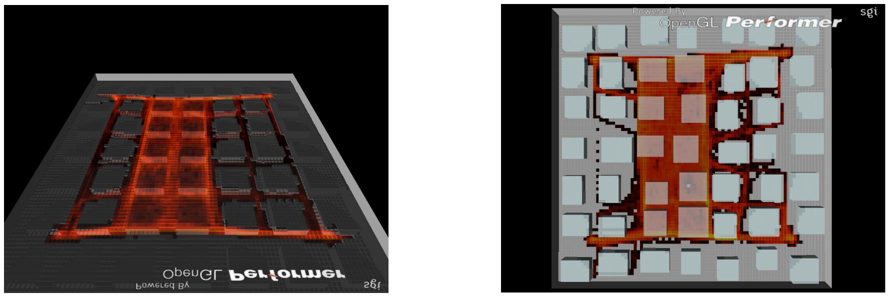



**Figure 16: Street alignment.** The grid of axial lines and flows around the shops in the alignment. Strong axiall lines are presented where the alignment is connected with a gateway.

### 2.5.3 Clusters

In this series of the experiments neighbourhoods, clusters of four or six shops are used in the environment. The idea was to recreate central shopping districts that are common in most cities and form a major attractor for the shoppers. In the first stage a cluster of six shops (appendix B10, 11) is inserted in the centre of the environment. The formation is rather similar to the street alignment (only number of shops change) and thus and the results present many similarities. The cluster creates as well a sink to the system presenting higher rates of movement, as the agents as soon as they detect the first shop they will remain in the area to visit and the rest. The pattern formed is again a grid of axial lines around the shops. The only difference with the street alignment is the time taken for the agents to locate the first shop as the cluster is formed by a smaller number of shops, especially in the random grid where more exploratory movement is required.

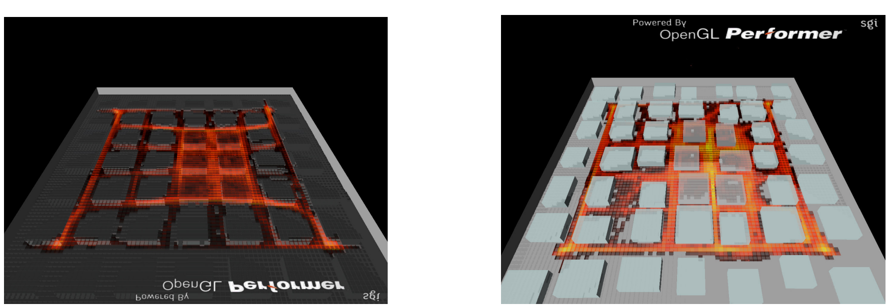



**Figure 17: Single cluster.** The patterns present similarities with the street alignments, as a grid of axial lines is formed again.

In the second part of this series the single cluster was divided in two clusters of four shops distanced from each other (appendix B12, 13). In the ordered orthogonal grid the two clusters present identical patterns and rates as their location is symmetrical to the gateways. In the random grid one of the two clusters was deliberately located exactly where the random factor in the random grid has created a small open space-square (described in phase one). The purpose was to study how an area that presents already high pedestrian rates will profit from the creation of retailing (strategic location, increase of rates). In contrast the second cluster is located in an area rather neutral and uninteresting in order to examine if the presence of shops will upgrade the area and increase the interest of agents-population. The experiments show that both areas are profited as they have a significant increase of flows and rates, which is more important for the second cluster located in more disadvantageous area and a great proof of land use dynamics. Strong axial links are created in the streets connecting the gateways and located on the sides of the cluster as almost all agents come from these directions. Very strong axial links are also created on the two streets that are common and connect the two clusters to each other. The clusters are visually connected that enables faster pedestrian movement to each other, an exchange of population and so shared distribution of rates and flows. This is a difference compare to the single cluster system where movement becomes more localised (static as it is seen in macro scale), a sink to the system.

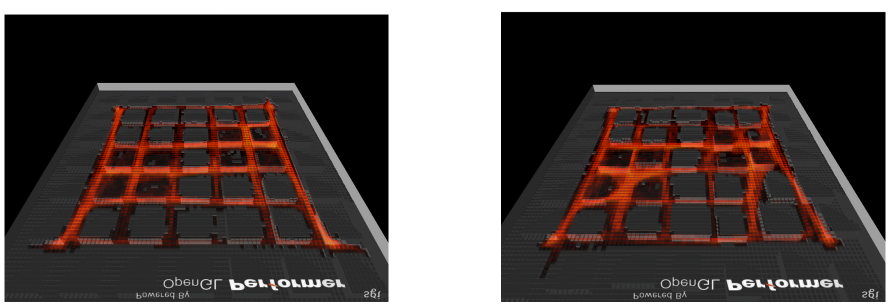


**Figure 18: Two clusters.** The symmetrical identical pattern in the orthogonal grid (left) and the more organic pattern in the random grid (right). The strong axial lines that connect the two clusters are easily seen.

In the third part of this series the second cluster was replaced by the open space. The agents as they enter the open space from the various streets-entrances they get visually connected with the cluster which becomes the focus of attention and start walking to that direction. That forms a very strong axial link of the two spaces which becomes more intense with an increase of rates and flows inside the cluster as it is the centre of the shopping activity of the environment. Even the 'tourist' agents seem to be affected by the strong movement flows towards the cluster and follow the crowd. The experiments show that the centre of activity and so the centre of the radial pattern in each case has been transferred on the bottom left corner of the open space, attached to the cluster. It is interesting as it can be seen from the experiments (appendix B16, 17) that in the cases of the three blocks open space as it is oriented vertically and has more street entry points, the patterns formed have a more clear radial formation with strong axial lines connecting the street-entrance of the cluster with the four streets-entrances from the other side of the open space.

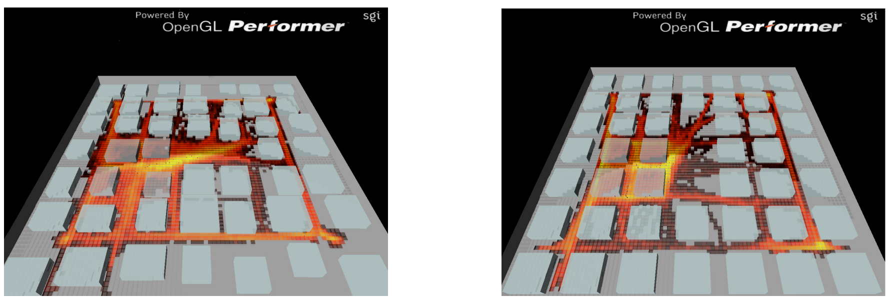



**Figure 19: Cluster attached on the open space.** The centre of activities have been transferred on the bottom left corner of the open spaces, in the entrance of the cluster. In the case of the three blocks open space (right) the radial pattern is easily recognized.

It can be concluded at this stage that the experiments show the dynamics of grouping shops together in formation of a street alignment or a cluster. These formations alter dramatically the pedestrian flows and rates presented in the first phase determined only by the spatial configuration. Shopping as an activity-attractor is much stronger in these cases than spatial configuration and the formations become the centre of activity in the environment, rewarded with higher visiting rates from the agents. This is compared to the random distribution of almost the same number of shops, which as they are separated from each other, an attractor on their own, depend more on the exploratory behaviour of the agents and thus spatial configuration. The experiments also show how beneficial for the agents is grouping in terms of movement cost, minimized search, knowledge of choices provided and so times saving as the distances between the shops are visible and closer.

### 2.5.2 Sides of open space

In this series of the experiments only case studies with open space are examined with addition of shops on one or two sides of the open space. The purpose was to investigate how retailing and the premium location of the shops in terms of their facades visibility will benefit from the high rates and flows shown in the first phase of the experiments and to what extent they will alter them. It was shown in the first phase that the geometrical centre of the open spaces is the cross by of all agents' movement spread radially, and that on the sides exactly in front of the blocks façade movement is rather minimized and urban blocks are ignored. The experiments show that the addition of shops to one side of the open space (appendix B18-22) has a great affect. In all cases the centre of activity has been transferred from the centre of the open spaces to the area exactly in front of the facades. All the shops receive extreme rates of pedestrian movement, centralised in the small street between the two shops in the experiments with the two blocks open space and infront of the central shop in the experiments with the three blocks open space. It is interesting that in the case when only shoppers are used (appendix B21), the open space becomes more like a transition area as the flows form rather a grid pattern around the shops similar to the street and cluster alignment. From all experiments studied, distributing shops on the sides of open spaces shows the most potentials and benefits, in terms of flows and number of visiting agents (of course an important factor is their monopolic identity as these experiments count only two to three shops in total). Spatial configuration has created strong pedestrian flows and the strategic positioning of the retailing shops in these cases make a great use of it.

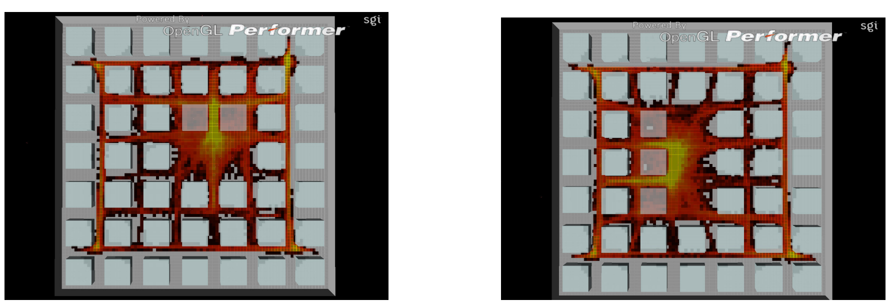



**Figure 20: Shops on the sides of the open spaces.** In both cases ths centre of activity has been transferred on the area infront of the facades.

In the second part of this series shops are added on both sides of the open spaces (appendix B23, 24). The experiments show that the centre of the activity-environment is again the centre of the open space as rates and flows are equally shared between the two sides. The patterns created are similar with phase one with the only difference that the rates are more uniform distributed in the whole area of the open spaces as the agents move from side to side to visit all the shops rather than use the space as a crossway linked with further destinations.

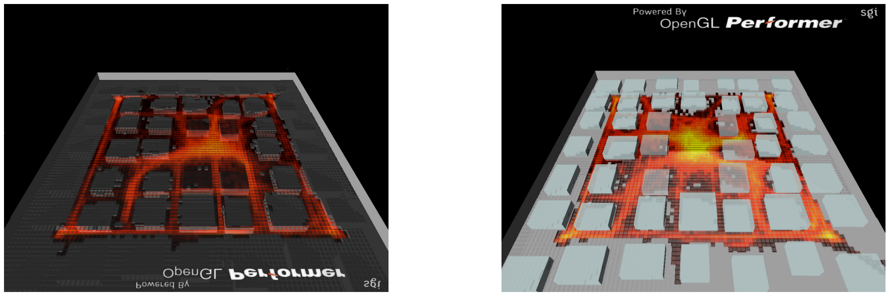



**Figure 21: Shops on both sides of the open spaces.** Rates are uniform distributed in all area of the open spaces.

## 2.6 Third phase

One of the greater opportunities that agent based systems provide to researchers, is their flexibility to include many different elements and factors simultaneously in the aid of the required analysis. Many different case studies and urban phenomena can be easily studied and analyzed. For the purpose of this thesis as it is focused on the particular aspect of retailing and pedestrian movement, modelling of the environment was kept simple only with the elements required to fulfil the first phases of the study. As a further step and future phases of the research, complexity can be increased as a start to create a fully emergent system. By adding continuously new (missing) elements in the environment someone can get closer on fully simulating a real urban scenario. One of these factors, urban phenomenon, studied in the third phase of the experiments is the case of a city's big event. Here as big events are considered events like a festival, a concert, a sport event, a street parade, a great opening or an open market used in this case, events which in general will form a major attraction for a part of the population that will visit the area just for this event. These kinds of events can easily become a reason-source to cause problems of crowding, safety and possible failure of infrastructure (mainly for the events that number of visiting persons can vary) in the particular urban area. Models-systems like the one developed in this thesis can be easily used as a method to predict these unpleasant phenomena and a mean to provide alternative solutions for security reasons, like the provision of alternative routes in congestion problems and escape routes if any need. Big events are typical phenomena in city's centre, in an effort to provide to the citizens entertainment and information, lead to cultural progress, economic development and prosperity to retailers and land owners. Thus study of them is totally essential.

In the third phase of the experiments (appendix C1-5) the scenario of an open market event is added in the study. The open market is modelled as three or five smaller urban blocks located in the centre of the open spaces. A third group of goal oriented agents is added in the environment for the purpose of this phase. These agents are attracted only by the event in a 45-55% of the total population (the rest are the shoppers as in phase two). The purpose was to investigate whether this event will have an impact on the shopping activities and the results produced in phase two. For a more realistic set up a 40-50% of the goal oriented agents is located in the area of the market from the beginning and does not enter from a gateway.

The experiments show that patterns and rates concerning the shops remained the same with phase two. The reasons are that number of 'shoppers' is the same with phase two and  that dimensions of walk able area, as width of streets and openings, allow all agents to move freely and thus reach their goal-destination. Crowding is an issue in the experiments but affects only the cost of movement of the 'shoppers' in terms of time delay and perhaps tiredness and not the end result of shops visiting rates. The only difference in rates is in the area of the open markets. All area of open space is highly visited as a result of the open market and presents high rates of pedestrian rates and a rather uniform, equal distributed flow in all the area of the open space.

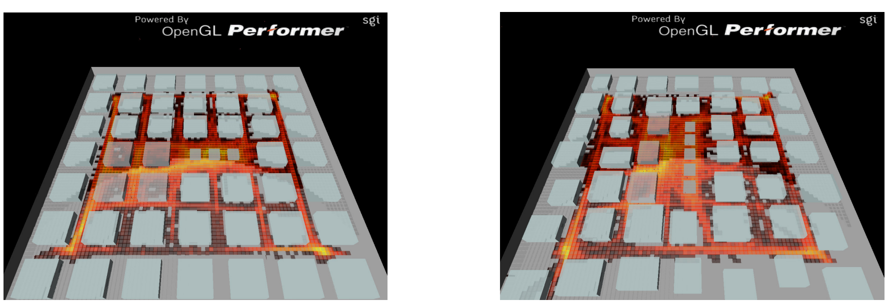



**Figure 22: The open market.** Rates of visiting shops are the same with phase two. The only difference is on the rates and flows in the open spaces whare the markets are located.

In these experiments it was considered that 'shoppers' have the same numbers with phase two and about the same with the market visitors. In real life scenario conditions will be most probably different which raises many issues. In general the event acts as an attractor of its own goal oriented agents. Shoppers most probably will try to avoid crowding and try to satisfy their goal not on that particular time of the event but at a different moment as they have that opportunity of choice. It is rather difficult to predict what percent of the population will be affected and take that decision. The shops will have then to make use of premium strategic location if any, in front of open space to attract population that will be in the area for the event but not have planned to visit these shops. These details show that as the system-model evolves with more complexity new issues-problems start to rise in terms of modelling as well. The main difficulty is that by adding more complexity and new parameters even modelling and scripting of the set up becomes a matter of complexity. The system-result will be emergent but the initial elements in micro scale (mainly in terms of agents behaviour and programming) require a more precisely analysis and investigation before they are included in the system as they are the ones that will determine the end result and have to be correct. One further methodological problem in this stage was that the increase of the number of urban blocks affected the random factor and so the spatial configuration of the random grid was different from the first two phases which restrained the ability to make comparisons and generate safer conclusions.

## Conclusions

The experiments show that as suggested by space syntax, markets in retail and commercial property are affected by the spatial configuration of the city more directly and at a finer-micro scale. In the experiments as in many urban environments there are clear evidence for different location strategies emerging for prime market attractor functions and other sensitive functions. Certain uses in the urban fabric can be categorised as trip generators and have the power to alter the flow distribution across pedestrian network. The experiments prove that a shop acts as an attractor on its own but is much more benefited and really affects movement when is grouped into a cluster or street alignment, forming by that a major attractor to the shopping population. In these cases, shops formation affects and has the strength to alter the pedestrian pattern and flows of the environment. Thus is the whole process of shopping activity in the long run that determines movement and not the individual shops visit. On the other hand when shops are randomly distributed is spatial configuration and so strategic location that provides high visiting rates and economic prosperity. It is proven for example that open spaces created either by keeping blocks free-empty or by the random factor, act as a major attractor for the agents. Shops located in the surrounding area, even if they are not grouped and are randomly distributed, are benefited from the high movement rates and flows and their well visible facades. The presence of people and their activities is also shown to be a major motivator for other pedestrians, and first path choices will tend to favour those already selected by other agents. Already defined movement and flows towards a shop will affect search behaviour of the other agents but always in the system, goals will be fulfilled and satisfied as ratio of walk able area to number of agents is sufficient to enable almost free movement to destination.

Methodology is efficient and sufficient. The experiments present interesting results but always rational, not unexpected and easily explained by our daily experience of every day life. The vision agents correspond to the information received visually perfectly, as this is proved from the patterns generated in phase two. The project proves as it was mainly seen in phase three that a broad range of set ups and types of analysis, with numerous different case studies can be easily and fast analyzed according to the different researchers’ requirements every time. All the experiments analyzed in this thesis, consider to be only the first-initial stages of a study that can lead to a fully complex and emergent system, clone of a real urban system.

The current version, to simplify complexity and obtain easier and faster data, is based on a rather simplified agent's movement behaviour. Parameters like cost of movement and its effects, tiredness, or time budget (time an agent stays in the system especially when he hasn't achieved and satisfied his goal, is he allow to leave the system in this case?) do not appear. The walking surface is not loaded with information like street furniture, trees, means of transportation and non pedestrianised areas. There is no place legibility or familiarity of place as agents enter the environment without knowing the spatial aggregation and location of stores. The reason is that the interest of this thesis is on spatial configuration and store location related to their visibility. In future versions though as the next stage of a progressing study, such parameters and thus complexity is planned to be added for more coherent results. An approach to this complexity was started to be investigated in phase three with the insertion of a 'big event', an open market. It will be interesting to study how these parameters and familiarity of the environment will alter decision making of the routes and so pedestrian flows. It is also very important, even for the first phases of the experiments already studied, to include more advanced methods of data gathering as currently all the information retrieved is based on the visual interaction of the user. This refers to time tables and diagrams which will show exact time taken in each case for example for the agents to visit a shop and counting as in how many shoppers entered a shop, from where and after how much time.

Furthermore it has to be concluded that the current framework is rather too simplified and constrained to represent real cities and that is rather more an idealised virtual city than an exact simulation of a real one. To be successfully applied to the simulation of urban systems, it is necessary that model will have to be heavily modified from the current parameterizations. Research undertaken at UCL has shown that it is achievable to import a 2D layout in drawing exchange format (DXF) [Turner, A., 2001b] in the platform used for the model. Considering that, future development of the model can be focus on using real urban environments with their parameters instead of totally virtual. That will enable a coherent study of a real scenario according to the users-research requirements. By that it can be studied for example how changes in existing retail uses may alter pedestrian movement and rates.

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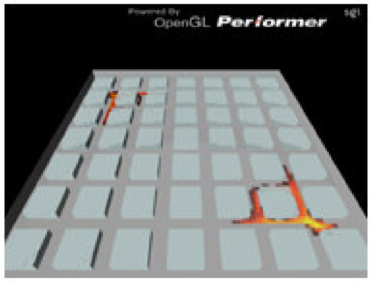
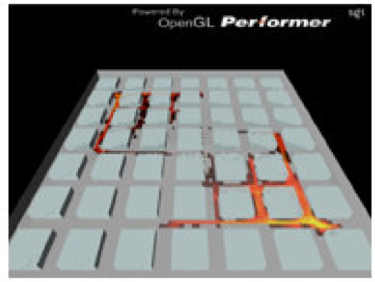
## Appendices

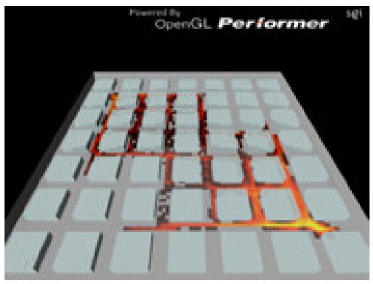
In the next pages analytical display of all case studies-experiments that were examined in this thesis are provided. Each page relates to an individual experiment and shows in process, in terms of print screens taken at different times, the agents' movements and the paths-flows that they were formed. For a better understanding of the streets integration and connectivity, in each case an inverse view of the model (last photo each time) is provided, which is clear-empty from urban blocks. There is as well a provision of the experiments settings: type of environment (spatial configuration), number of agents and their type in terms of behaviour if any, gateways, open space, number of shops and the logic of their distribution. Each case study is coded, i.e. A5, as sometimes there are references in the main text.

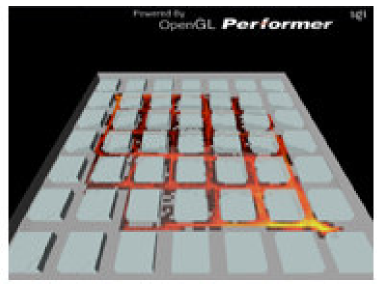
Appendix A presents all experiments related to the first phase of the experiments with no retailing, where the agents are not goal-oriented and move according to the information received from their visual field. Appendix B presents all experiments related to the second phase of the experiments with the presence of shops (coloured blocks) in various distributions and taste vectors for the agents. Appendix C presents the experiments of the third phase with the presence of some of the same shops formation of phase two but with an addition of an event, a market located in the centre of the open spaces.

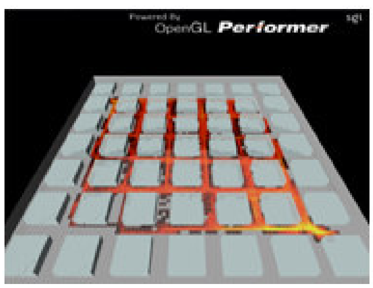
## Appendix A

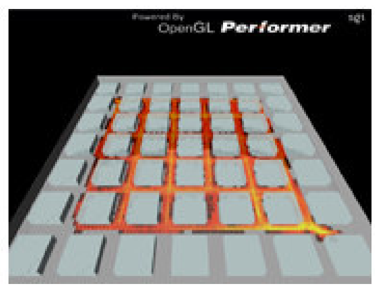


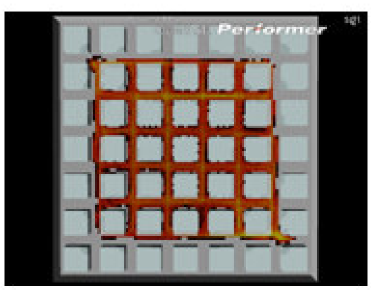



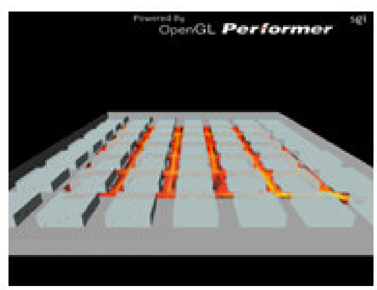



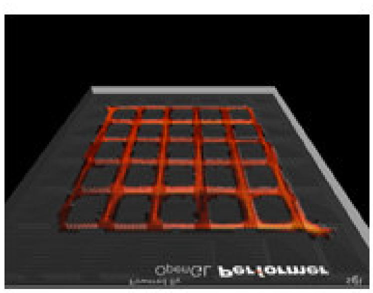



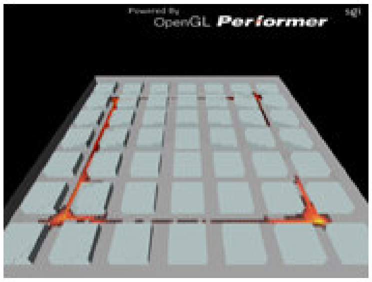
**A1**

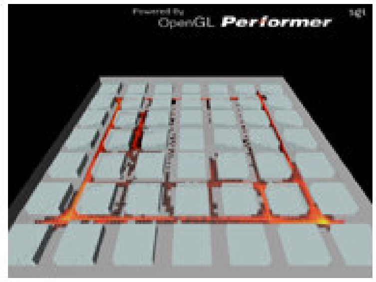
Type: grid

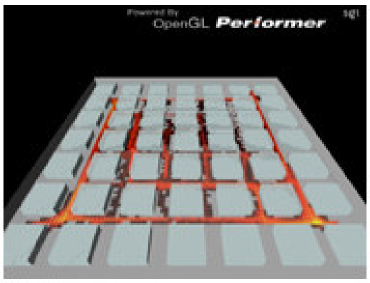
Gateways: 2 corners

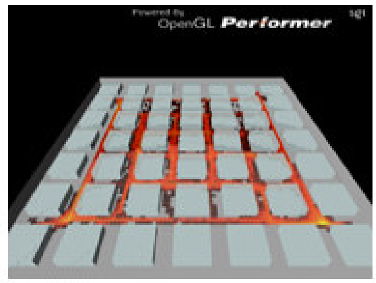
Number of agents: 2 x 60

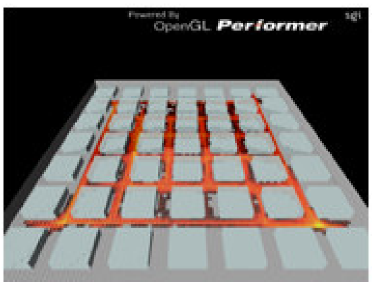
Open space: -

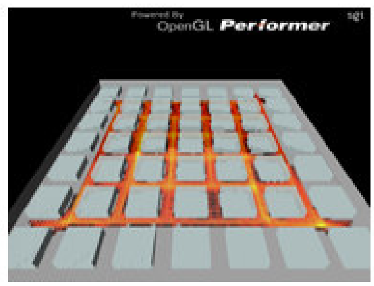


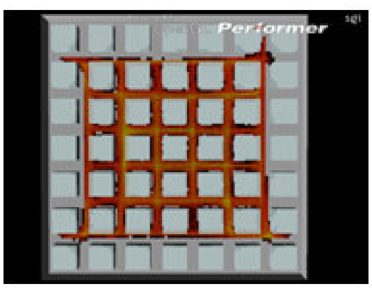


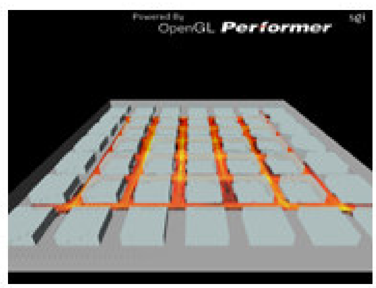


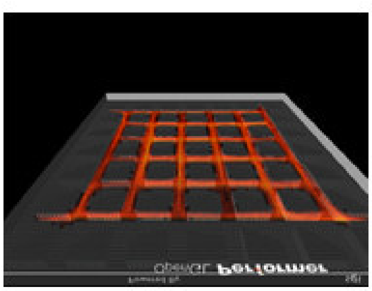












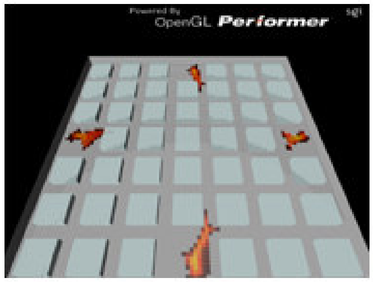
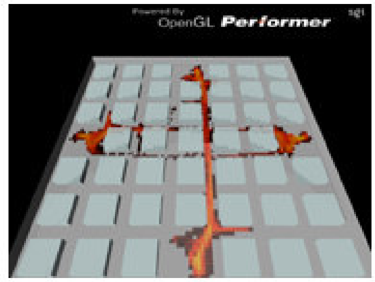
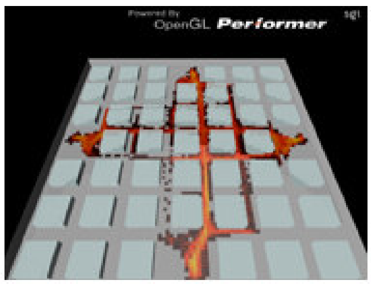
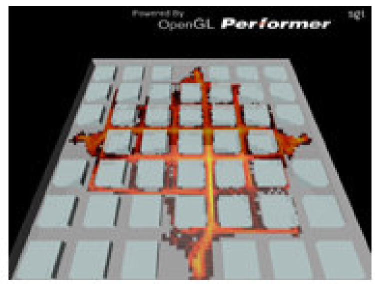
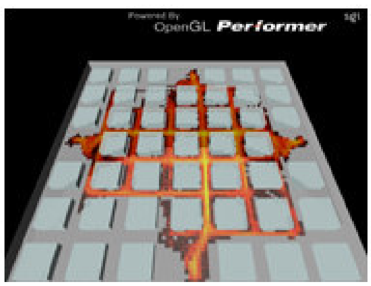
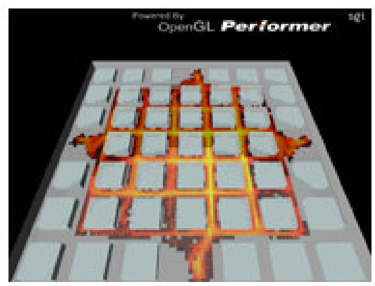
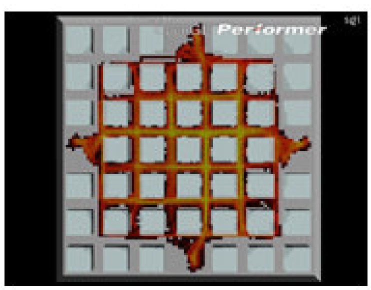
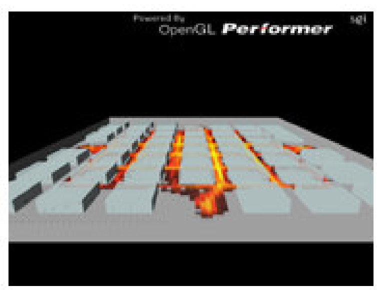
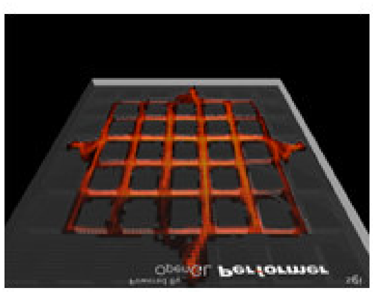
**A2**

Type: grid

Gateways: 4 corners

Number of agents: 4 x 30

Open space: -

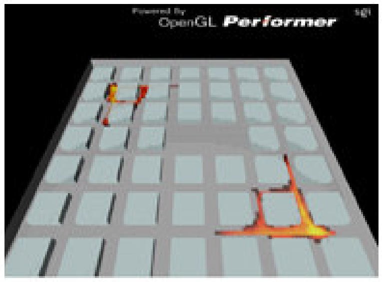
**A3**

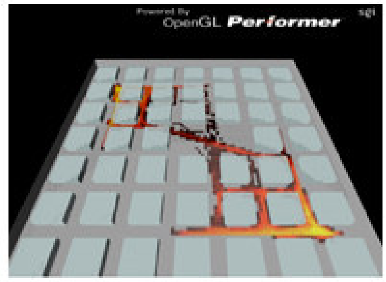
Type: grid

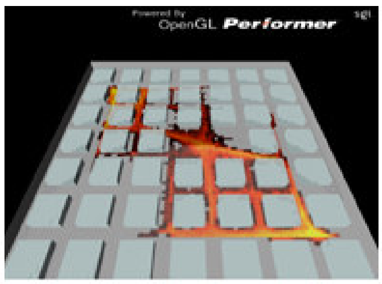
Gateways: 4 sides

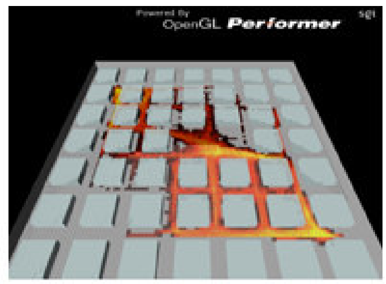
Number of agents: 4 x 35

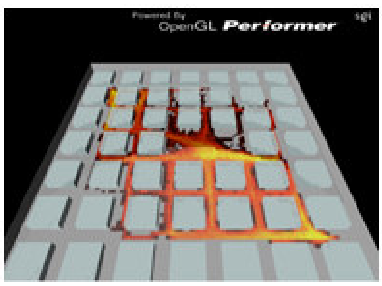
Open space: -

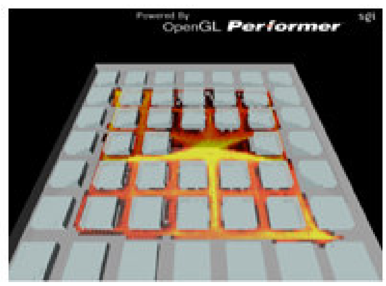


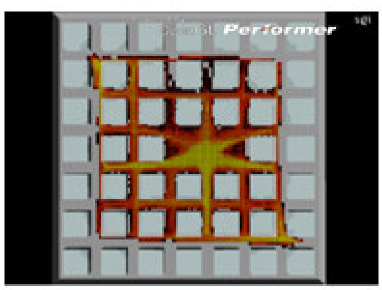



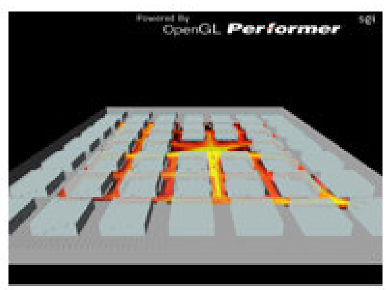



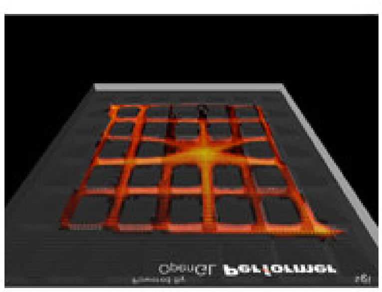



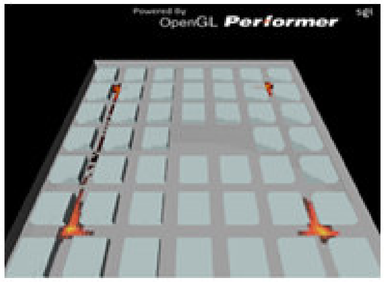
**A4**

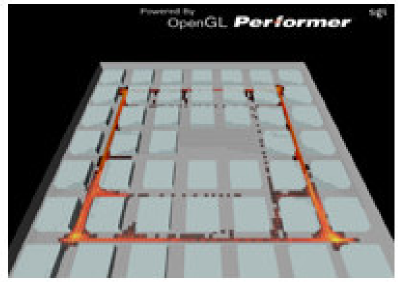
Type: grid

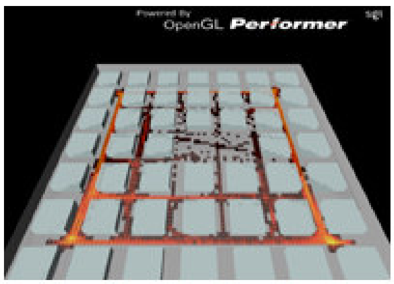
Gateways: 2 corners

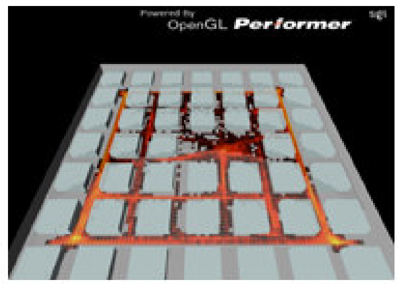
Number of agents: 2 x 70

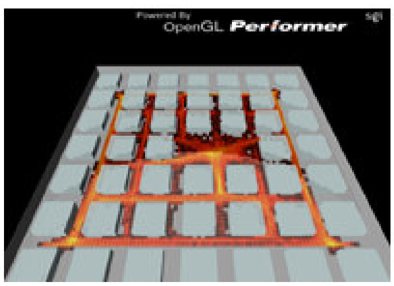
Open space: 2 blocks

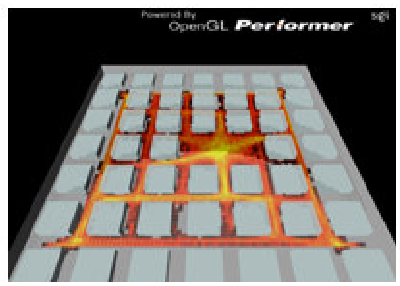


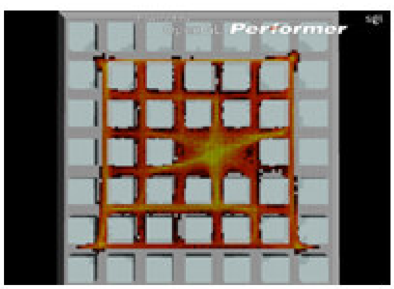


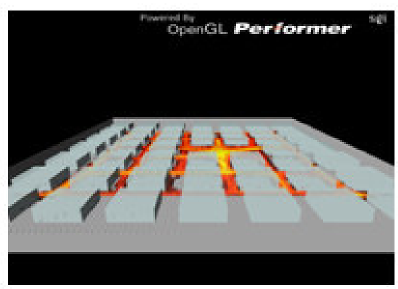


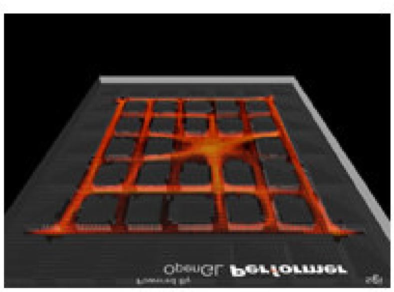












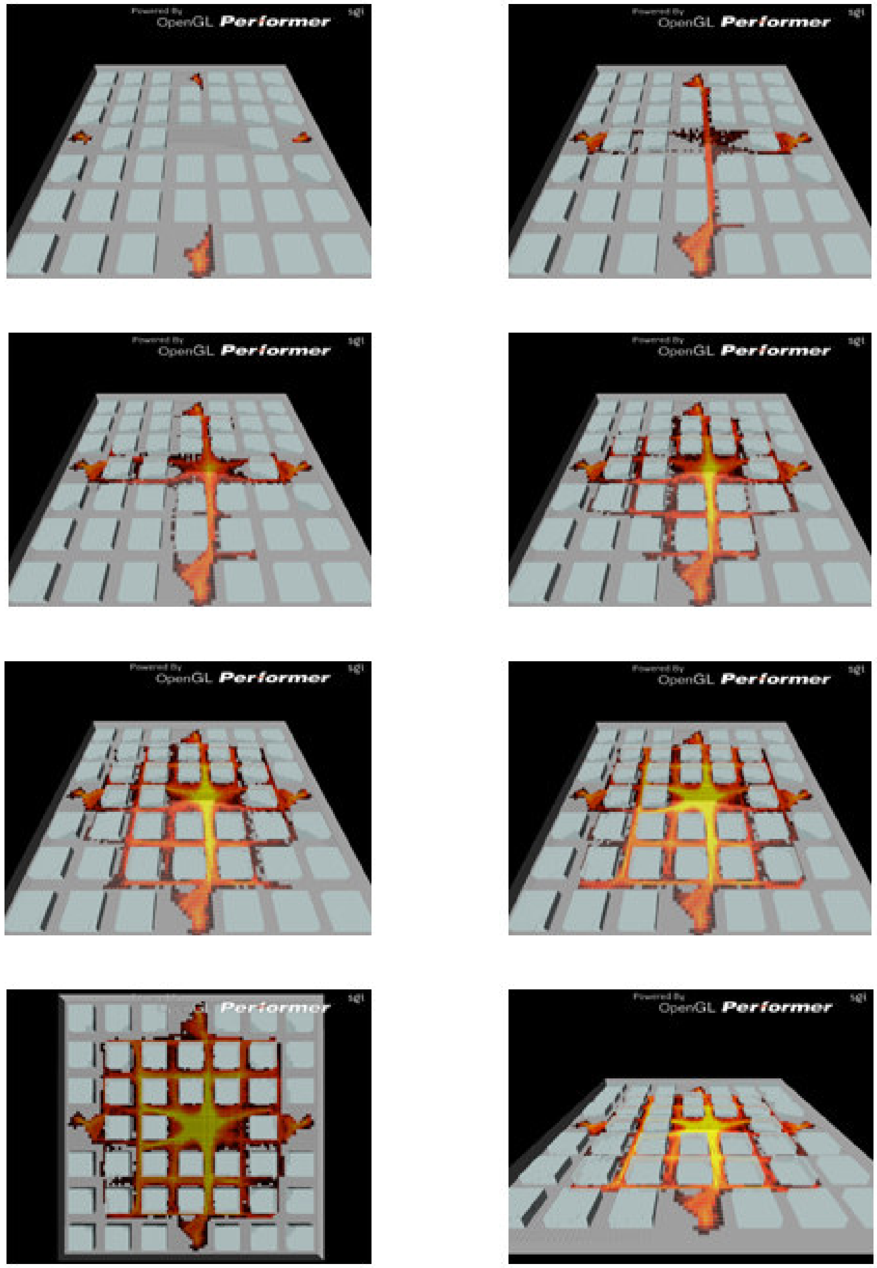
**A5**

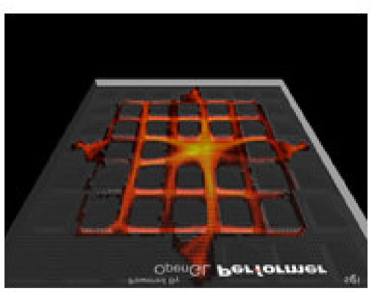
Type: grid

Gateways: 4 corners

Number of agents: 4 x 35

Open space: 2 blocks



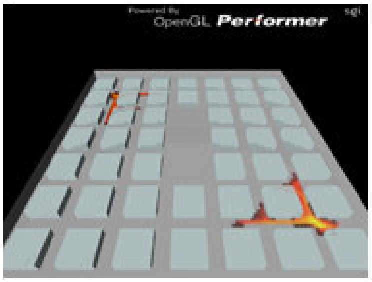
**A6**

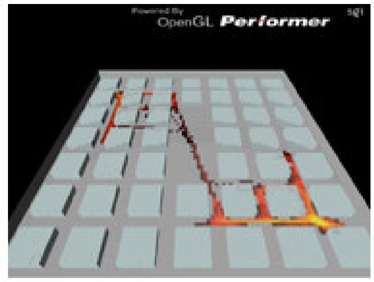
Type: grid

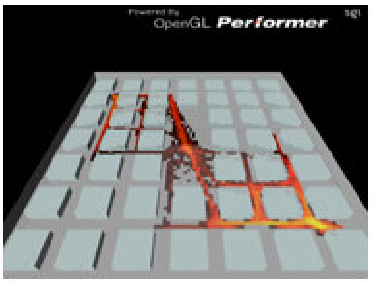
Gateways: 4 sides

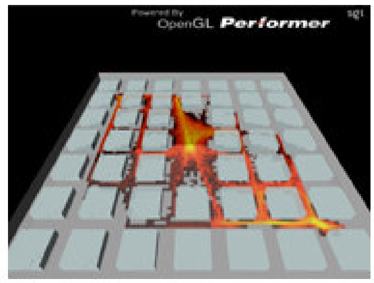
Number of agents: 4 x 35

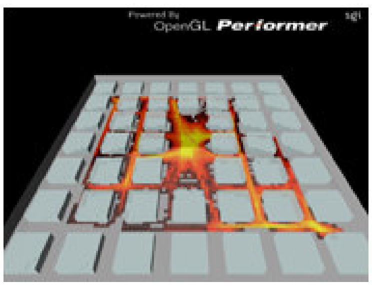
Open space: 2 blocks

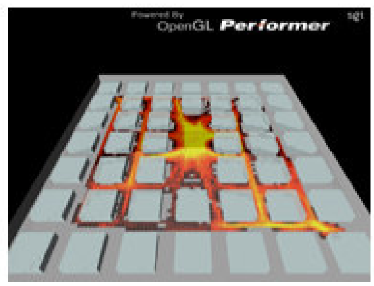


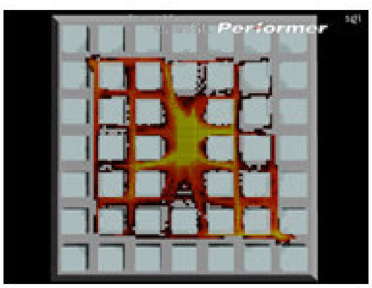



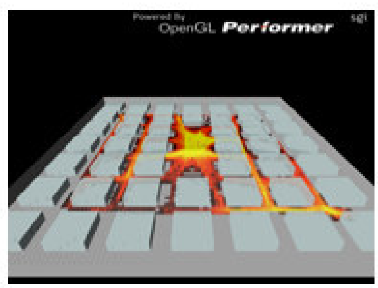



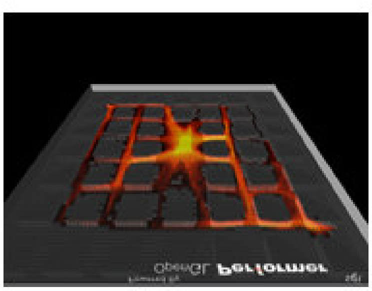



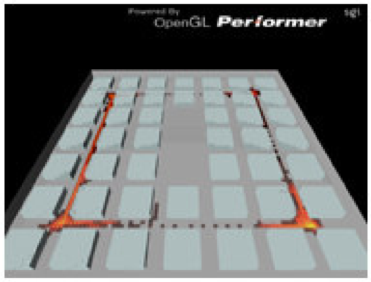
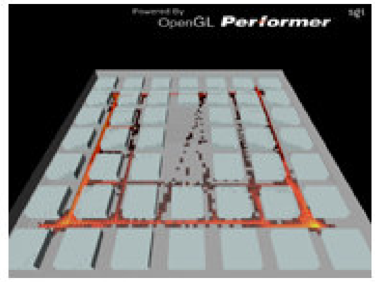
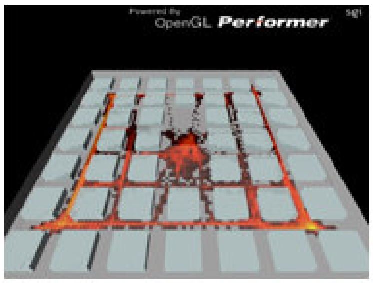
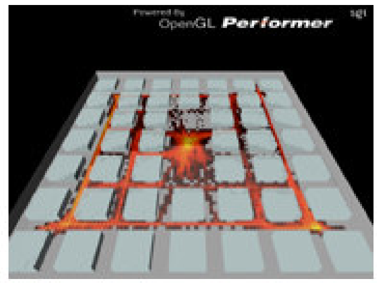
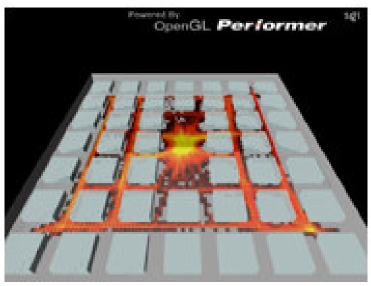
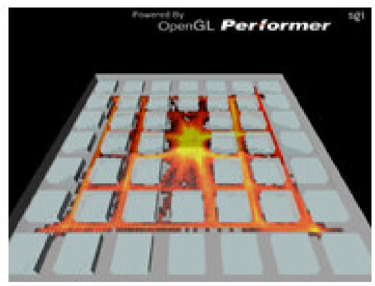
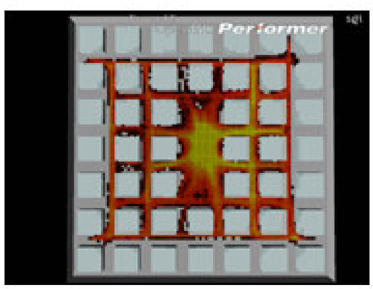
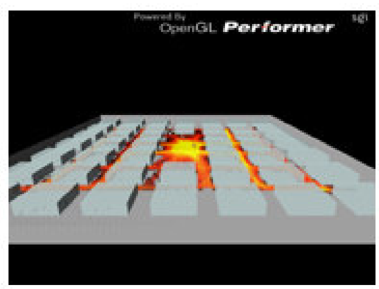
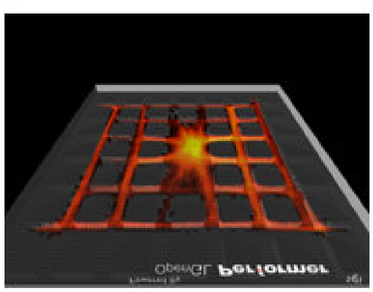
**A7**

Type: grid

Gateways: 2 corners

Number of agents: 2 x 60

Open space: 3 blocks

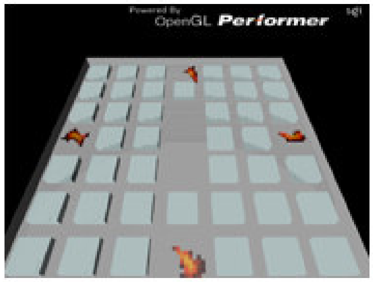
**A8**

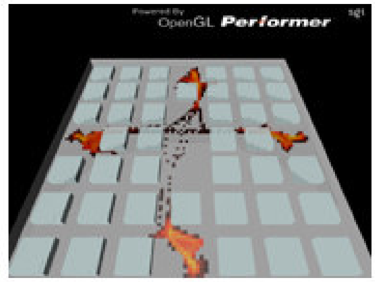
Type: grid

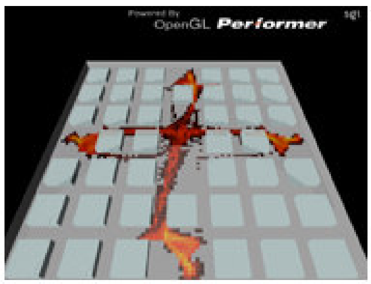
Gateways: 4 corners

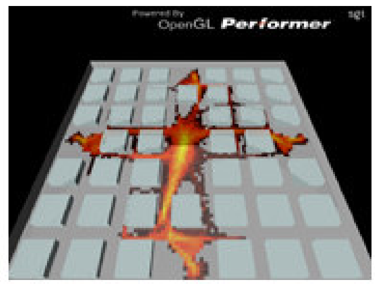
Number of agents: 4 x 30

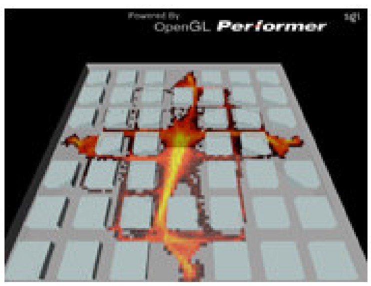
Open space: 3 blocks

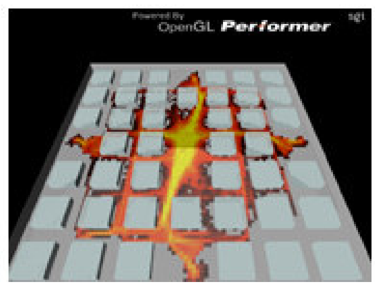


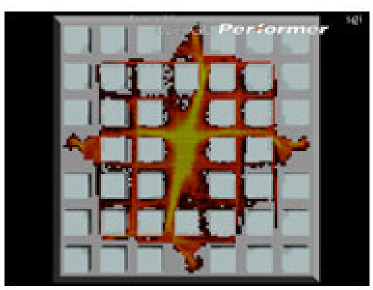
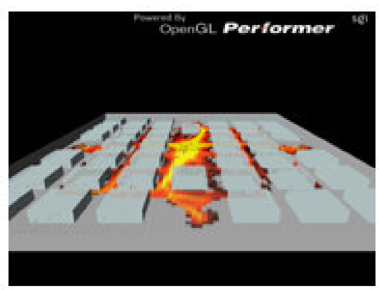


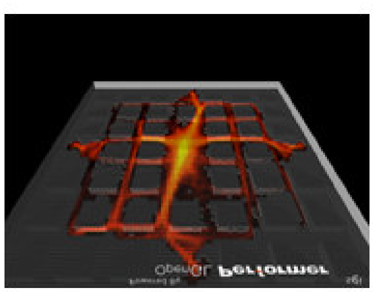










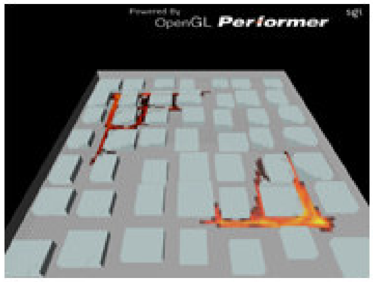
**A9**

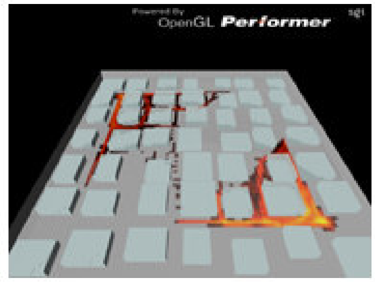
Type: grid

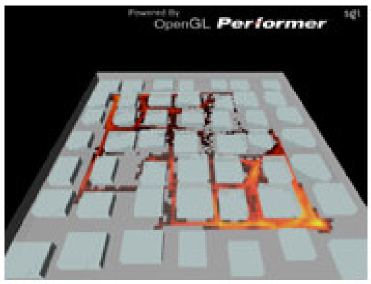
Gateways: 4 sides

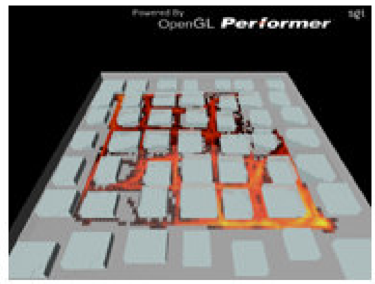
Number of agents: 4 x 35

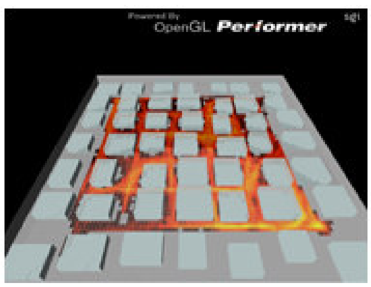
Open space: 3 blocks

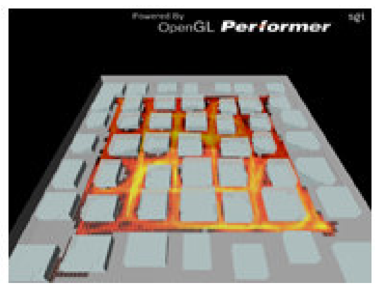


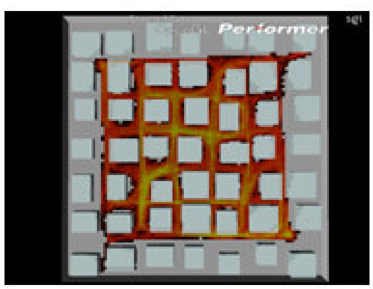



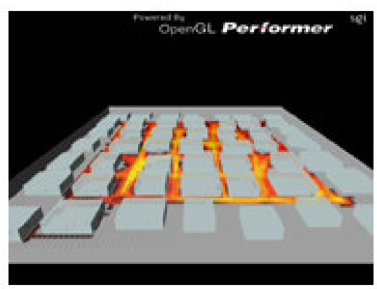



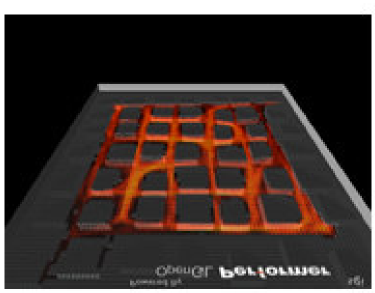





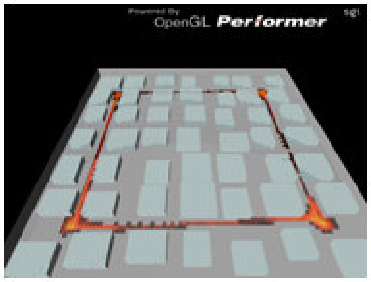
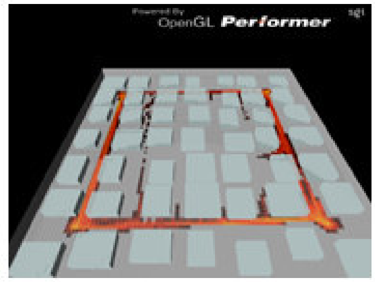
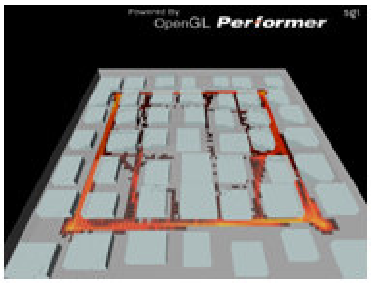
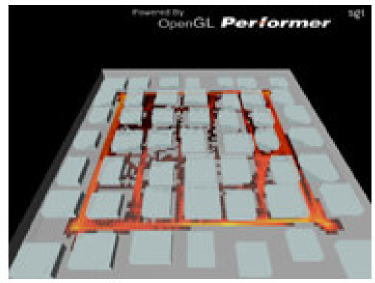
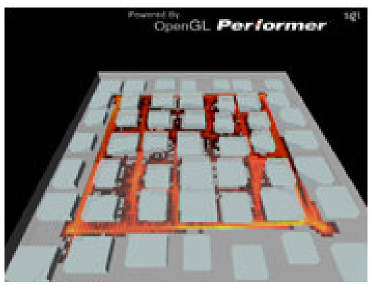
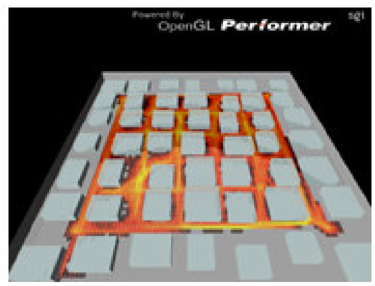
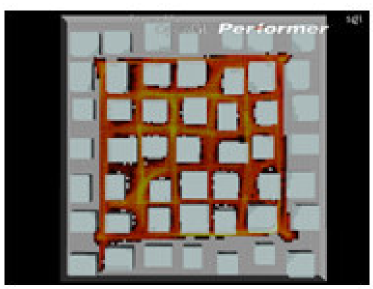
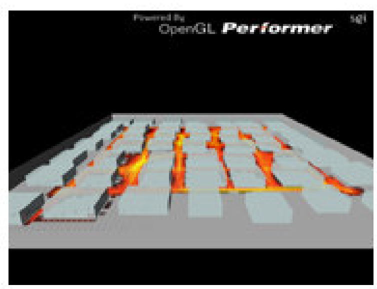
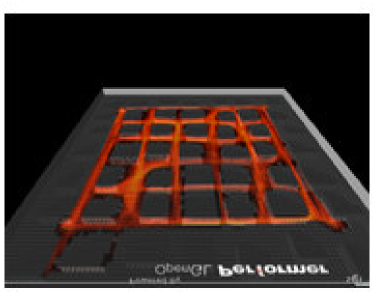
**A10**

Type: random grid

Gateways: 2 corners

Number of agents: 2 x 60

Open space: -

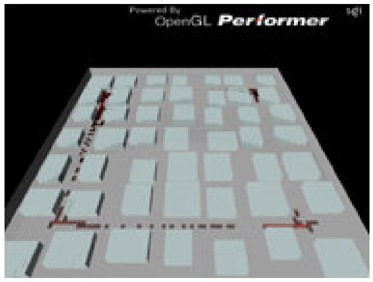
**A11**

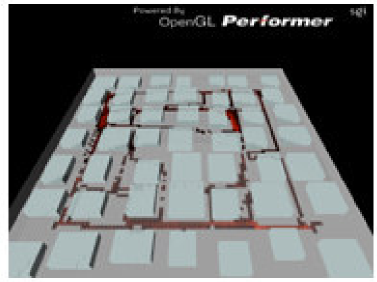
Type: random grid

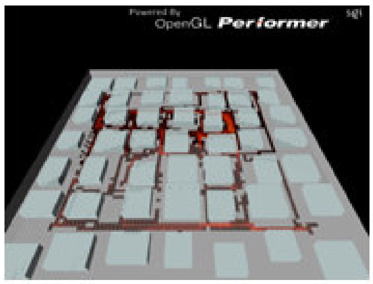
Gateways: 4 corners

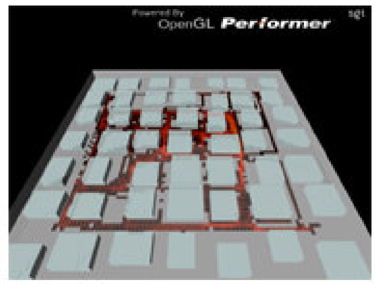
Number of agents: 4 x 35

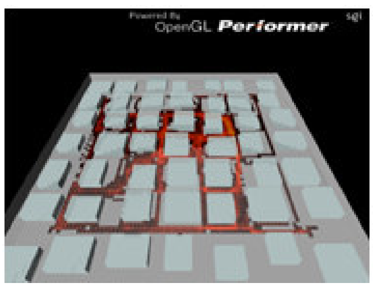
Open space: -

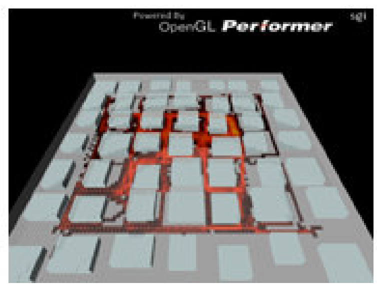


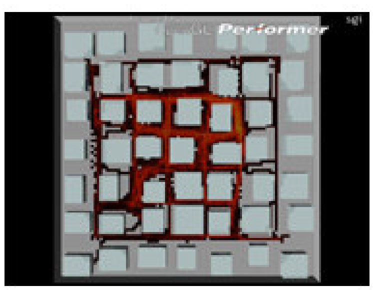



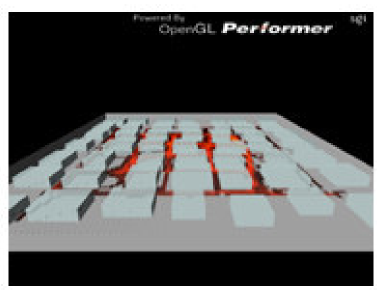



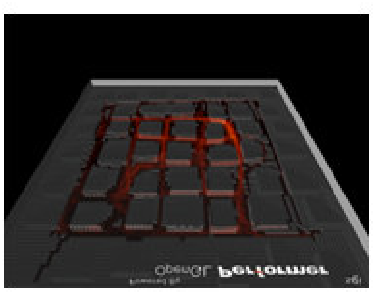





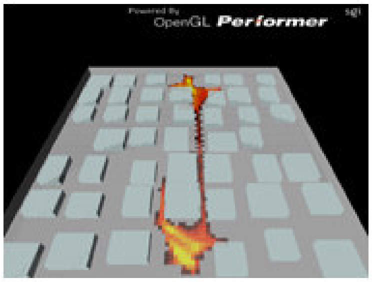
**A12**

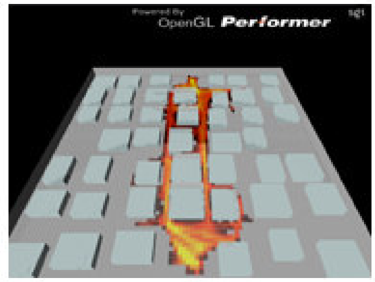
Type: random grid

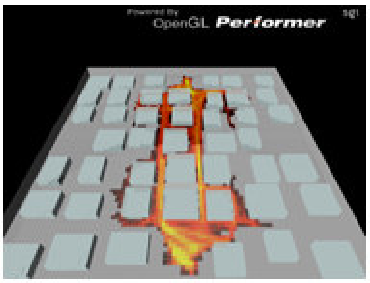
Gateways: 4 Corners

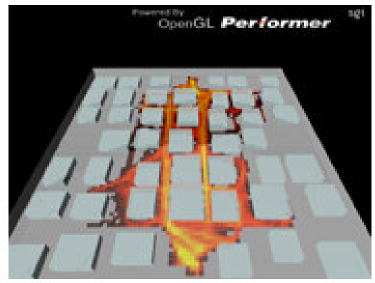
Number of agents: 4 x 5

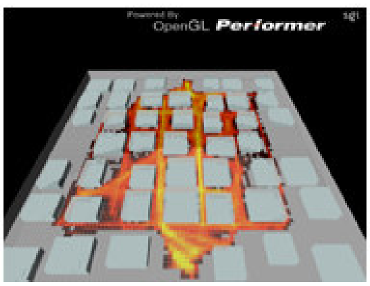
Open space: -

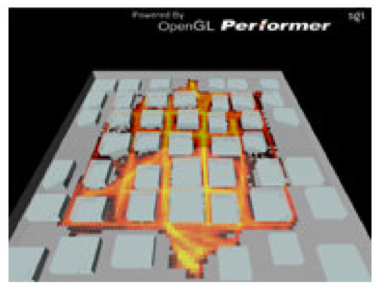


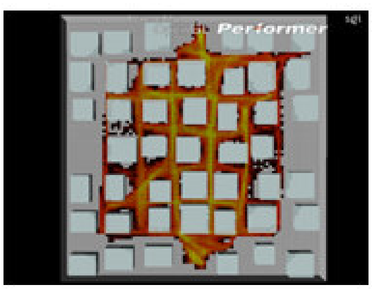



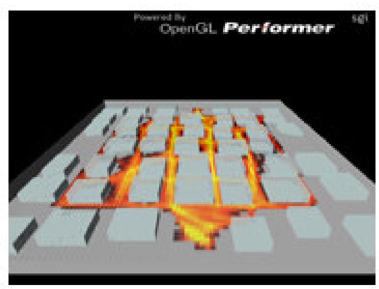



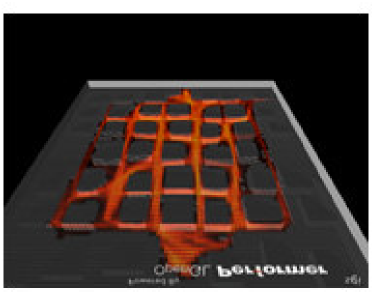



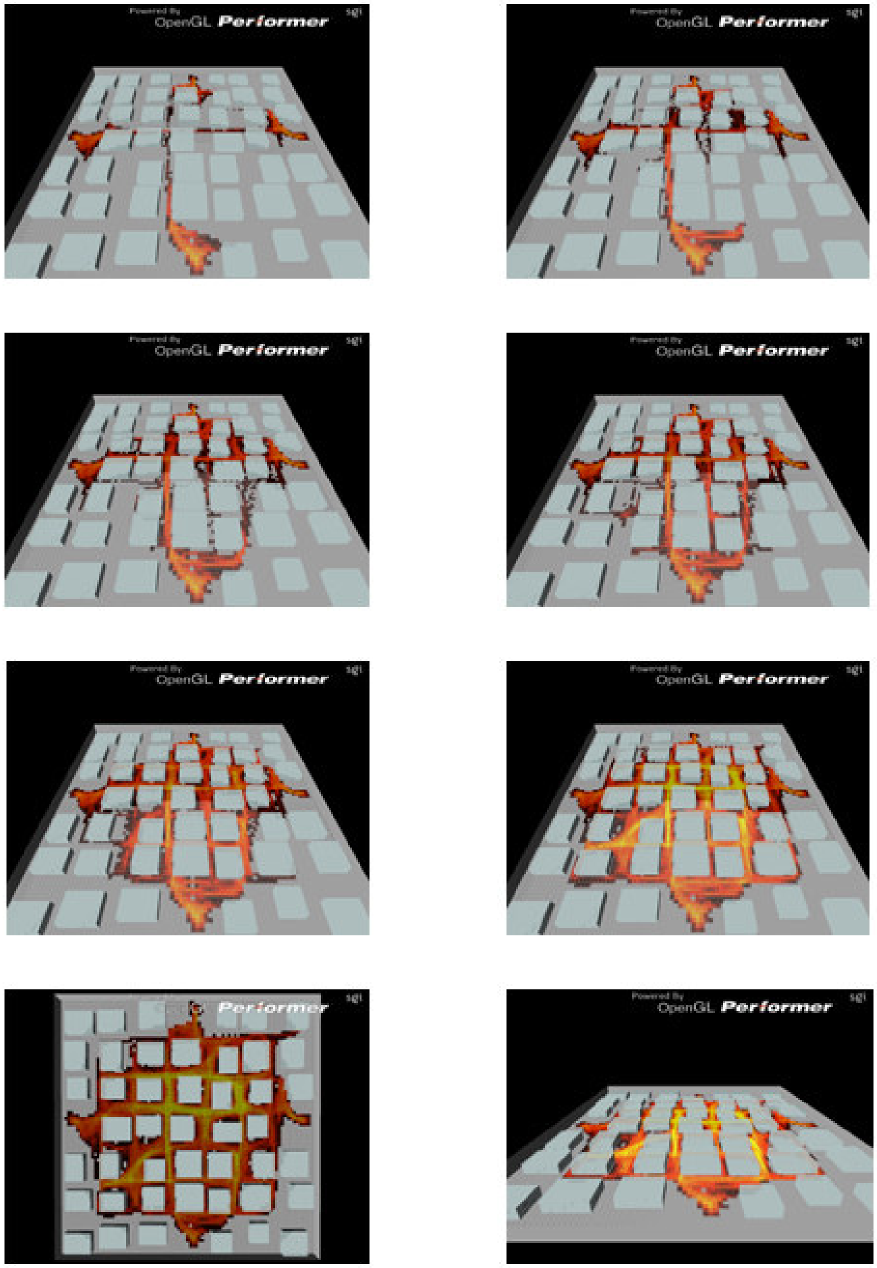
**A13**

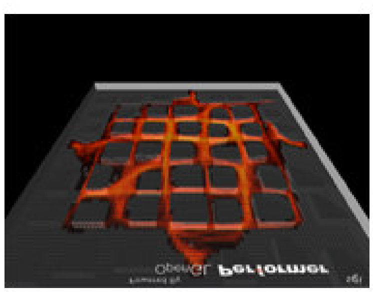
Type: random grid

Gateways: 2 sides

Number of agents: 2 x 70

Open space: -





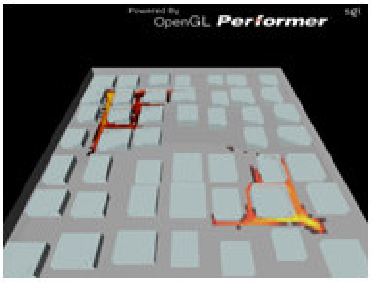
**A14**

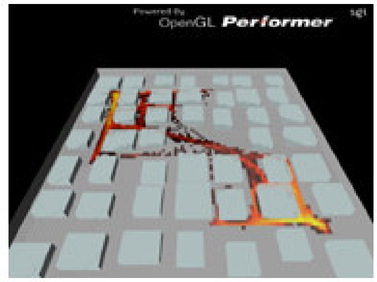
Type: random grid

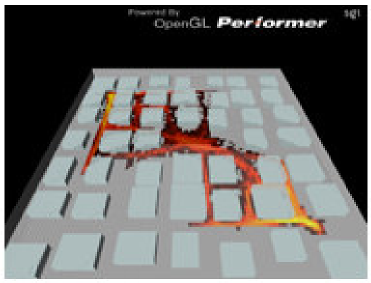
Gateways: 4 sides

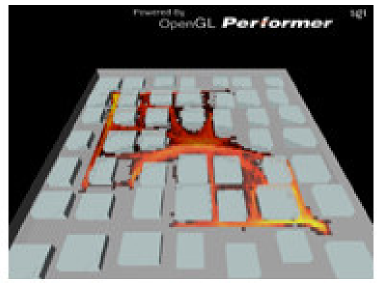
Number of agents: 4 x 35

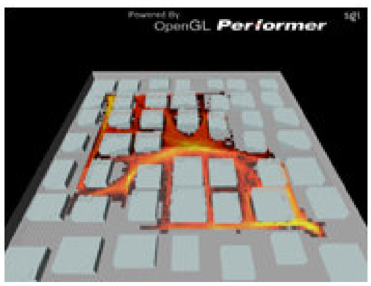
Open space: -

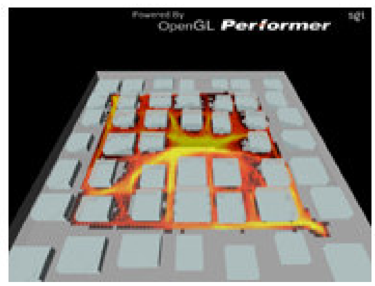


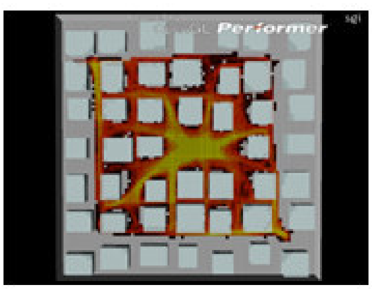



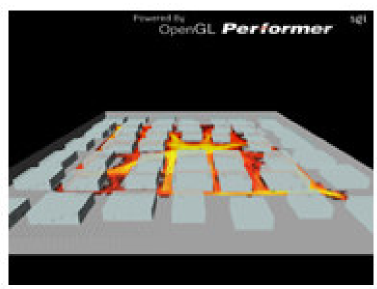



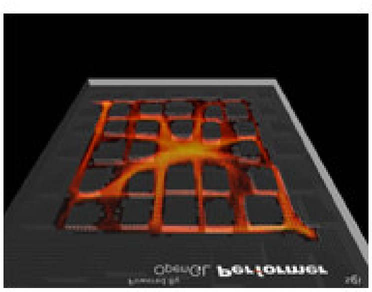





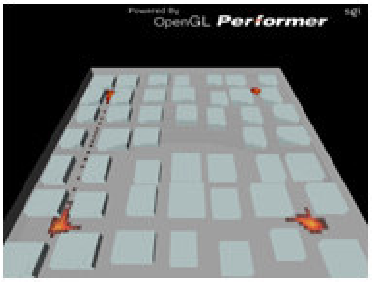
**A15**

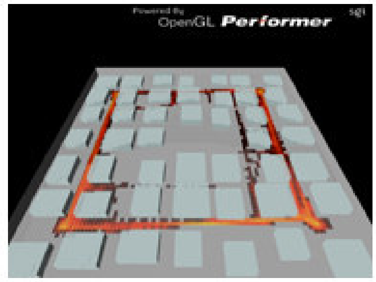
Type: random grid

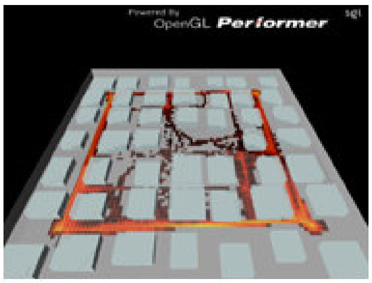
Gateways: 2 corners

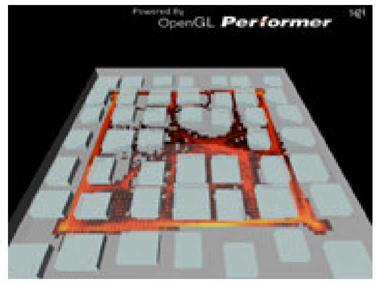
Number of agents: 2 x 70

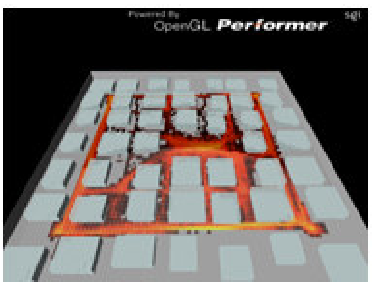
Open space: 2 blocks

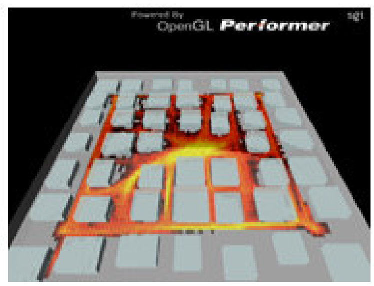


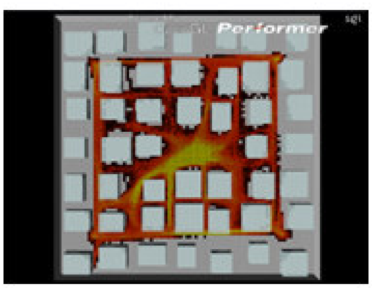



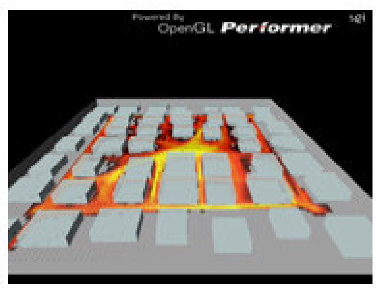



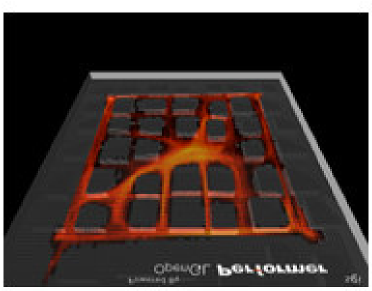



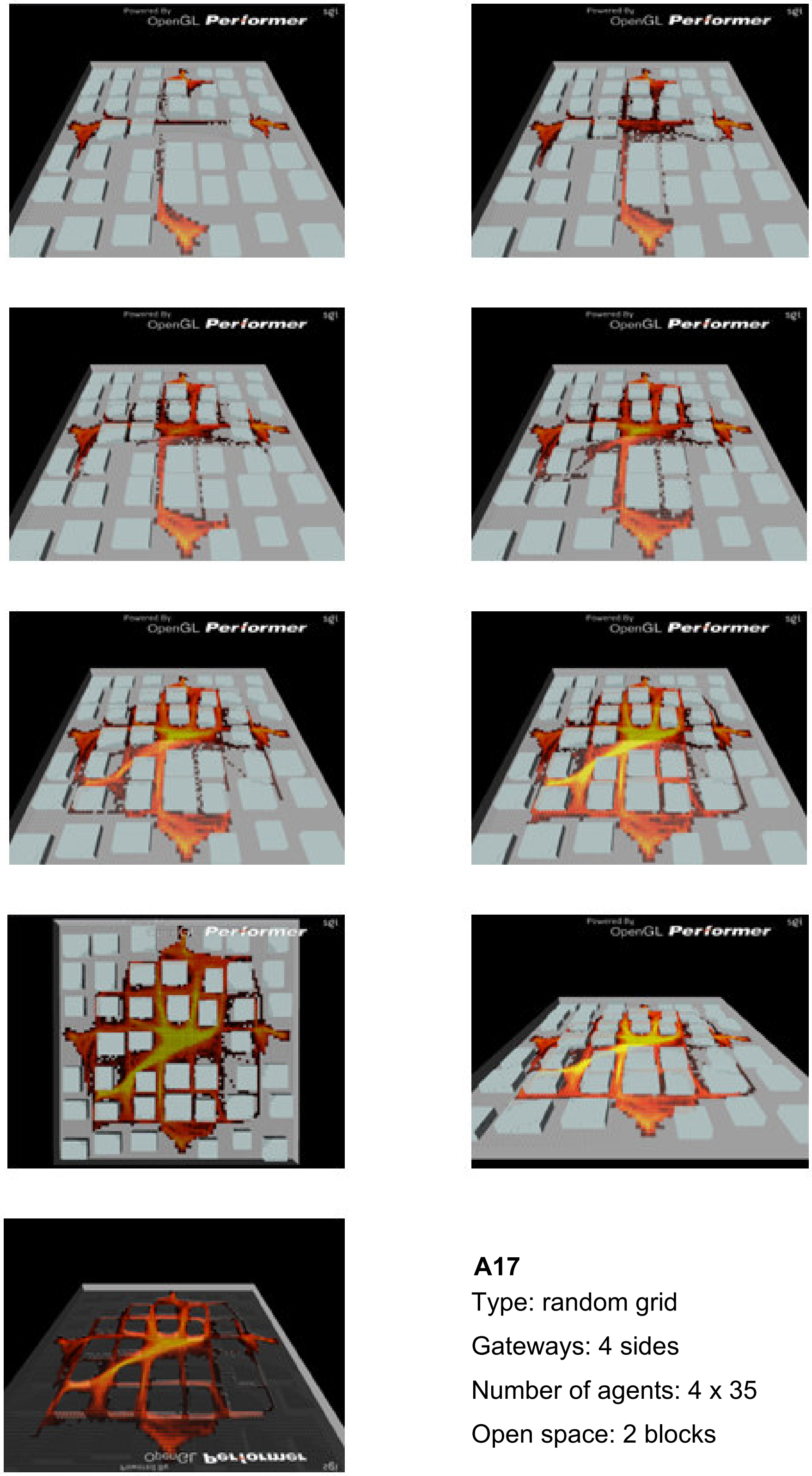
**A16**

Type: random grid

Gateways: 4 corners

Number of agents: 4 x 35

Open space: 2 blocks



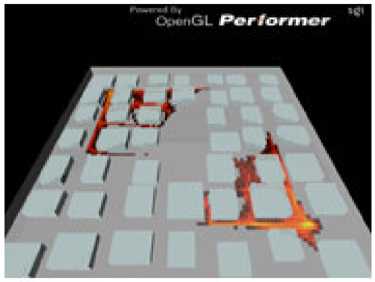

**A17**

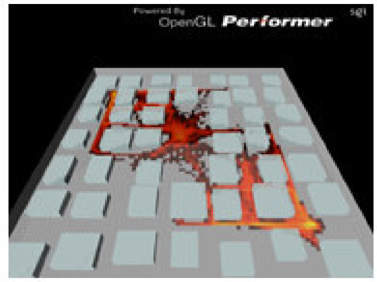
Type: random grid

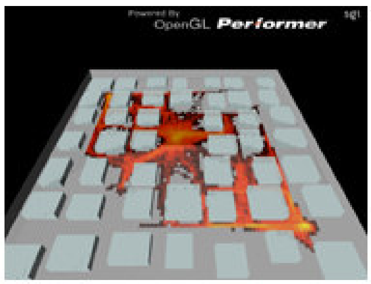
Gateways: 4 sides

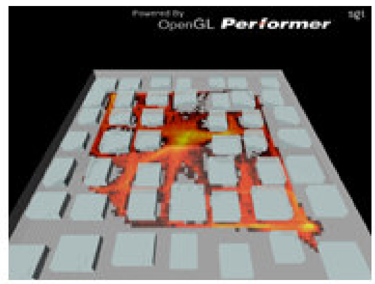
Number of agents: 4 x 35

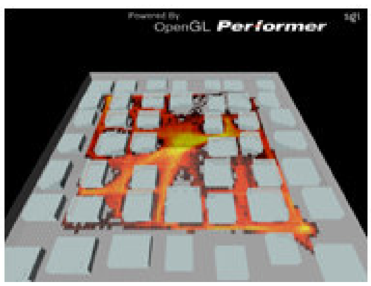
Open space: 2 blocks

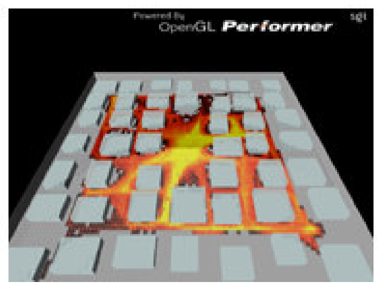


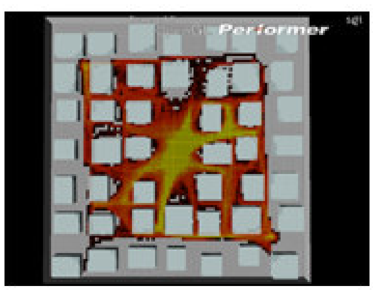



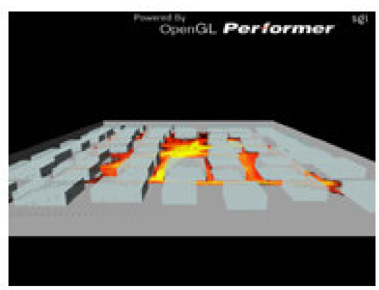



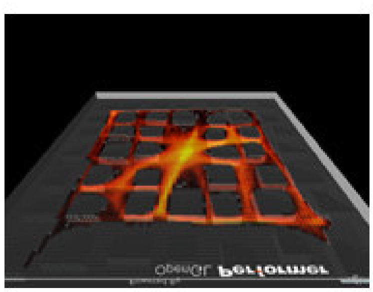



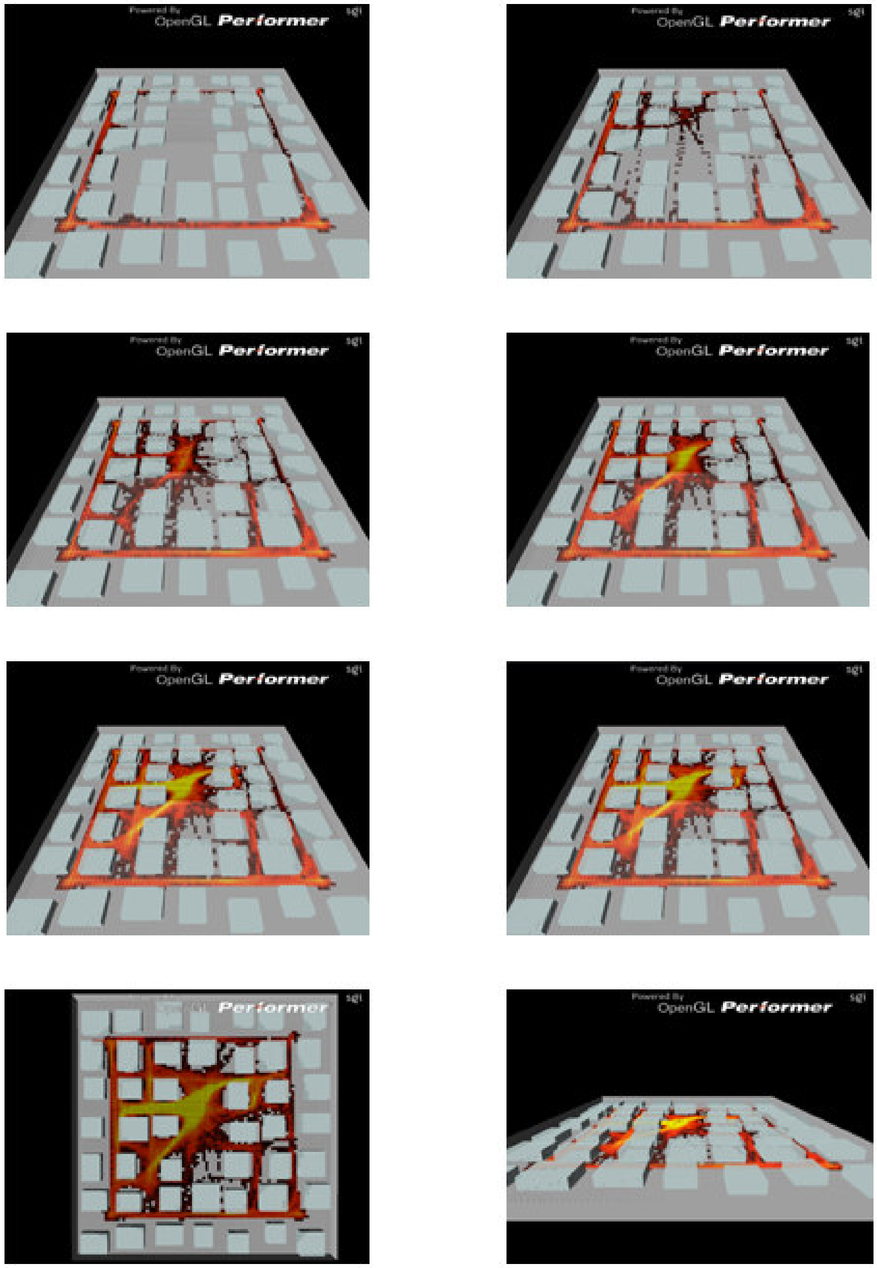
**A18**

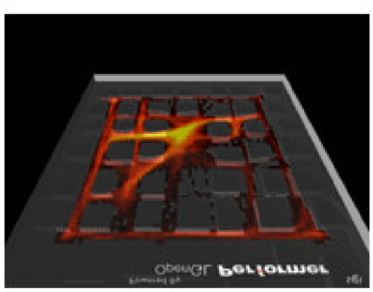
Type: random grid

Gateways: 2 corners

Number of agents: 2 x 50

Open space: 3 blocks



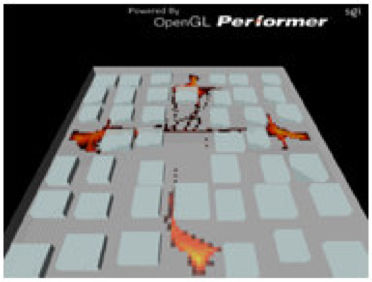

**A19**

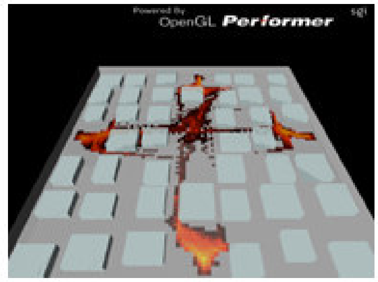
Type: random grid

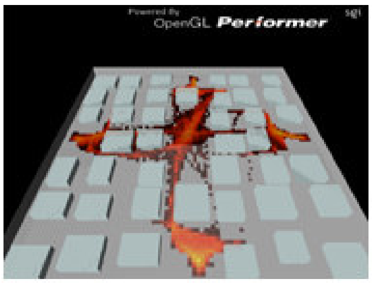
Gateways: 4 corners

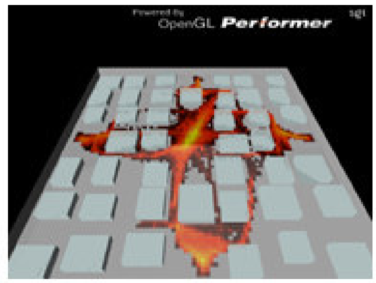
Number of agents: 4 x 30

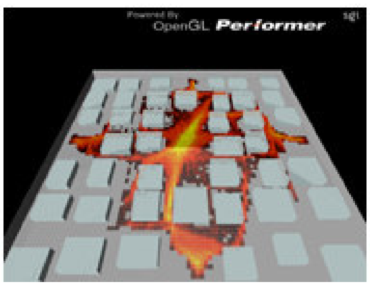
Open space: 3 blocks

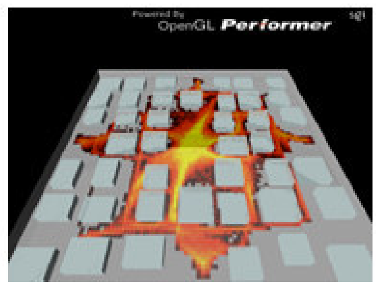


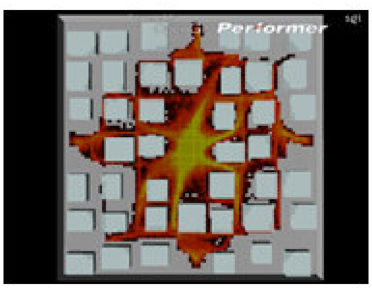



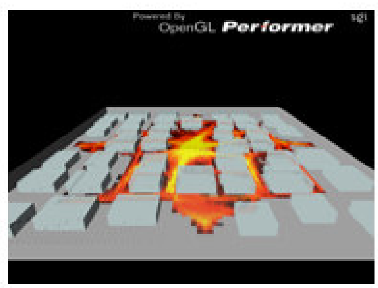



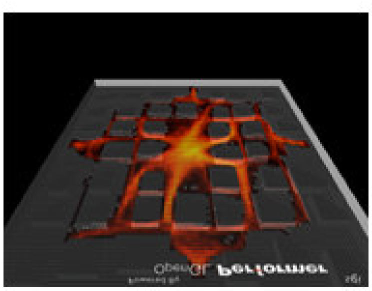



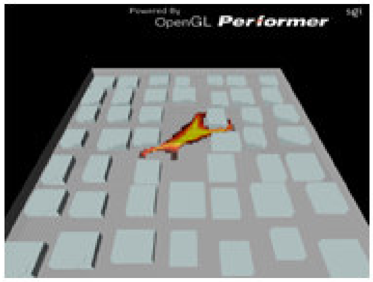
**A20**

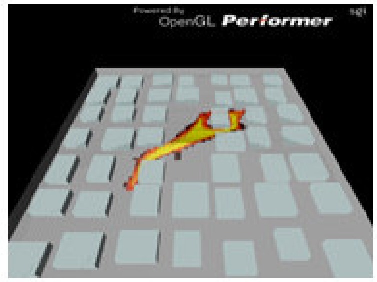
Type: random grid

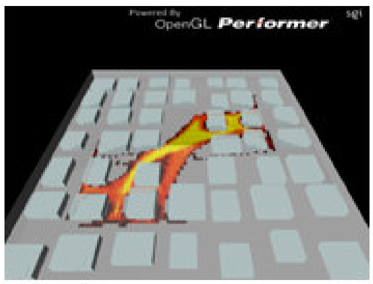
Gateways: 4 sides

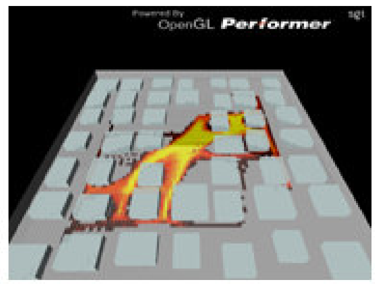
Number of agents: 4 x 35

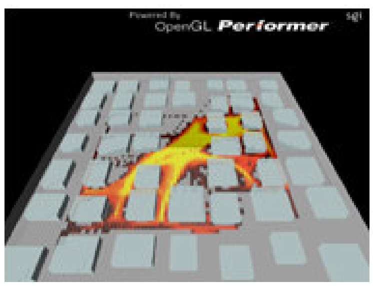
Open space: 3 blocks

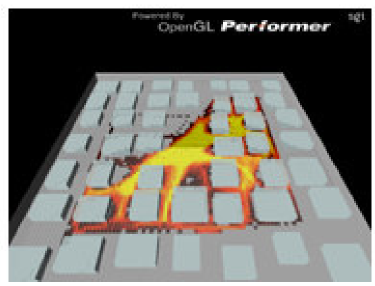


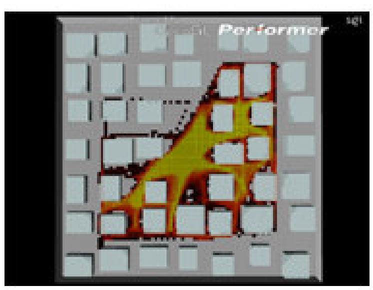


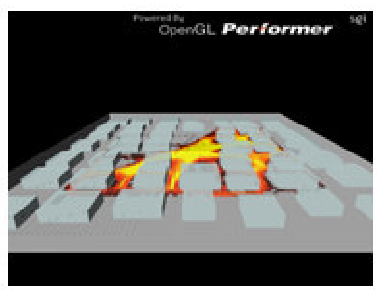


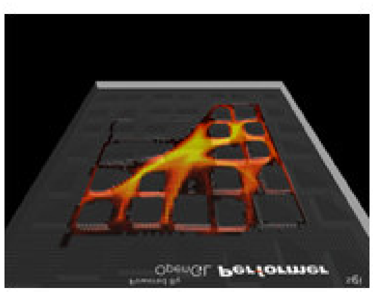












**A21**

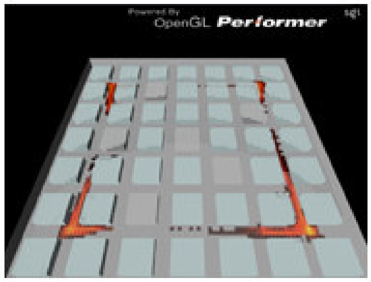
Type: random grid

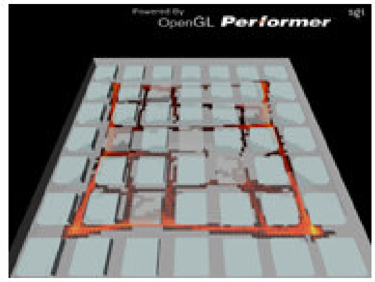
Gateways: center

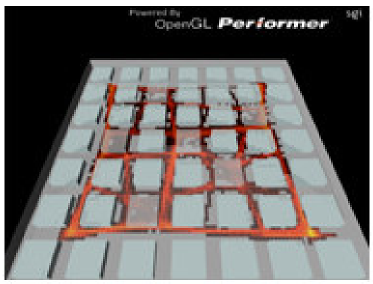
Number of agents: 140

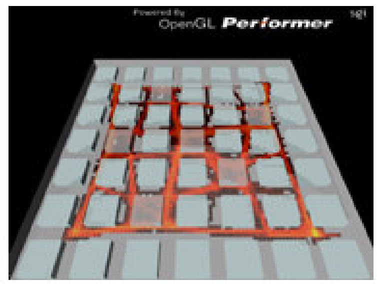
Open space: 3 blocks

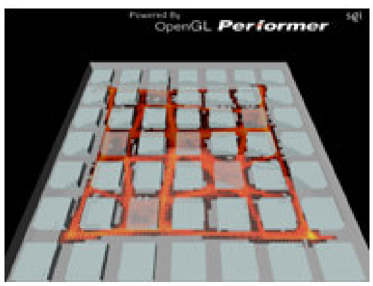
## Appendix B

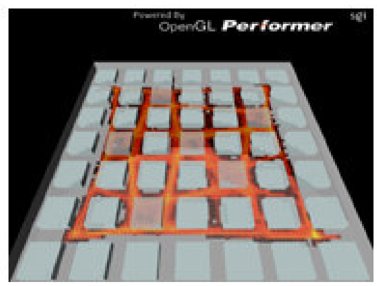


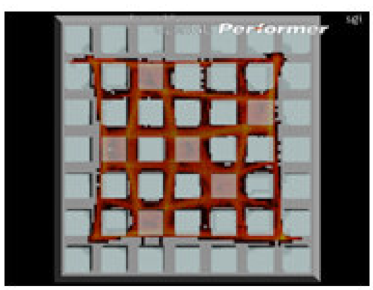



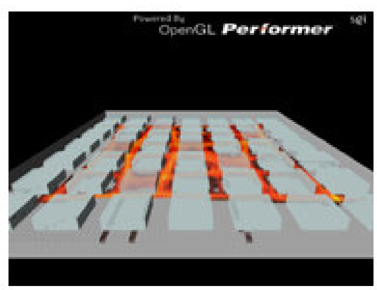



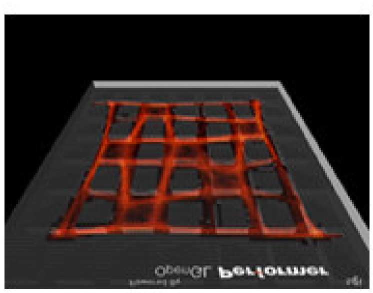





**B1**

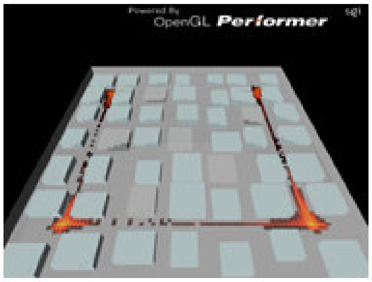
Type: grid

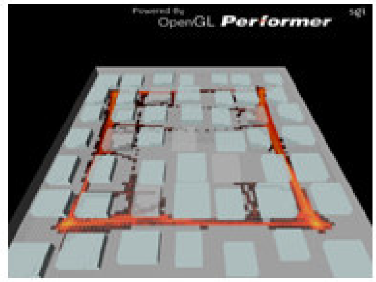
Gateways: 4 corners

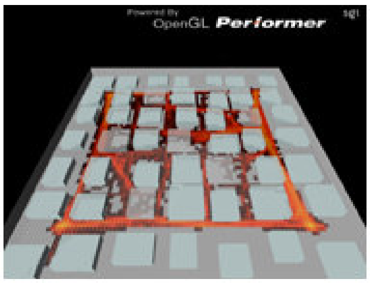
Shops: 6 - random distribution

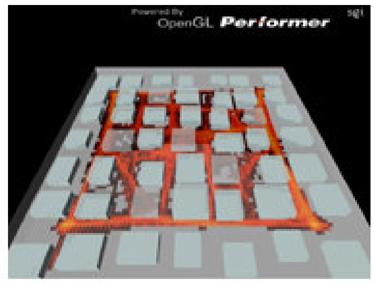
Number of agents: 4 x 40 shoppers

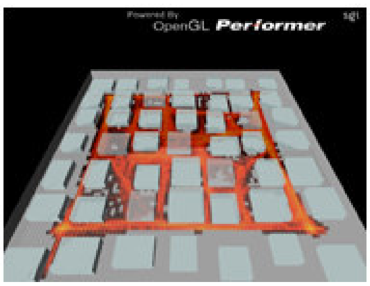
Open space: -

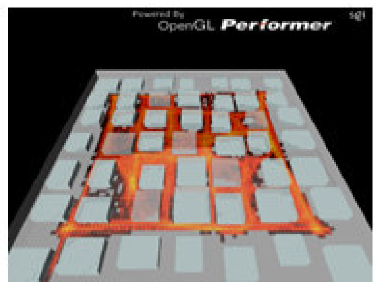


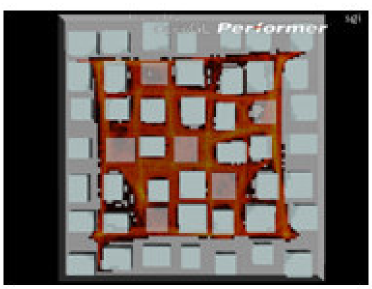



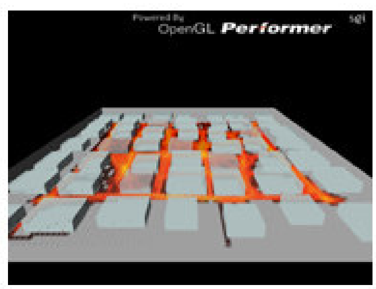



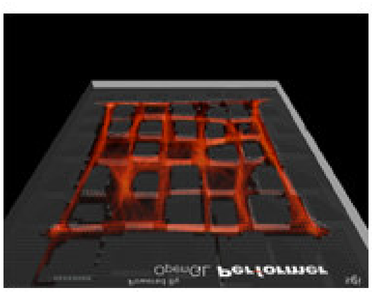



**B2**

Type: random grid

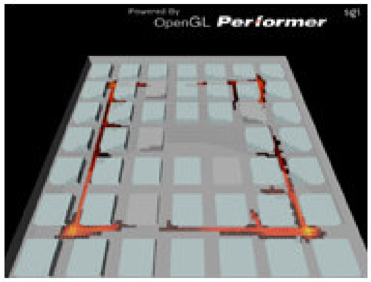
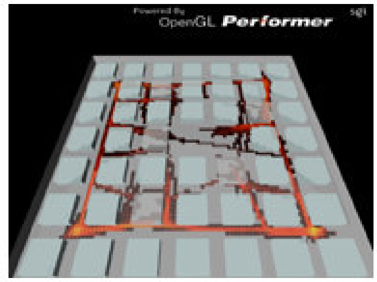
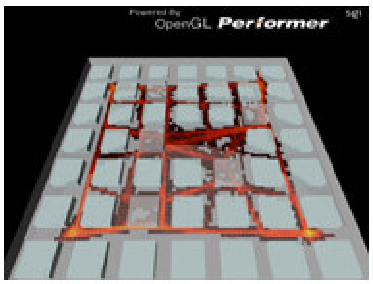
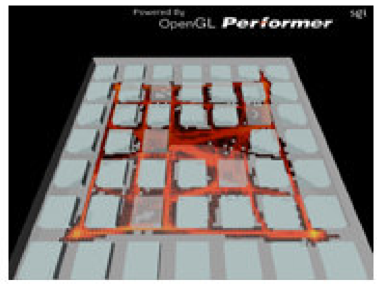
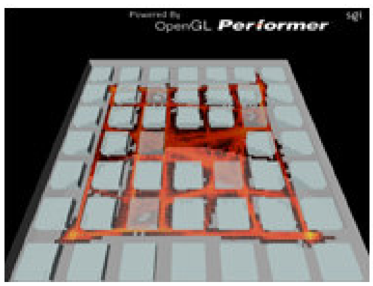
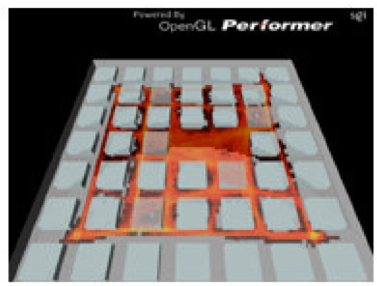
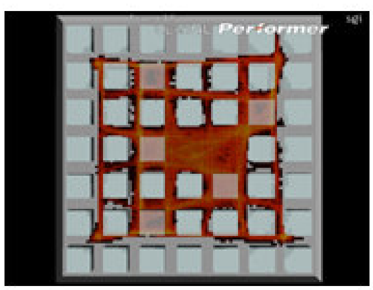
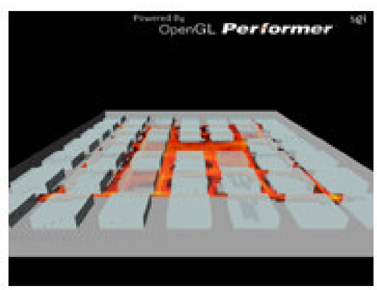
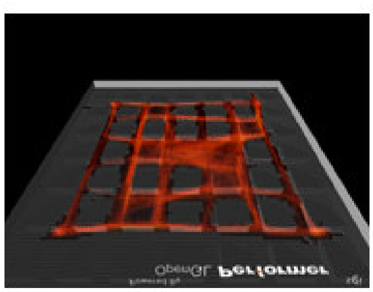
Gateways: 4 corners

Shops: 6 - random distribution

Number of agents: 4 x 25 shoppers

4 x 15 tourists

Open space: -

**B3**

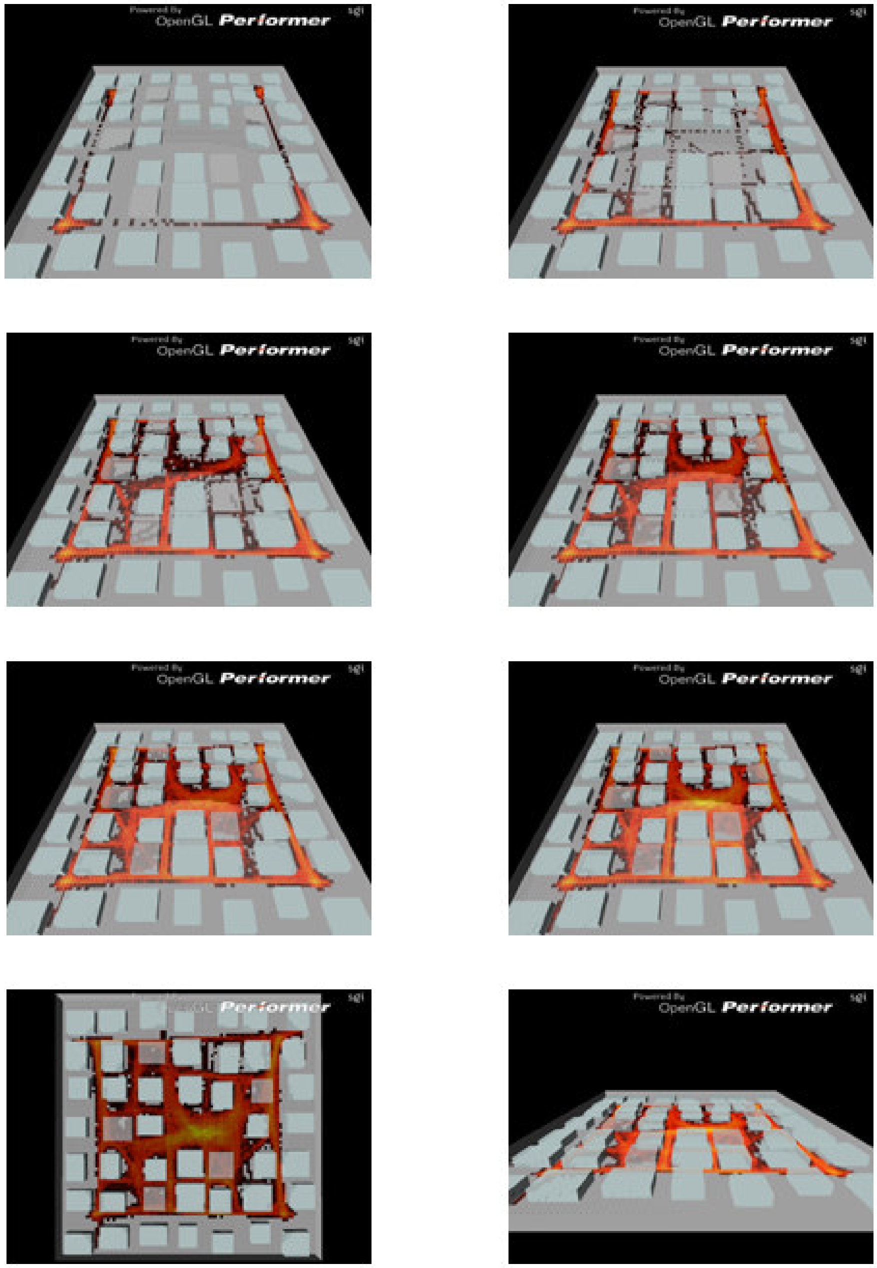
Type: grid

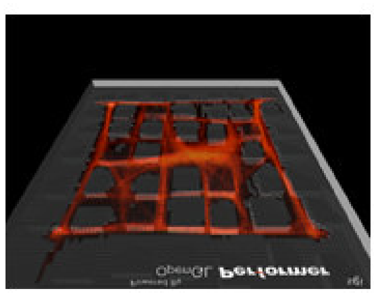
Gateways: 4 corners

Shops: 5 - random distribution

Number of agents: 4 x 40 shoppers

Open space: 2 blocks




**B4**

Type: random grid

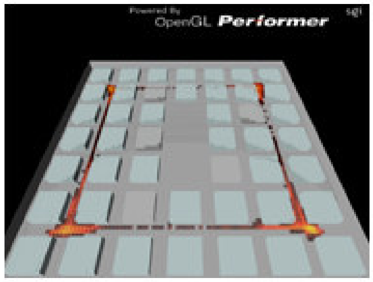
Gateways: 4 corners

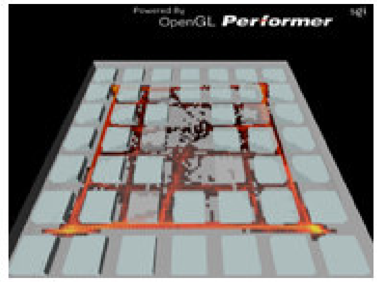
Shops: 5 - random distribution

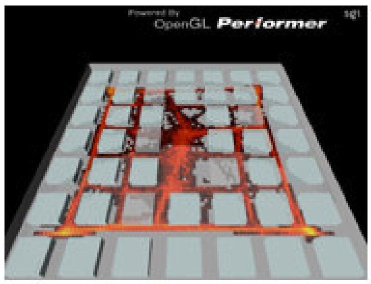
Number of agents: 4 x 25 shoppers

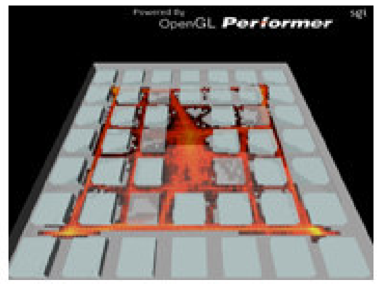
4 x 15 tourists

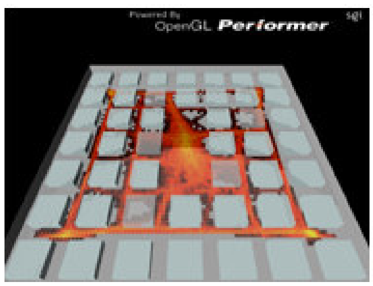
Open space: 2 blocks

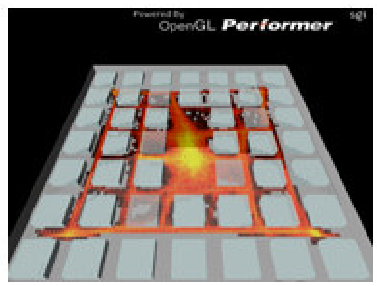


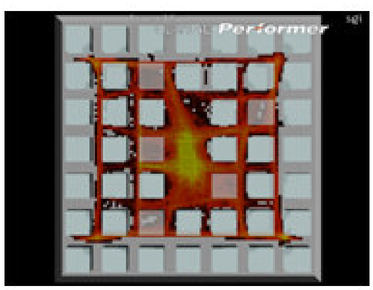



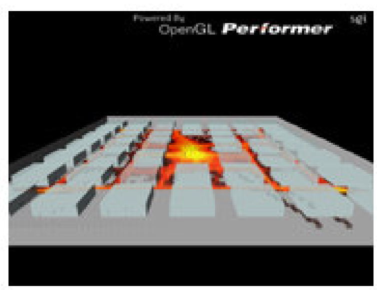



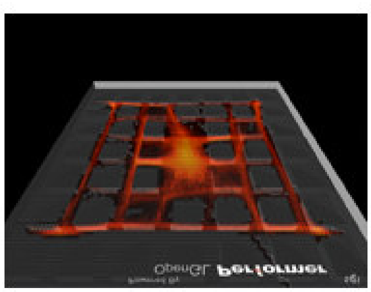





**B5**

Type: grid

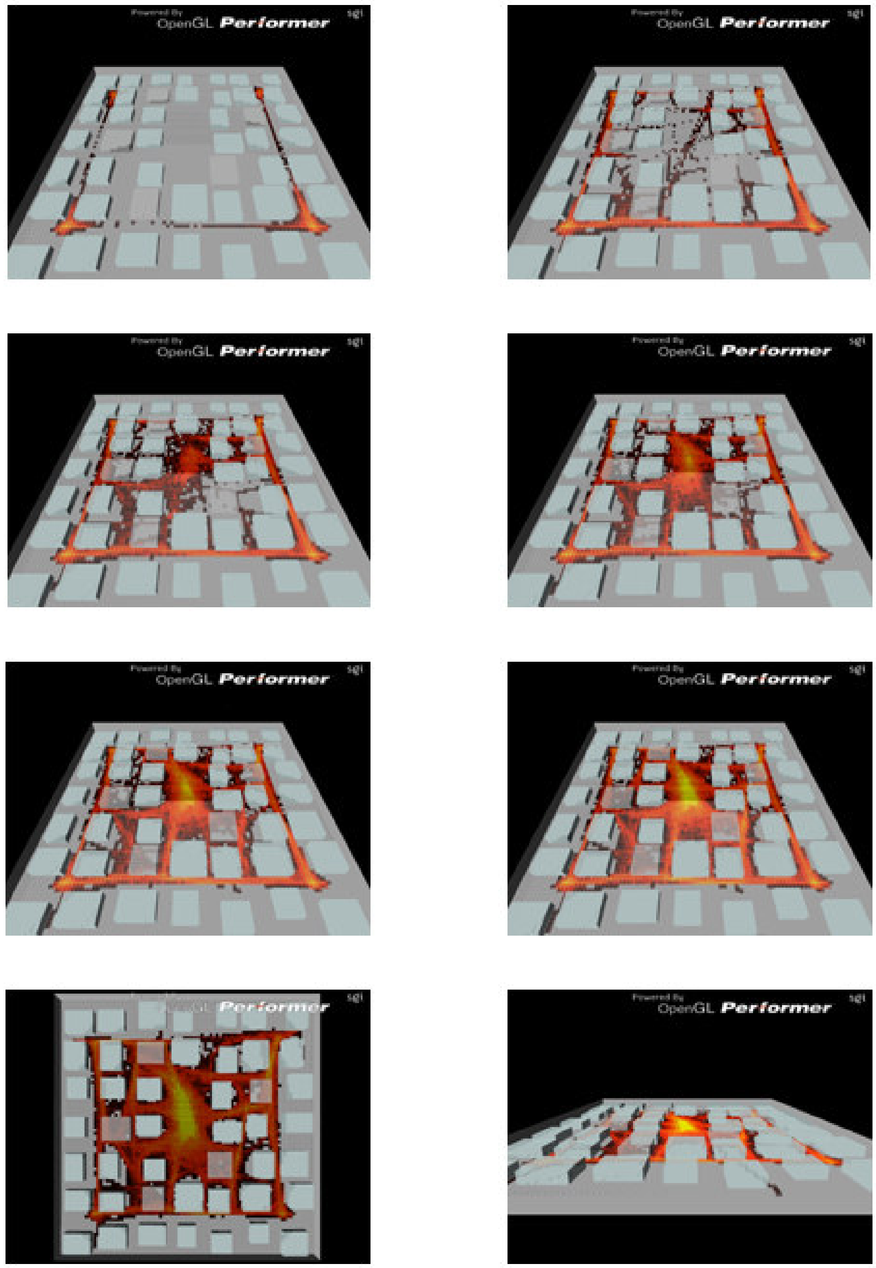
Gateways: 4 corners

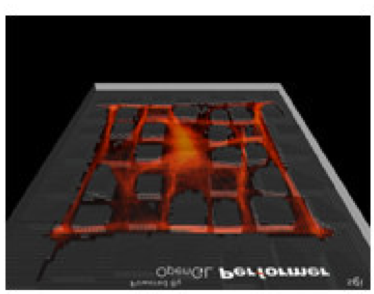
Shops: 5 - random distribution

Number of agents: 4 x 25 shoppers

4 x 15 tourists

Open space: 3 blocks



**B6**

Type: random grid

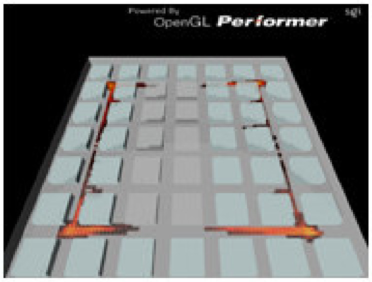
Gateways: 4 corners

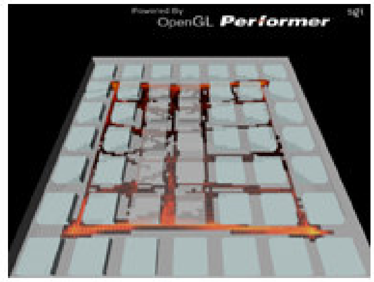
Shops: 4 - random distribution

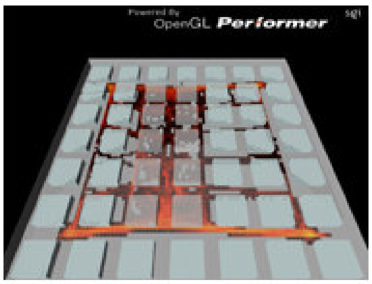
Number of agents: 4 x 25 shoppers

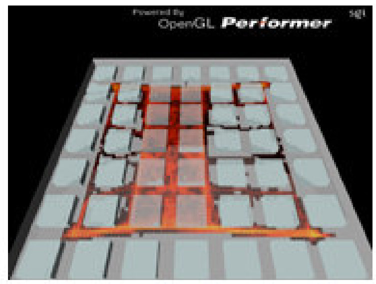
4 x 15 tourists

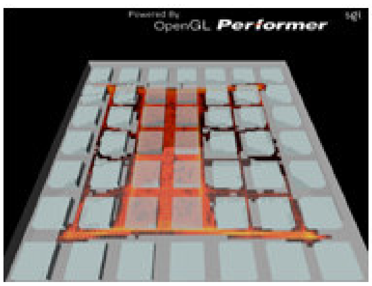
Open space: 3 blocks

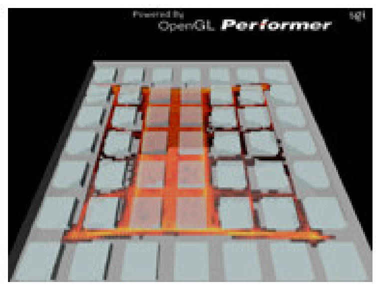


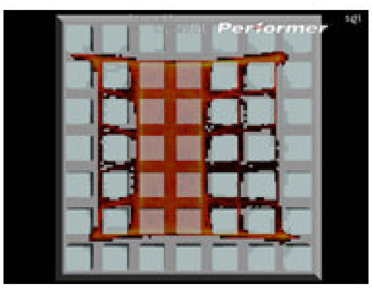


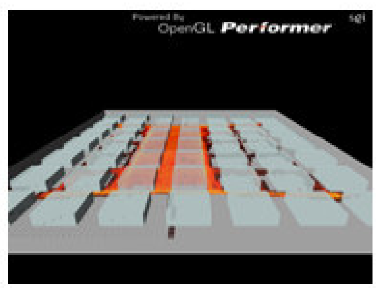


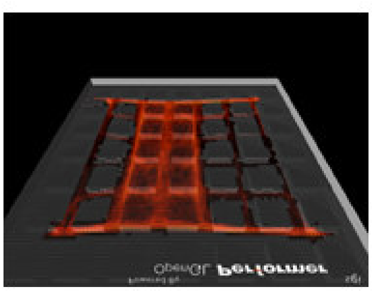












**B7**

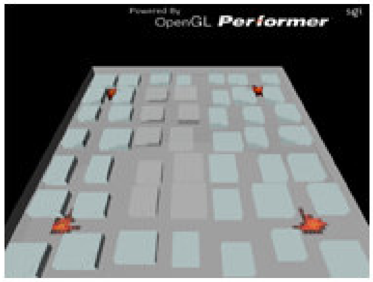
Type: grid

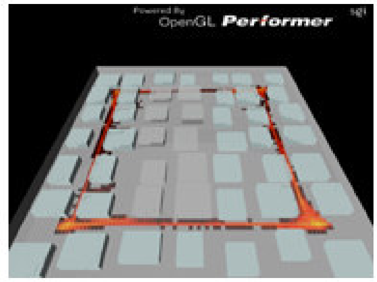
Gateways: 4 corners

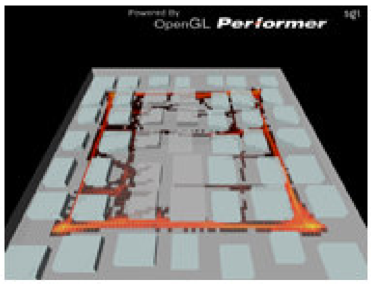
Shops: 10 - street alignment

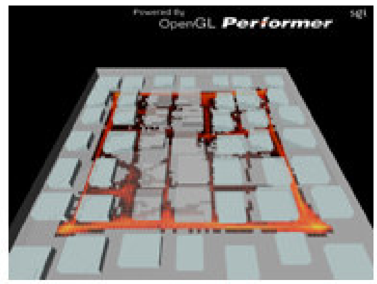
Number of agents: 4 x 40 shoppers

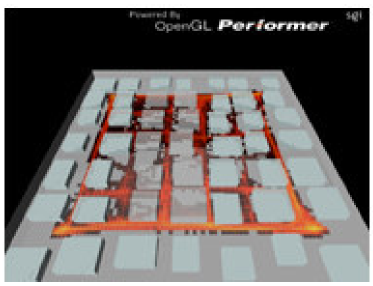
Open space: -

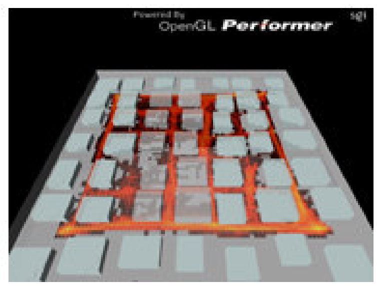


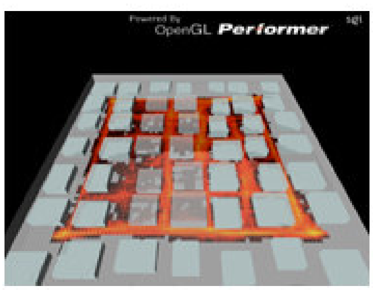


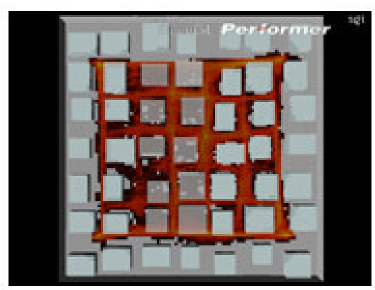
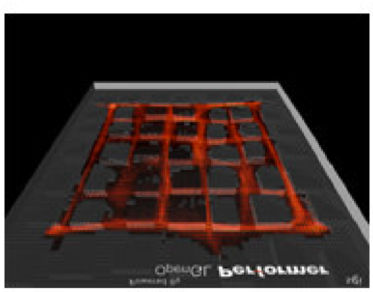










**B8**

Type: random grid

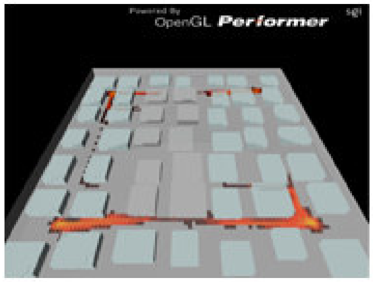
Gateways: 4 corners

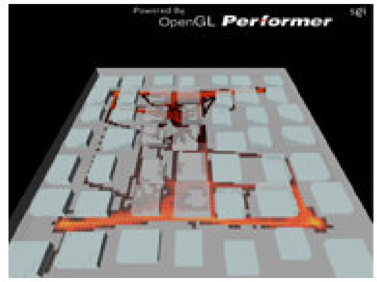
Shops: 10 - street alignment

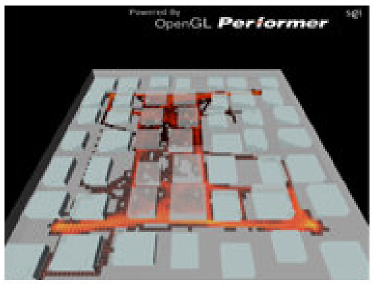
Number of agents: 4 x 25 shoppers

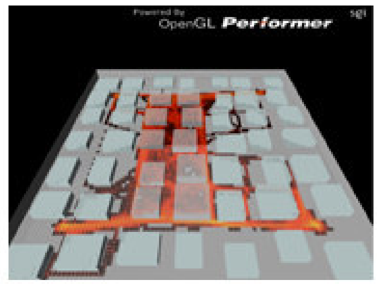
4 x 15 tourists

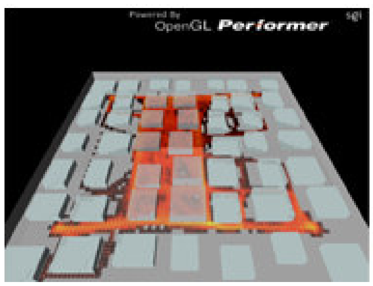
Open space: -

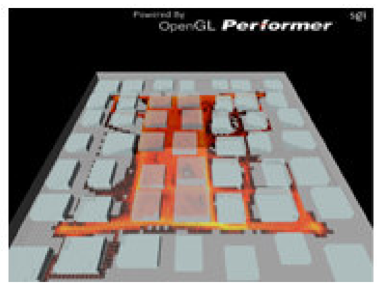


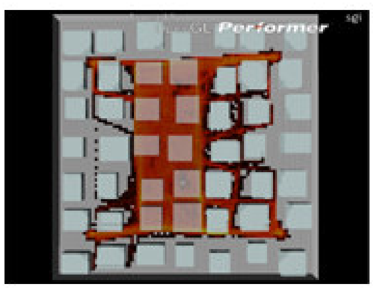


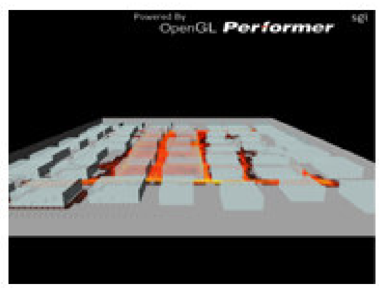


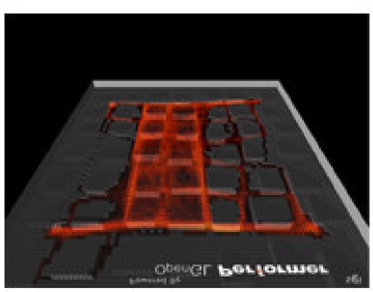












**B9**

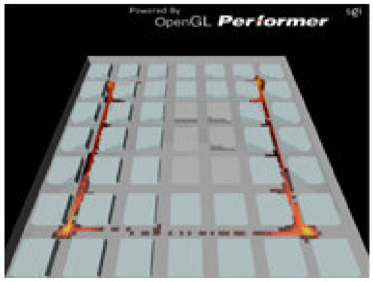
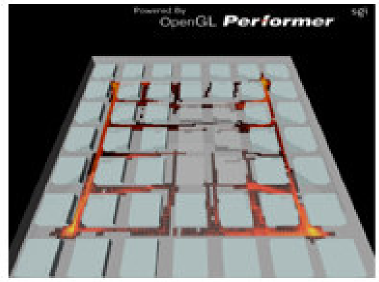
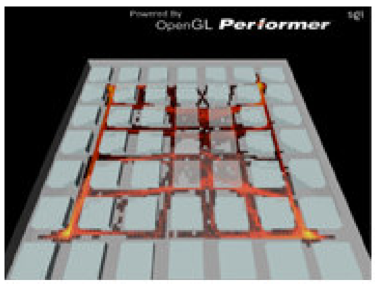
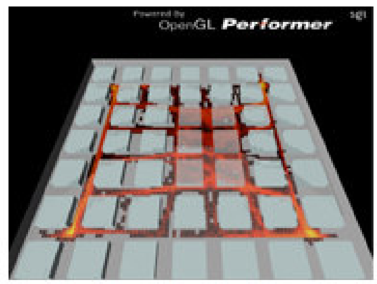
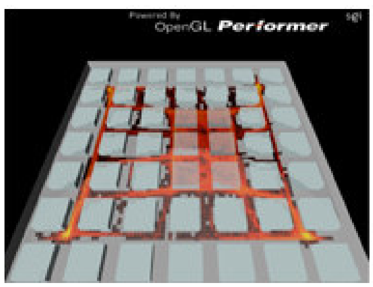
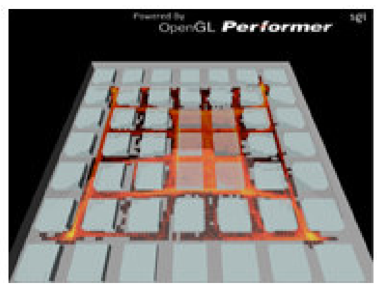
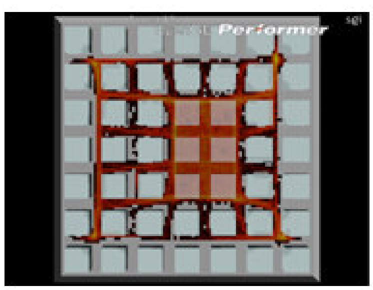
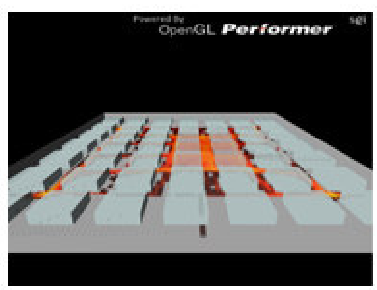
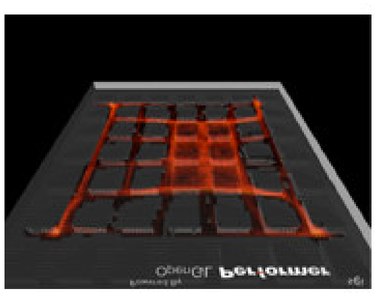
Type: random grid

Gateways: 4 corners

Shops: 10 - street alignment

Number of agents: 4 x 40 shoppers

Open space: -

**B10**

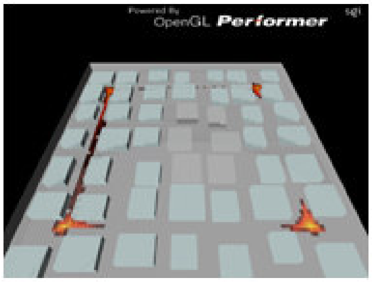
Type: grid

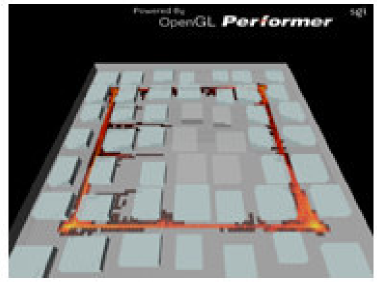
Gateways: 4 corners

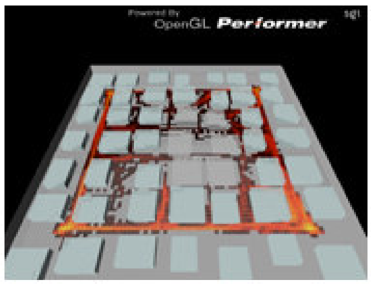
Shops: 6 – single cluster

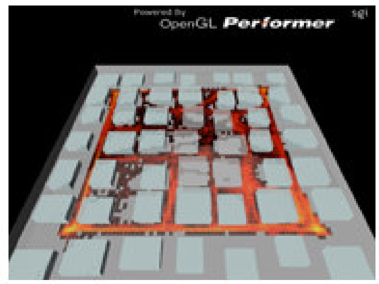
Number of agents: 4 x 40 shoppers

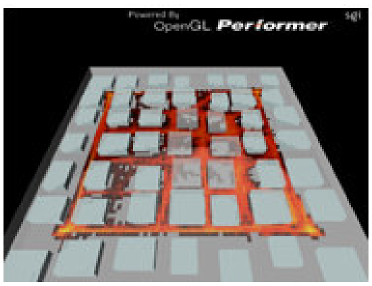
Open space: -

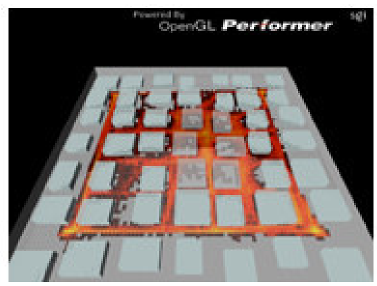


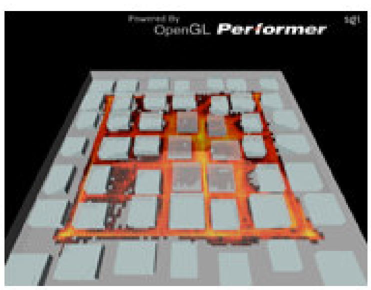


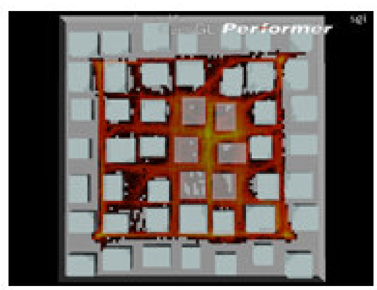
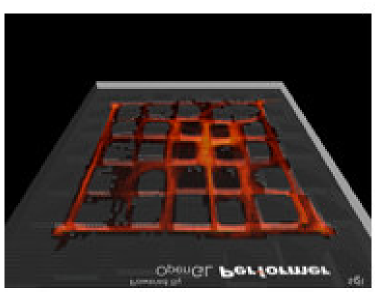










**B11**

Type: random grid

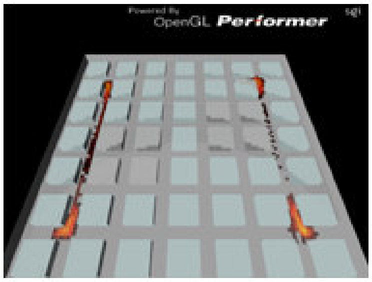
Gateways: 4 corners

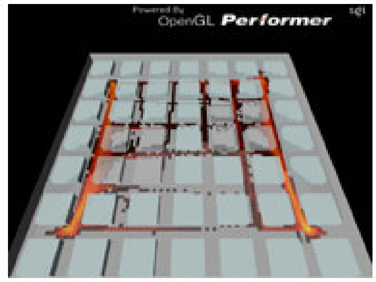
Shops: 6 – single cluster

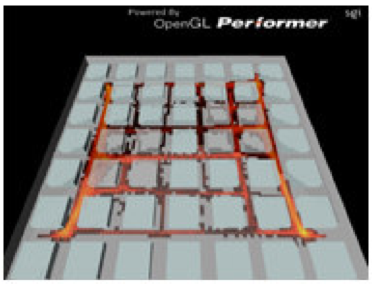
Number of agents: 4 x 25 shoppers

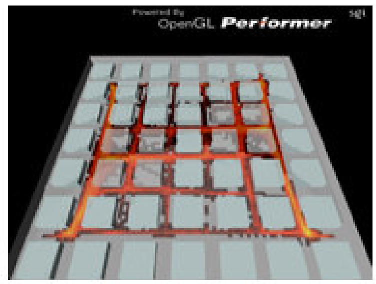
4 x 15 tourists

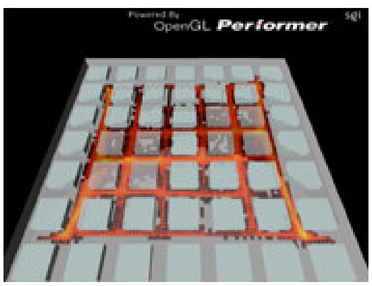
Open space: -

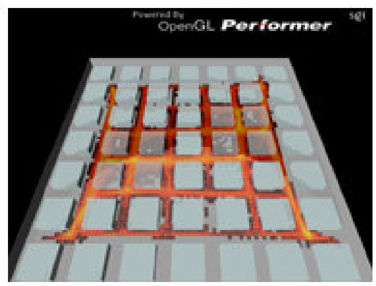


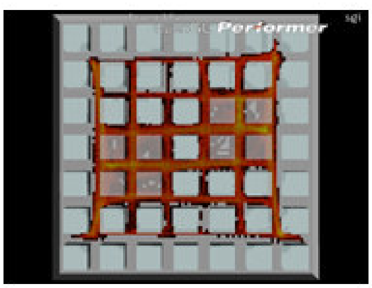
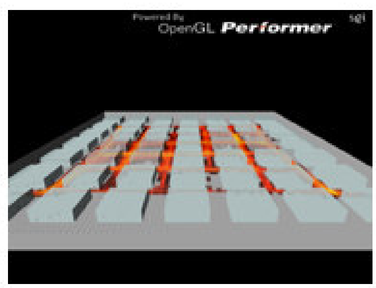


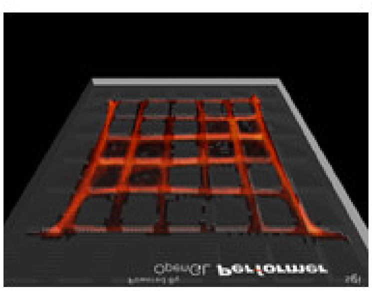










**B12**

Type: grid

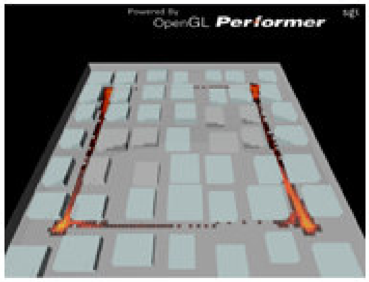
Gateways: 4 corners

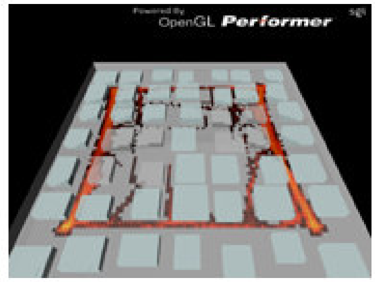
Shops: 8 - two clusters

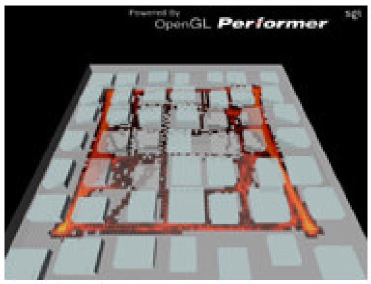
Number of agents: 4 x 25 shoppers

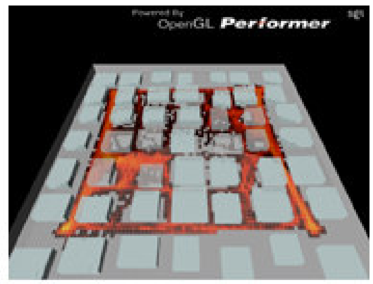
4 x 15 tourists

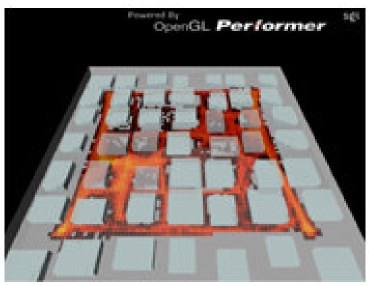
Open space: -

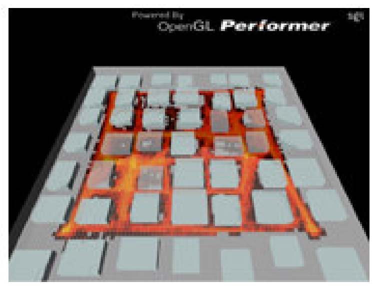


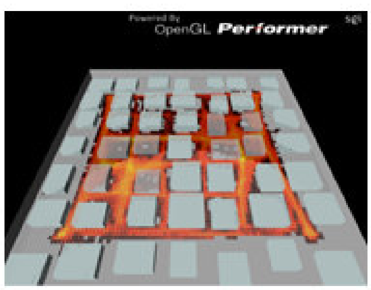



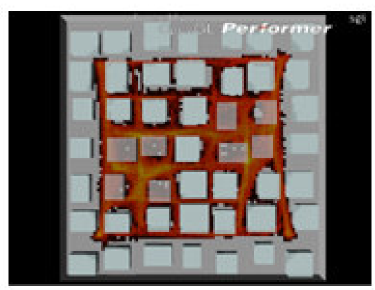



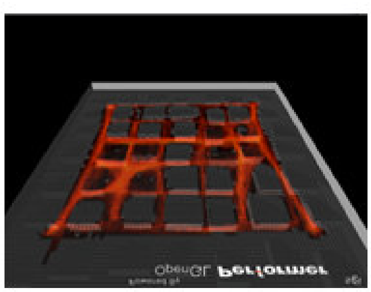





**B13**

Type: random grid

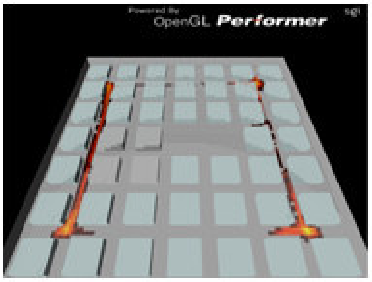
Gateways: 4 corners

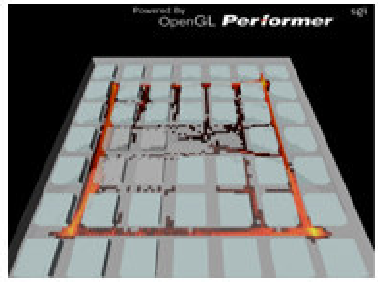
Shops: 8 - two clusters

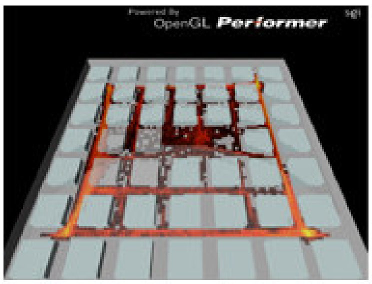
Number of agents: 4 x 25 shoppers

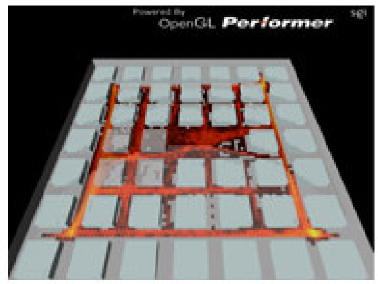
4 x 15 tourists

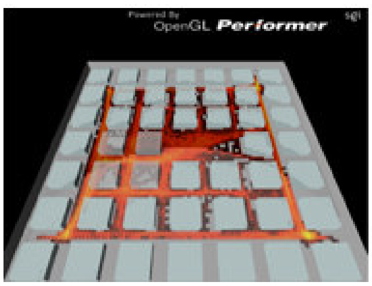
Open space: -

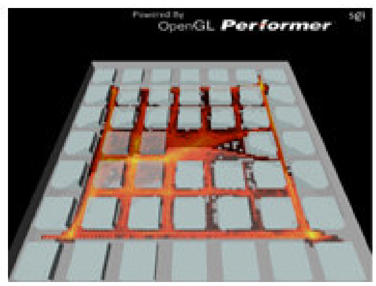


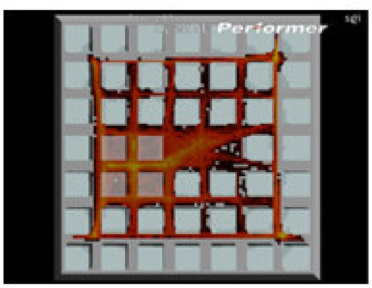



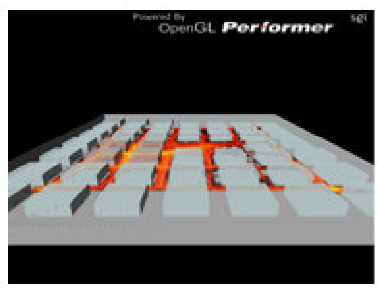



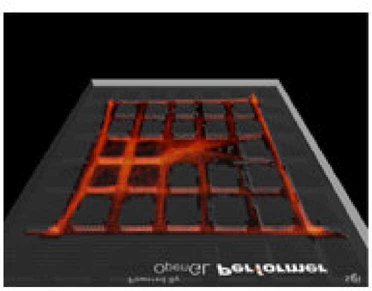



**B14**

Type: grid

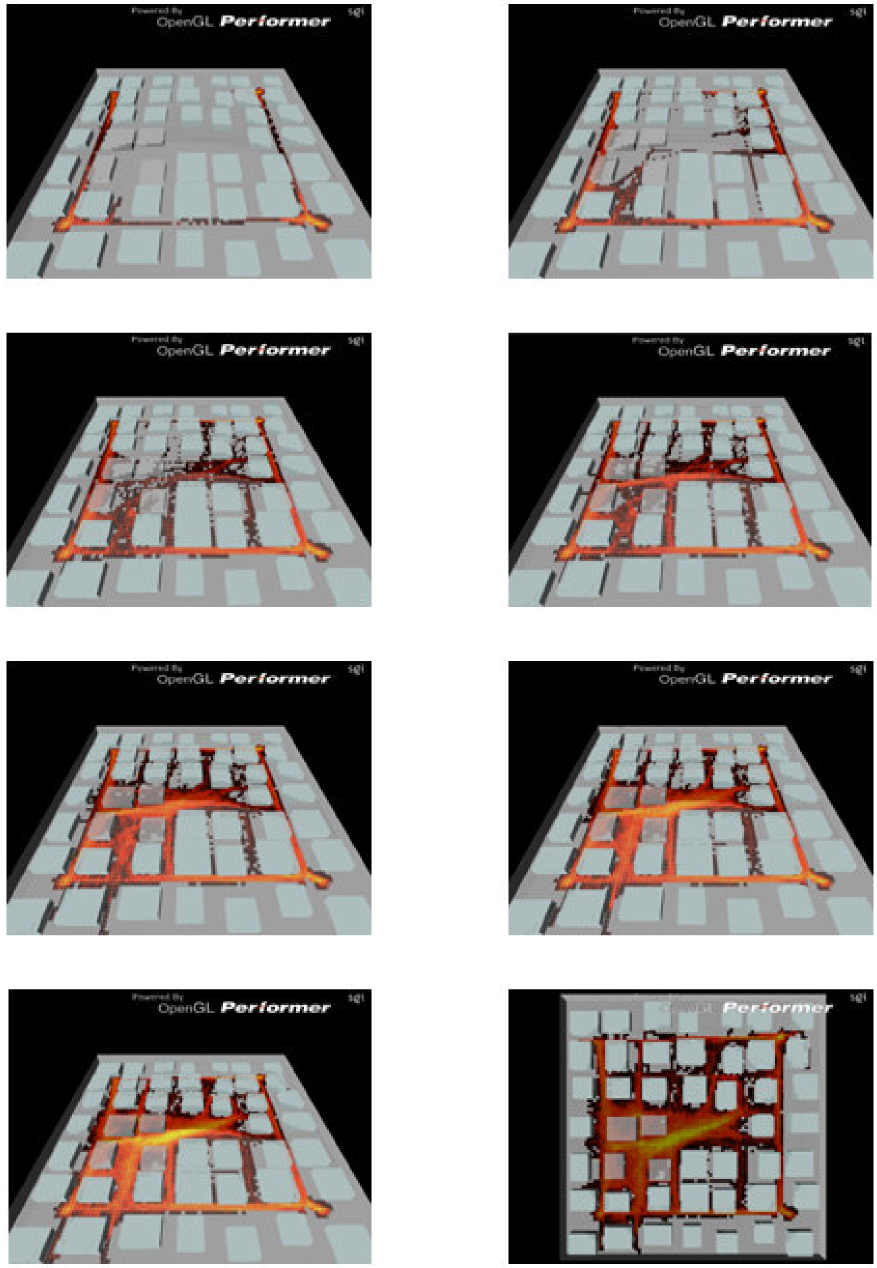
Gateways: 4 corners

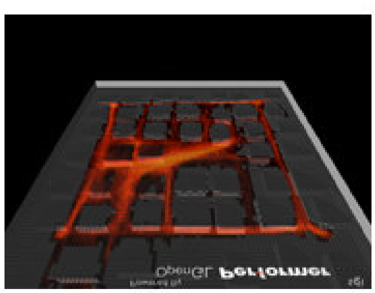
Shops: 4 – single cluster

Number of agents: 4 x 25 shoppers

4 x 15 tourists

Open space: 2 blocks



**B15**

Type: random grid

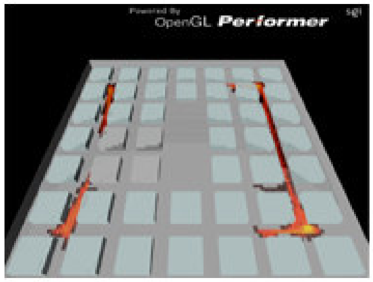
Gateways: 4 corners

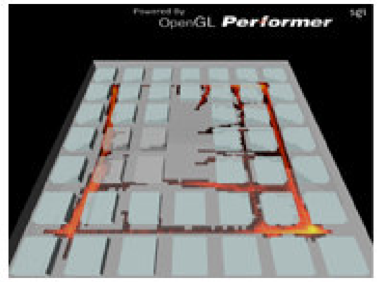
Shops: 4 – single cluster

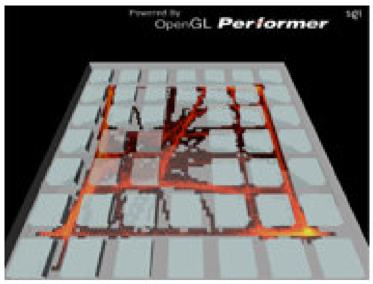
Number of agents: 4 x 25 shoppers

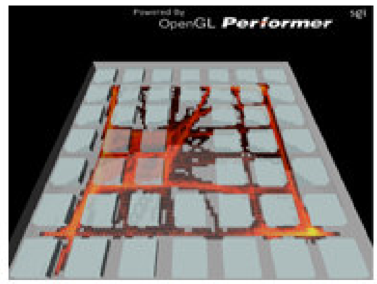
4 x 15 tourists

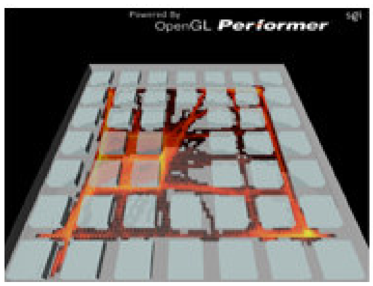
Open space: 2 blocks

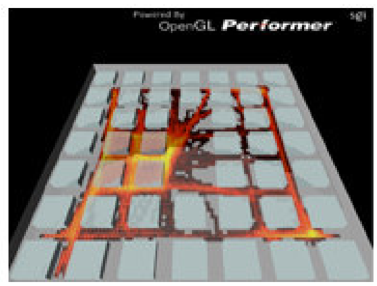


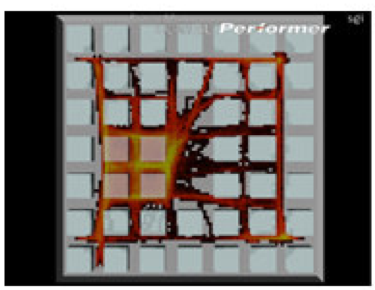



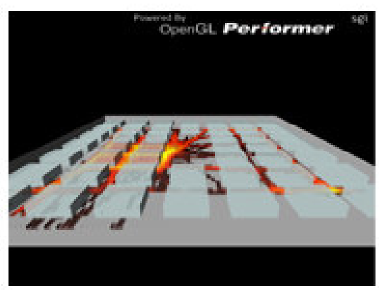



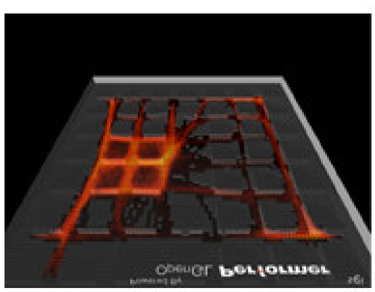



**B16**

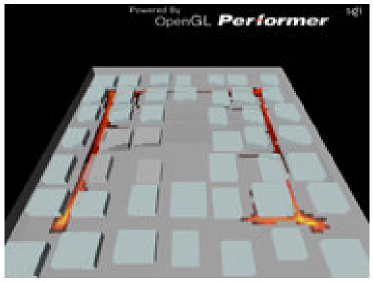
Type: grid

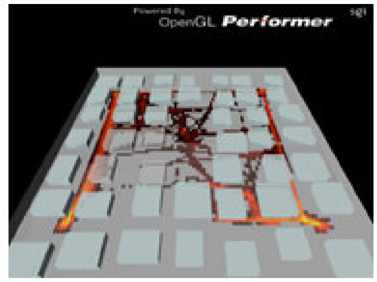
Gateways: 4 corners

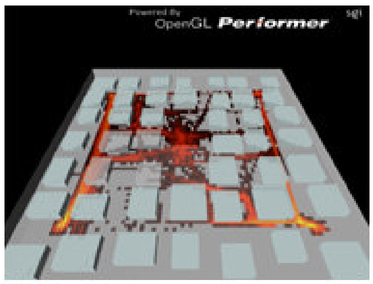
Shops: 4 – single cluster

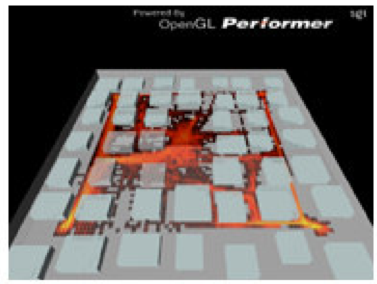
Number of agents: 4 x 40 shoppers

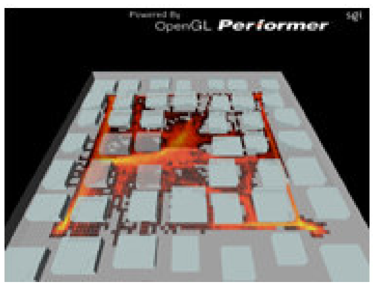
Open space: 3 blocks

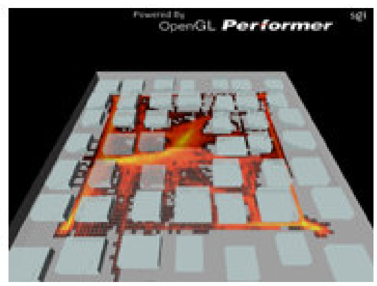


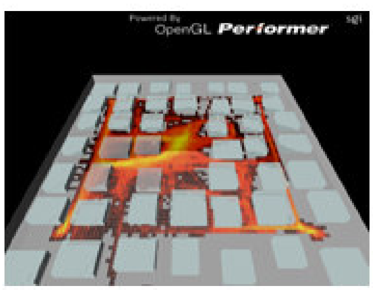



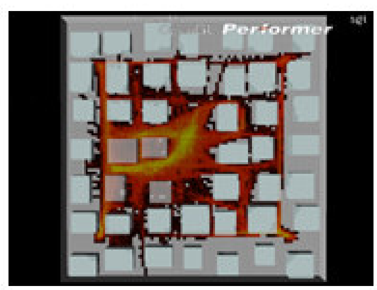



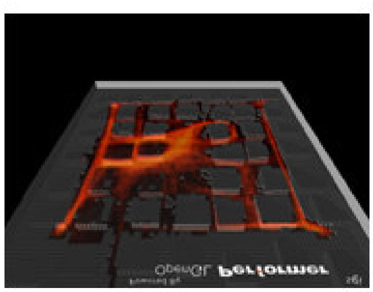



**B17**

Type: random grid

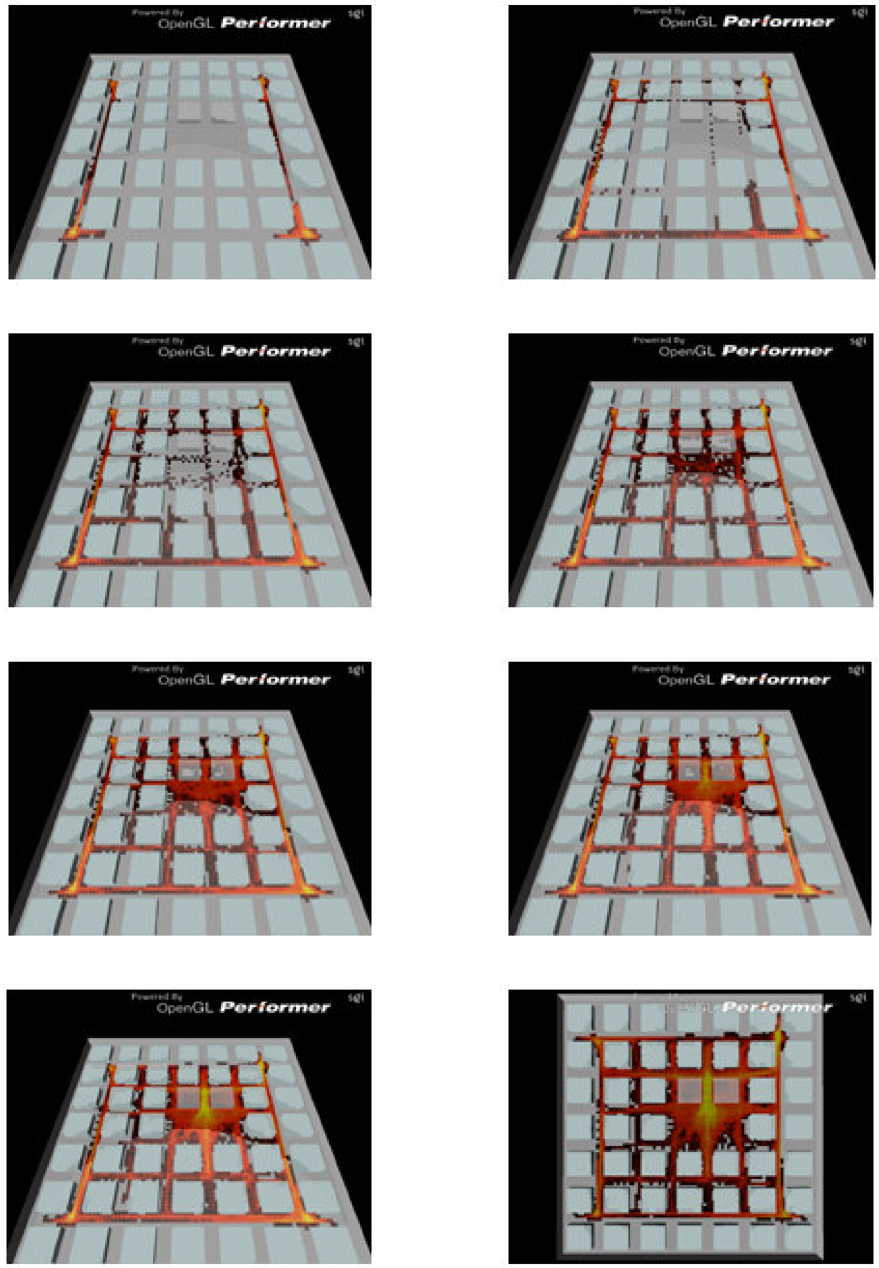
Gateways: 4 corners

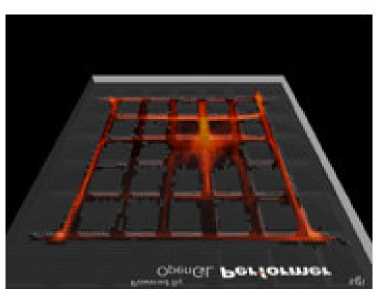
Shops: 4 – single cluster

Number of agents: 4 x 25 shoppers

4 x 15 tourists

Open space: 3 blocks



**B18**

Type: grid

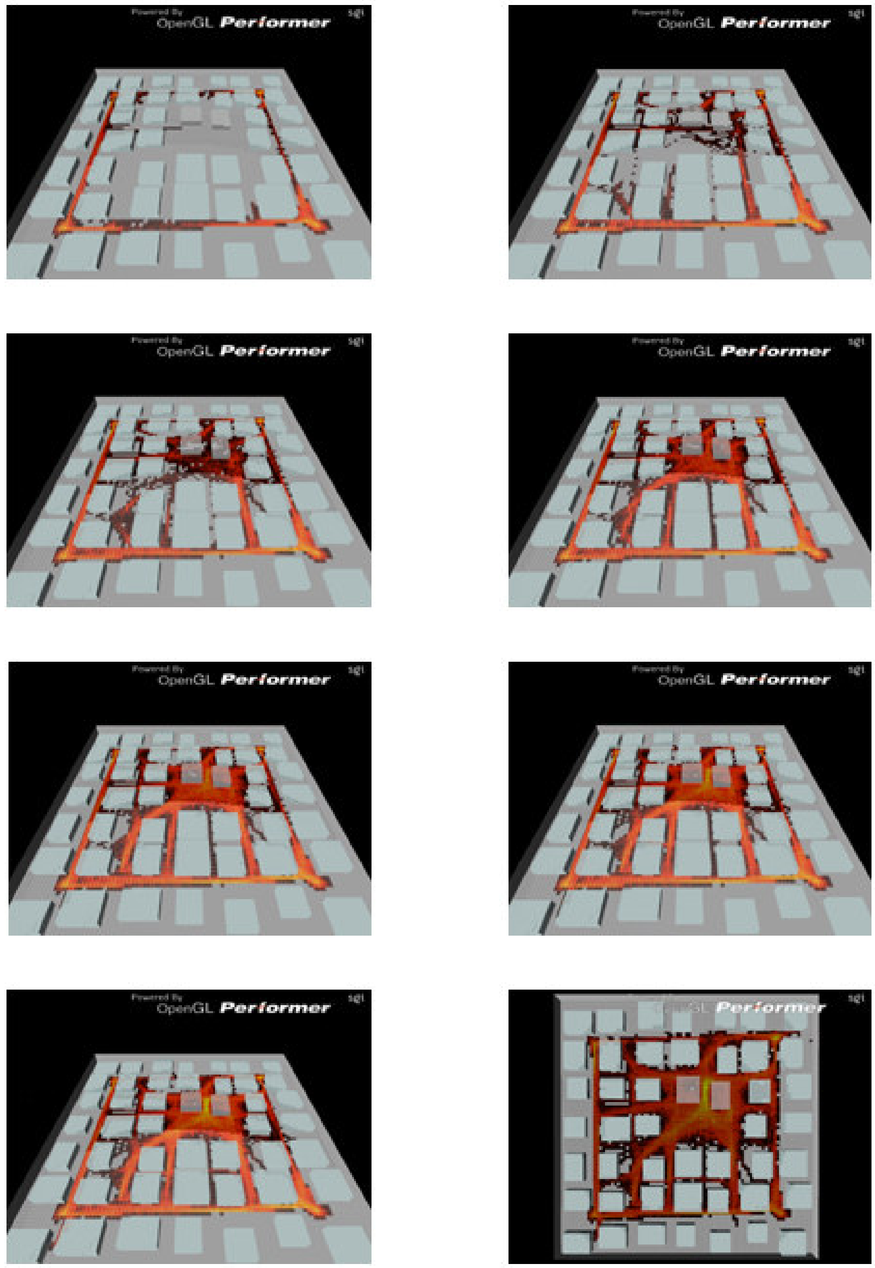
Gateways: 4 corners

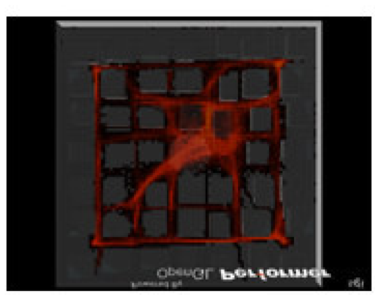
Shops: 2 - side of open space

Number of agents: 4 x 25 shoppers

4 x 15 tourists

Open space: 2 blocks





**B19**

Type: random grid

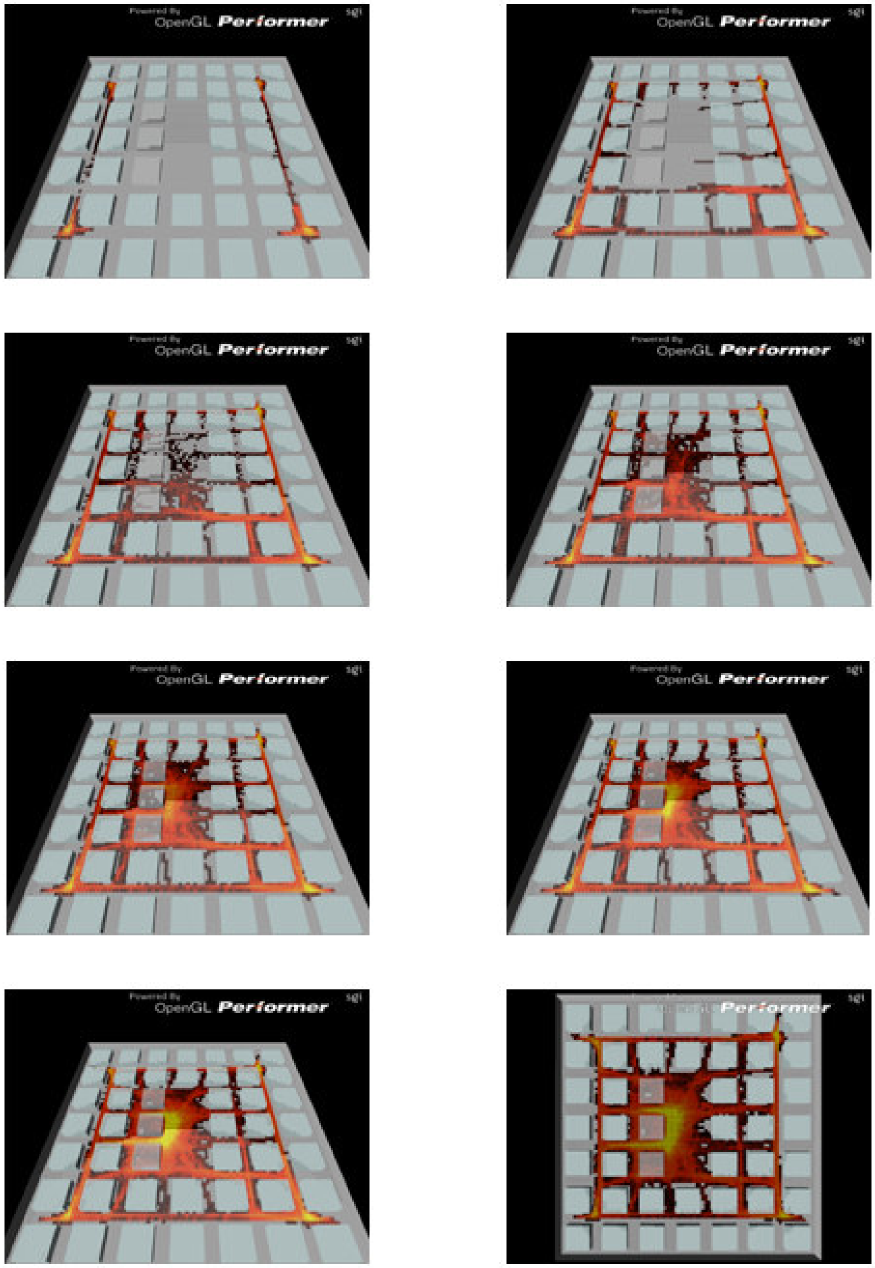
Gateways: 4 corners

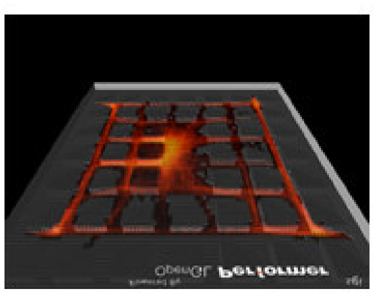
Shops: 2 - side of open space

Number of agents: 4 x 25 shoppers

4 x 15 tourists

Open space: 2 blocks



**B20**

Type: grid

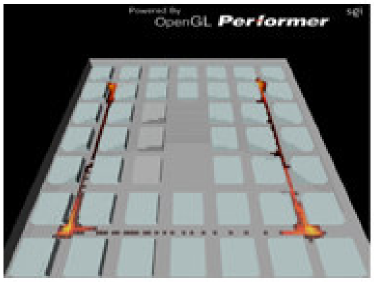
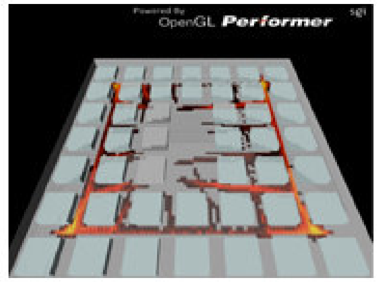
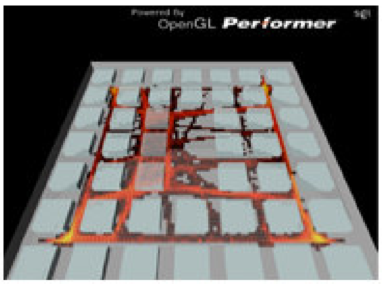
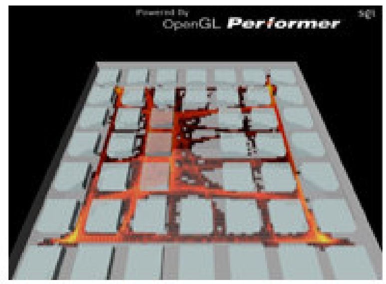
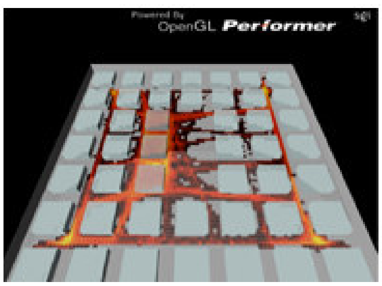
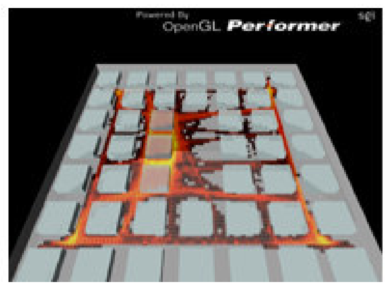
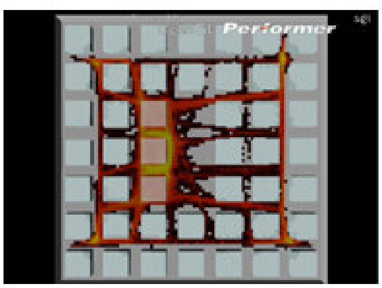
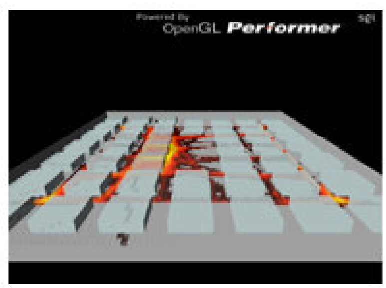
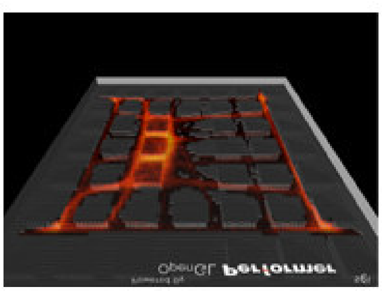
Gateways: 4 corners

Shops: 3 - side of open space

Number of agents: 4 x 25 shoppers

4 x 15 tourists

Open space: 3 blocks

**B21**

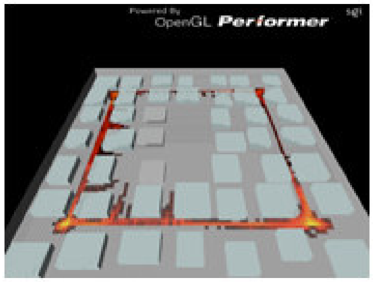
Type: grid

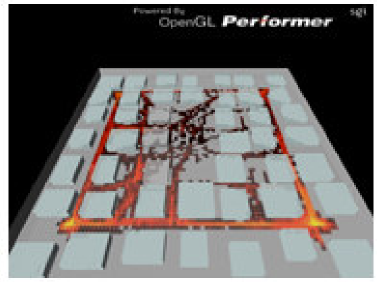
Gateways: 4 corners

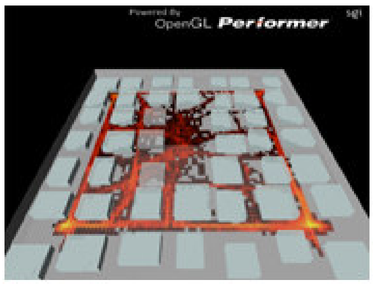
Shops: 3 - side of open space

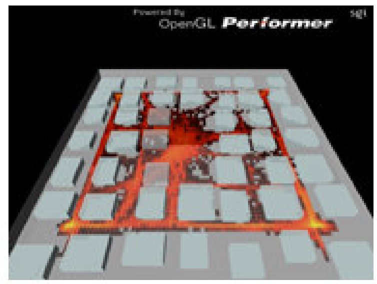
Number of agents: 4 x 40 shoppers

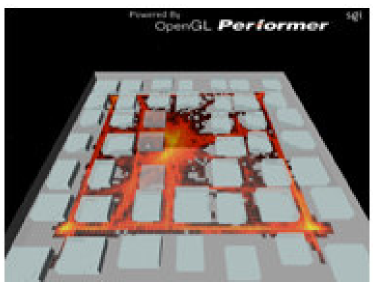
Open space: 3 blocks

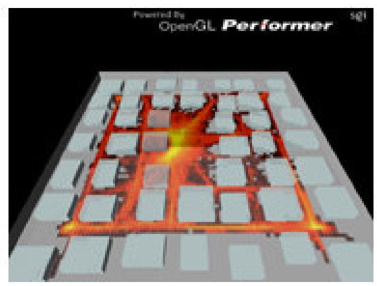


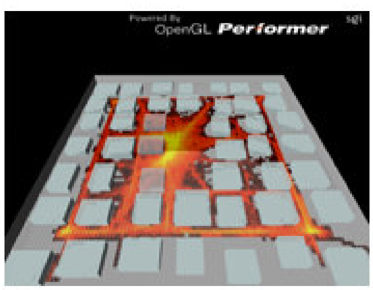


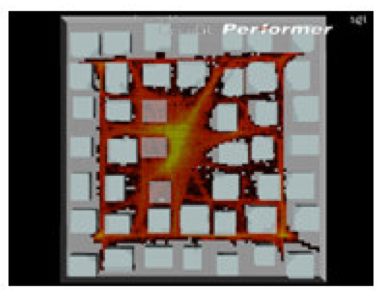


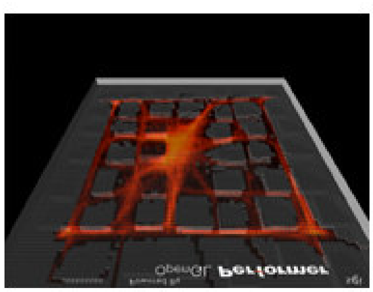












**B22**

Type: random grid

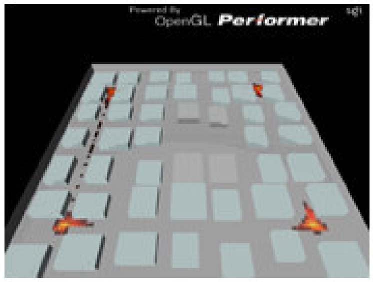
Gateways: 4 corners

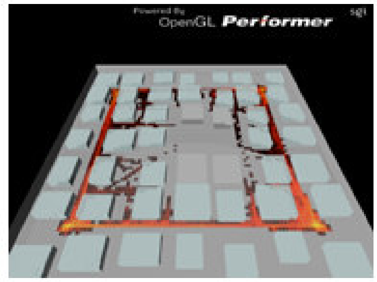
Shops: 3 - side of open space

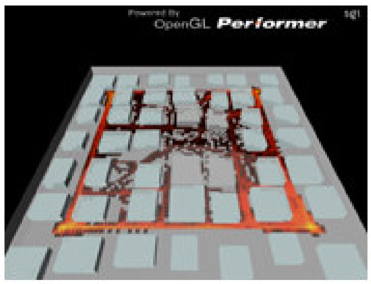
Number of agents: 4 x 25 shoppers

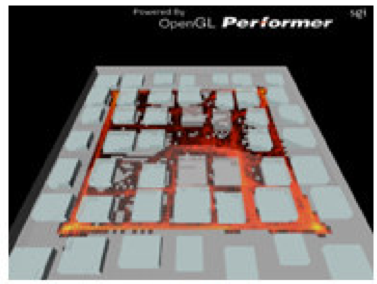
4 x 15 tourists

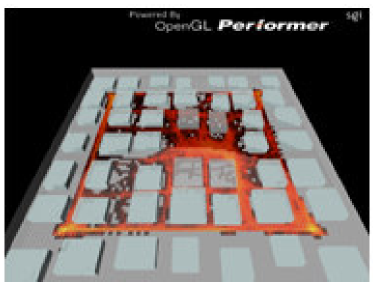
Open space: 3 blocks

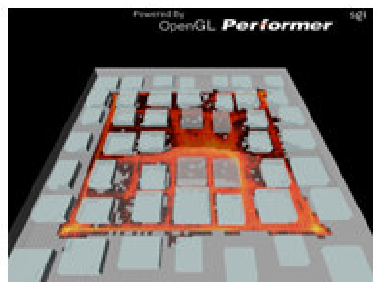


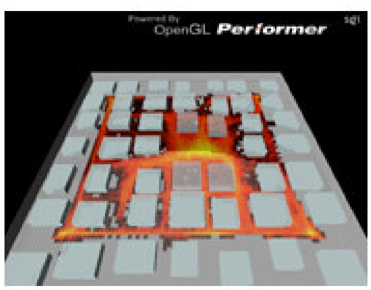



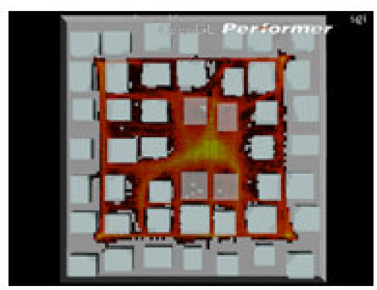



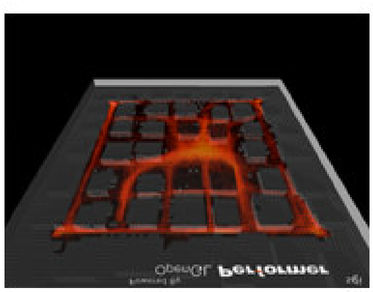





**B23**

Type: random grid

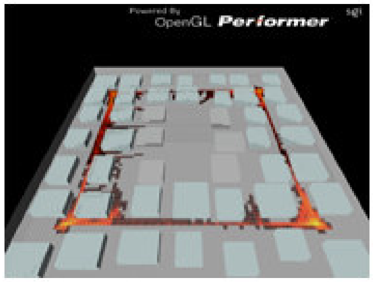
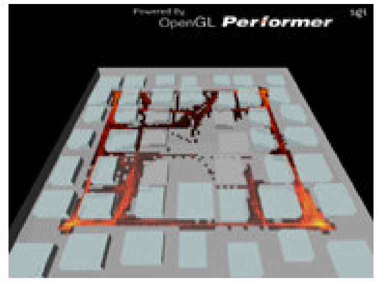
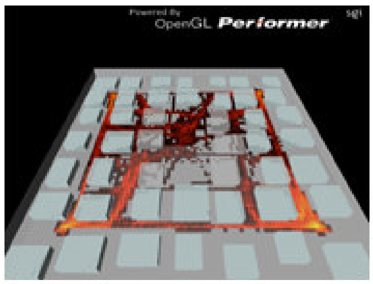
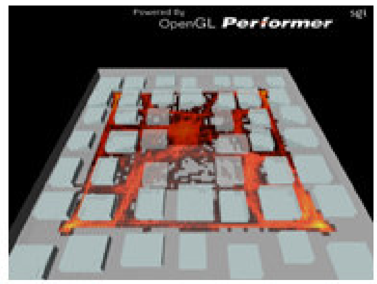
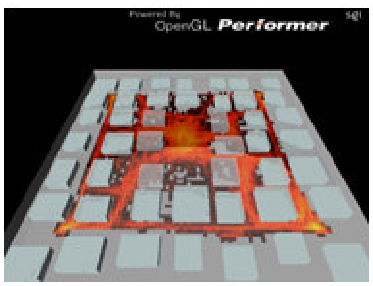
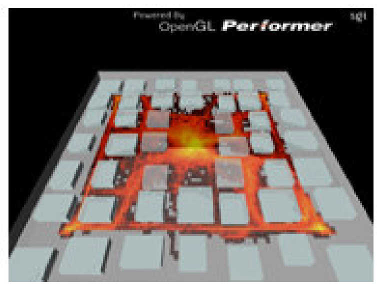
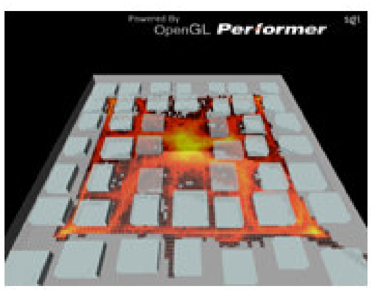
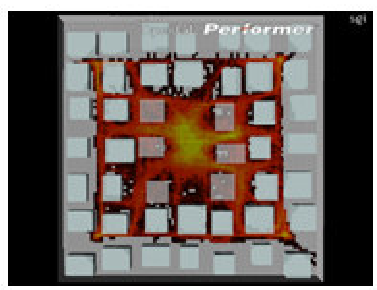
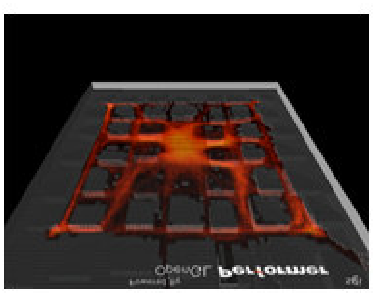
Gateways: 4 corners

Shops: 4 - two sides of open space

Number of agents: 4 x 25 shoppers

4 x 15 tourists

Open space: 2 blocks

**B24**

Type: random grid

Gateways: 4 corners

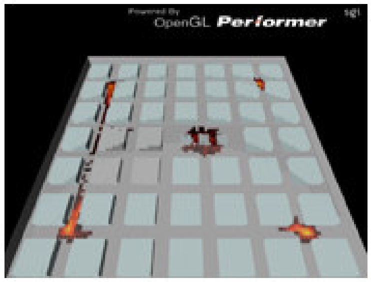
Shops: 6 - two sides of open space

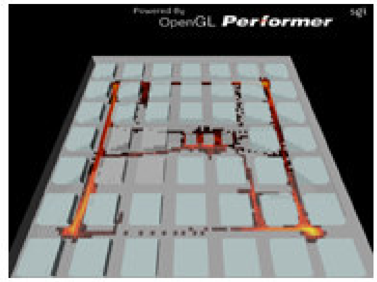
Number of agents: 4 x 25 shoppers

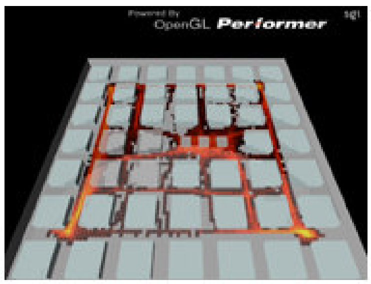
4 x 15 tourists

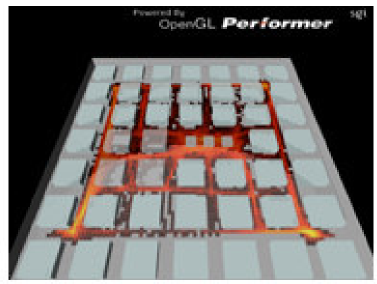
Open space: 3 blocks

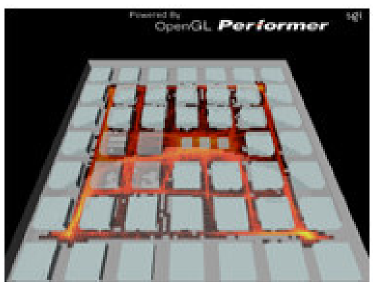
## Appendix C

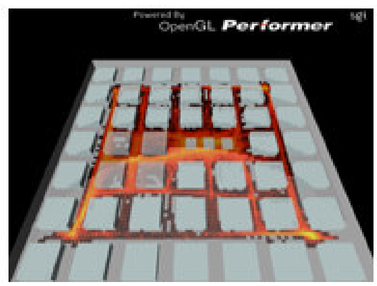


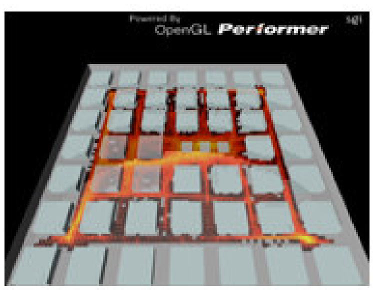



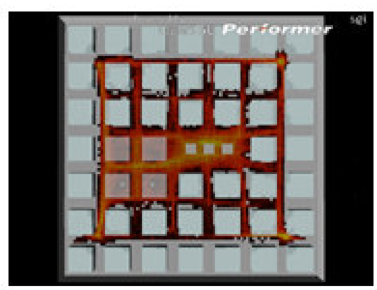



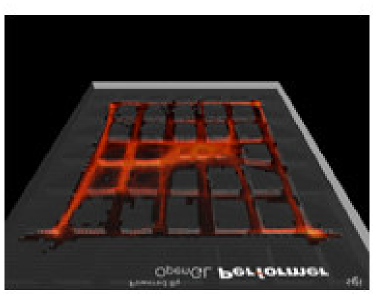



**C1**

Type: grid

Gateways: 4 corners

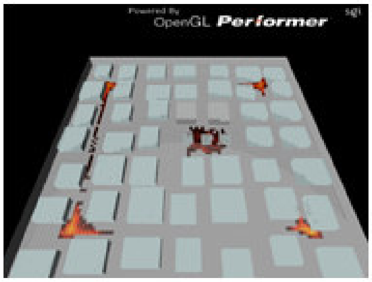
Shops: 4 – single cluster

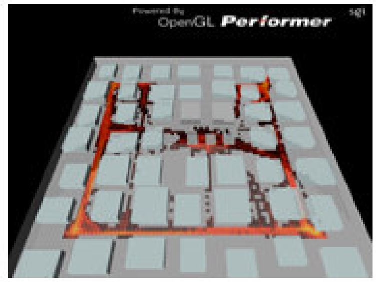
Market: 3 shops

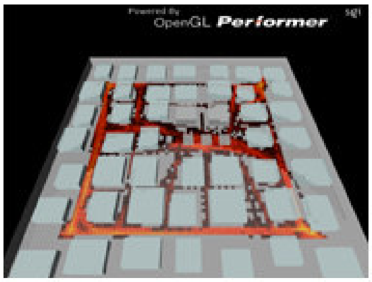
Number of agents: 4 x 25 shoppers

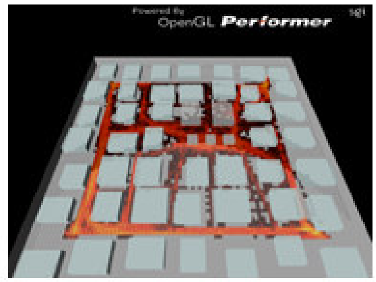
120 market visitors

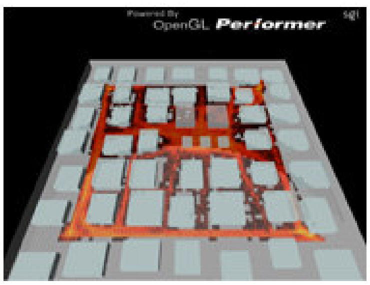
Open space: 2 blocks

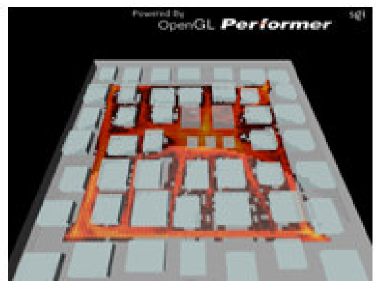


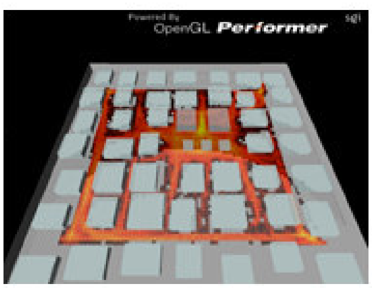



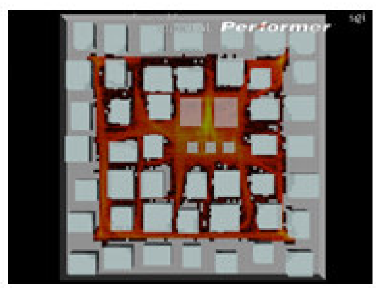



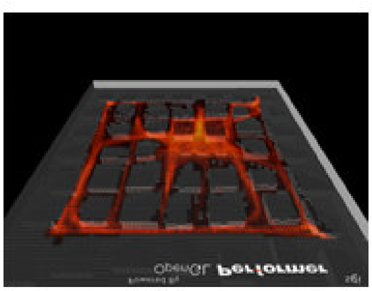



**C2**

Type: random grid

Gateways: 4 corners

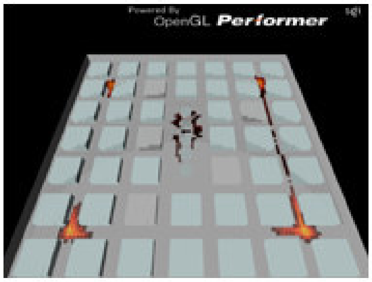
Shops: 2 – side of open space

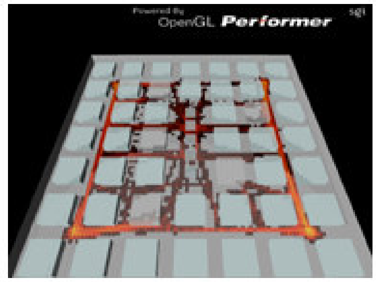
Market: 3 shops

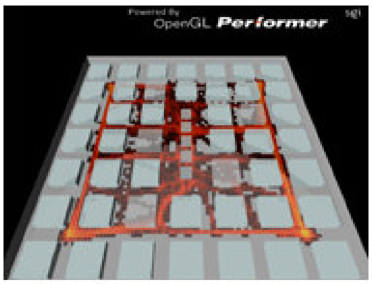
Number of agents: 4 x 25 shoppers

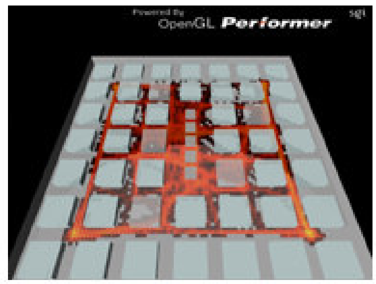
120 market visitors

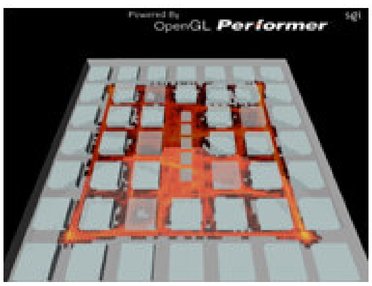
Open space: 2 blocks

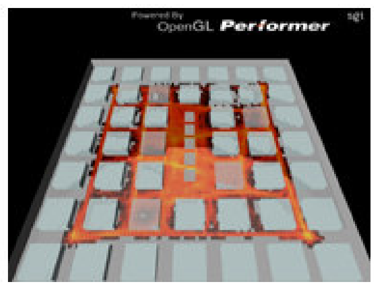


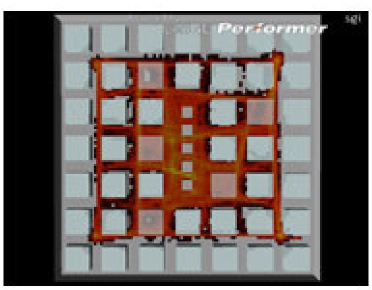



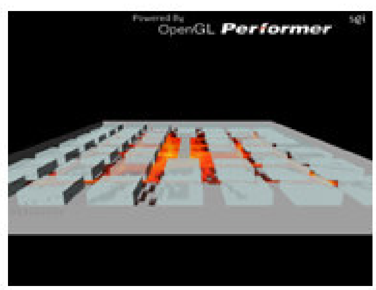



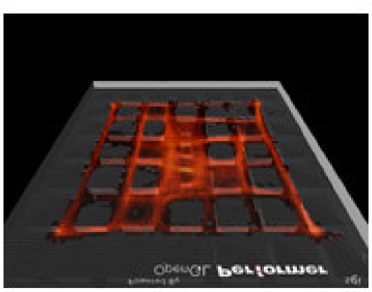





**C3**

Type: grid

Gateways: 4 corners

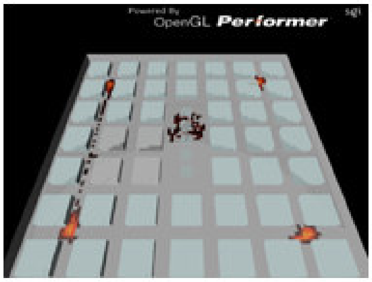
Shops: 5 - random distribution

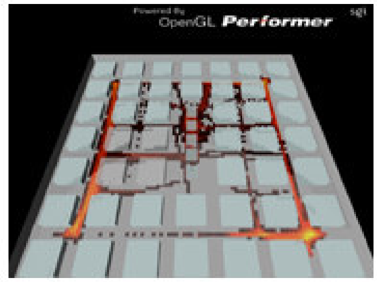
Market: 5 shops

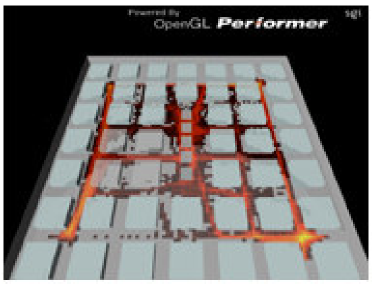
Number of agents: 4 x 25 shoppers

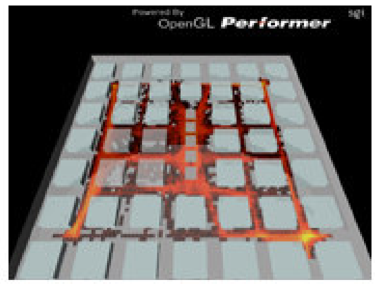
90 market visitors

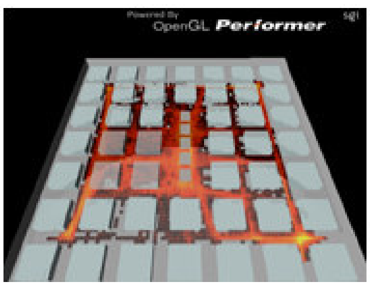
Open space: 3 blocks

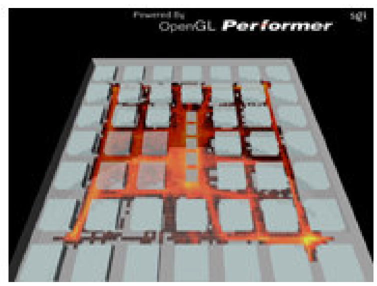


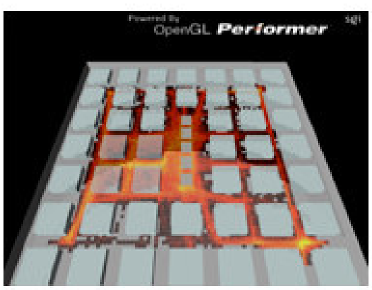



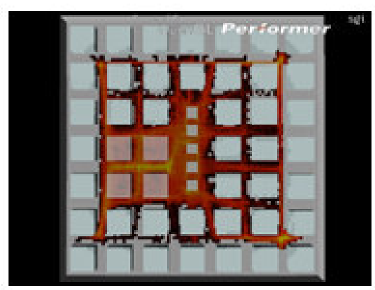



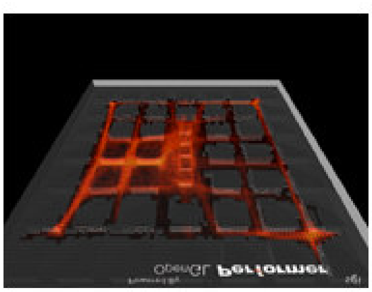



**C4**

Type: grid

Gateways: 4 corners

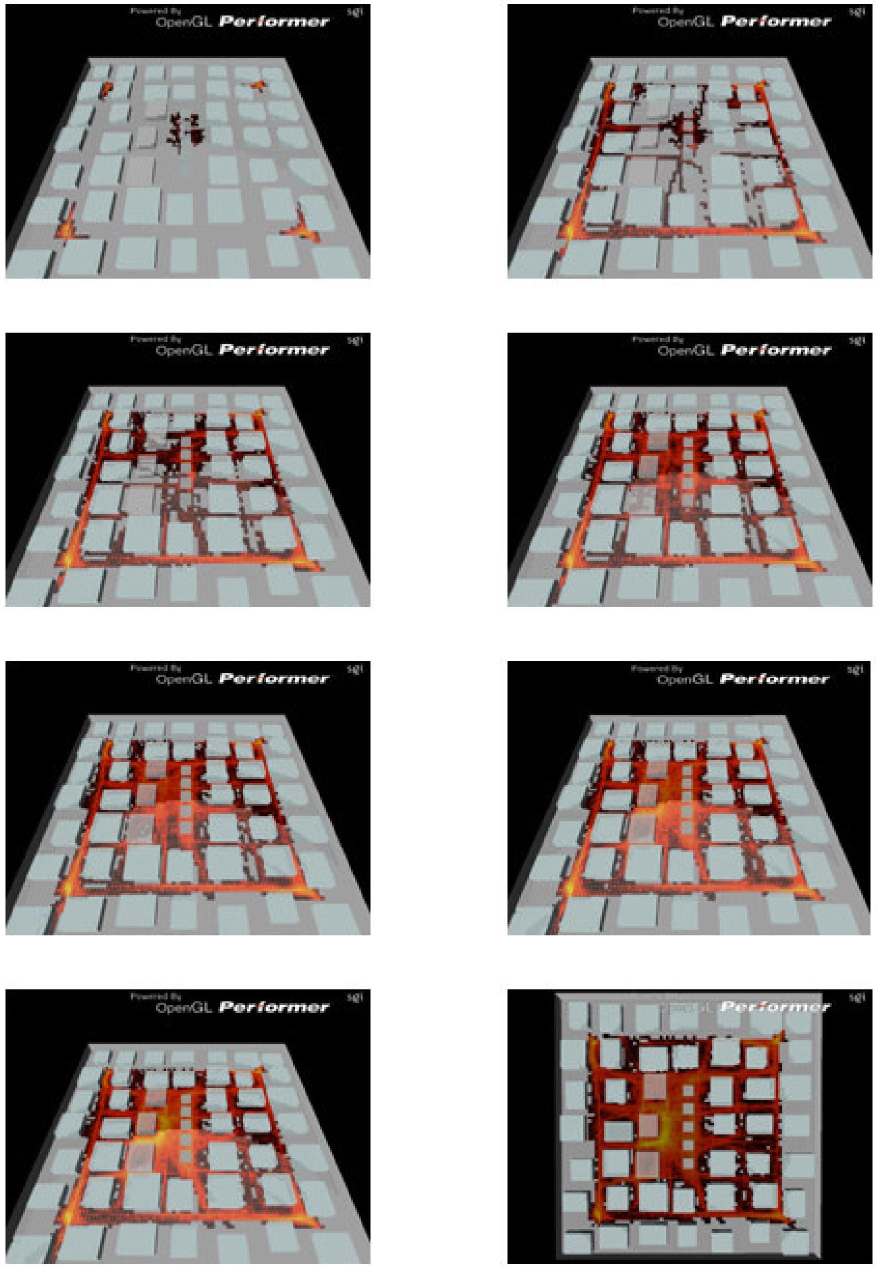
Shops: 4 – single cluster

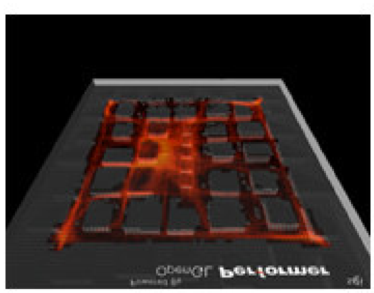
Market: 5 shops

Number of agents: 4 x 25 shoppers

120 market visitors

Open space: 3 blocks



**C5**

Type: random grid

Gateways: 4 corners

Shops: 3 – side of open space

Market: 5 shops

Number of agents: 4 x 25 shoppers

110 market visitors

Open space: 3 blocks