Towards a Multi-Agent Model for Visualizing Simulated User Behavior to Support the Assessment of Design Performance

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We introduce the outline of a multi-agent model that can be used for visualizing simulated user behavior to support the assessment of design performance. We will consider various performance indicators of building environments, which are related to user reaction to design decisions. This system may serve as a media tool in the design process for a better understanding of what the design will look like, especially for those cases where design or planning decisions will affect the behavior of individuals. The system is based on cellular automata and multi-agent simulation technology. The system simulates how agents move around in a particular 3D (or 2D) environment, in which space is represented as a lattice of cells. Agents represent objects or people with their own behavior, moving over the network. Each agent will be located in a simulated space, based on the cellular automata grid. Each iteration of the simulation is based on a parallel update of the agents conforming local rules. Agents positioned within an environment will need sensors to perceive their local neighborhood and some means with which to affect the environment. In this way, autonomous individuals and the interaction between them can be simulated by the system. As a result, designers can use the system to assess the likely consequences of their design decisions on user behavior. We think that the system provides a potentially valuable tool to support design and decision-making processes, related to user behavior in architecture and urban planning.

Introduction

Media may serve different roles in the design process. In many cases, media have been used as a means of visualization, allowing experts and users alike to better understand what the design will look like. Such visualization is of critical importance in improving the readability of 2D representations.

Other performance indicators of buildings and urban environments depend on user reaction to design decisions. Architects and urban planners are often faced with the problem to assess how their design or planning decisions will affect the behavior of individuals. Various performance indicators are related to the behavior of individuals in particular environments.

One way of addressing this problem is to develop models which relate user behavior to design parameters. For example, models of pedestrian behavior have been developed to support planning decisions related to the location of facilities, parking policies, etc. (e.g. Kurose *et al*, 1999).

Although the output of such models tend to be quantitative and in tabular form, graphical representations and 3D simulations might be a more powerful tool of assessing design performance in terms of such user-behavior. We therefore formulated a research project that aims at exploring the possibilities of developing such a tool in a virtual reality environment using multi-agent simulation and cellular automata.

In a cellular automata model, space is represented as a uniform lattice of cells with local states, subject to a uniform set of rules, which drives the behavior of the system. These rules compute the state of a particular cell as a function of its previous state and the states of the adjacent cells. An extension of the basic cellular automata model allows the state of any particular cell to be influenced by more the states not only of the contingent cells, but also by the states of more remote cells. State changes may depend on the aggregate effect of the states of all other cells, or some subset of these. Another extension is to build models in which cells preserve state information and calculate their next state on the basis of their neighbors and their own history of state changes. Agent technology will be implemented to build a framework for multi-agent simulation. Objects or people moving across the network are represented in terms of agents. Each agent will be located in a simulated space, based on the cellular automata grid. Agents positioned within an environment will need sensors to perceive their local neighborhood and some means with which to affect the environment. The choice for a multi-agent model is motivated by their promise to simulate autonomous individuals and the interaction between them (Gilbert and Troitzsch, 1998).

Agent technology will also be used to simulate the outcome of the model and the simulation. Designers can use the system to assess the likely consequences of their design decisions on user behavior. In Dijkstra and Timmermans (1997) point out by an illustration of wayfinding that a simulation model, as a decision support tool could be very useful to apply possible modifications to design concepts.

The paper is organized as follows. First, we will discuss some essentials of cellular automata and agents. Next, we will briefly discuss the principles of multi-agent simulation, and after that the outline of the proposed model. We will conclude with a brief discussion.

Essentials of cellular automata

Principles

Cellular automata are mathematical models of spatially distributed processes. They consist of an array of cells, each with a finite set of possible states. The purpose of the model is to simulate dynamic processes. The state of the cells evolves synchronously in discrete time steps as a function of its state and a set of rules, which relates the cell to other cells in the system.

Although originally introduced in the late 1940s by John von Neumann (von Neumann, 1966), it was not until the late sixties when John Horton Conway developed the first simple and most famous example of cellular automata (Berlekamp *et al*, 1982). A systematic study of

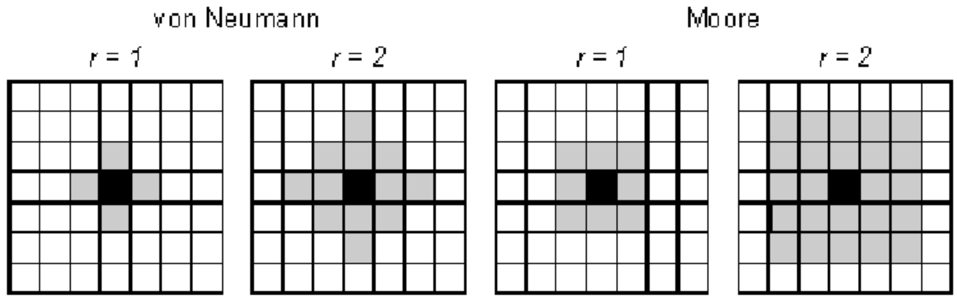


Figure 1. Different neighborhoods

cellular automata was pioneered by Stephan Wolfram (Wolfram, 1994). The basic definition of cellular automata can be formulated as follows:

Cellular automata are discrete dynamical systems whose behavior is completely specified in terms of a local relation (Ferber, 1999).

We can characterize a cellular automaton by the following features:

Cell-The basic element is the cell. Each cell can be in one of a finite set of possible states. For instance, the states could represent attitudes, individual characteristics, or actions. A state could also be seen as a property or an internal variable.

Grid-The cells are arranged in a regular grid. The grid usually forms a 1-dimensional line of cells, a 2-dimensional rectangular array or a 3-dimensional network (cube).

State-The state of a cell at any time step is determined by a set of rules in accordance with the principle of homogeneity. Homogeneity means that each cell is updated according to the same rules. The set of rules specifies how the state depends on the previous state of that cell and the states of the cell's neighborhood.

Time-The time evolution through the simulation is governed by discrete steps and by update rules according the principles of parallelism and locality. Parallelism means that the individual cell updates are performed independently of each other. Locality means that when a cell is updated, the state of a cell at time t+1 is a function of its own state and the states of the cell's neighborhood at time t.

The state of a cell depends of the neighborhood of the cell, that is the set of cells that it interacts with. In a grid these are normally the cells closest to the cell in question. The radius (r) refers to how many cells on either side are used to calculate the next state of a cell. Different definitions of neighborhoods are possible.

Formal definition and dynamics of cellular automata

Cellular automata are dynamical systems. Space, time and the states of the systems are discrete. The time evolution is governed by update rules (transition rules) that act only locally. As discussed before, cellular automata consist of an array of cells (grid) of some dimension d. A cell can be in one of s different states at a given time. At each discrete time stamp, each cell may change its state in a way determined by the local transition rules of the particular cellular automata. The transition rules describe precisely how a given cell should change states, depending on its current state and the states of its neighbors. All cells are updated synchronously. Thus the state of the entire grid advances in discrete time steps. Which cells are in the neighborhood of a given cell must be specified explicitly.

Let *G* be a grid of dimension d (the cells are the elements of *G*), *S* is a finite set of cellular states,

N is a finite set (of size *n* =|*N*|) of neighborhood indices such that "i Î N , "x Î G : i + x Î G

To obtain a cellular space we associate with *G*, the following is applicable:

• The neighborhood function g, defined by $g(x) = \{x + y_1 , x + y_2 , ..., x + y_n \}$ for all x Î G and where y_i $(i=1,2, ..., n)$ Î G is fixed.

• The structure (S, s_0, f) is called a finite cellular automaton, s0 is a distinguished element of S called the quiescent state, and f is the local transition function from n-tuples of elements of S into S. The function f is subject to restriction, $f(s_0, s_0, ..., s_0) = s_0$.

• The state $s^t(x)$ of a cell at time t is precisely the state of its associated automaton at time t. Each cell x is connected to the *n* neighboring cells $x+y_1$, $x+y_2$, ..., $x+y_n$. One of the neighbors of x is x itself and therefore we assume that $y_1=0$.

• The neighborhood state function h^t : G à Sn is defined by $h^t (x) = (s^t(x), s^t(x + y_2), ..., s^t(x + y_n))$.

• The neighborhood state of a cell *x* at time *t* is related to the cellular state of that cell at time *t+1* by $f(h^t(x)) = s^{t+1}(x)$.

• A configuration C_t : Gà S is a function that associates a state with each cell of the grid. The effect of the transition function f is to change the configuration Ct into the new configuration C_{t+1} according to Ct+1 (x) = f ({C_t (i) | iÎ N(x)}).

Thus, cellular automata are dynamical systems in which space and time are discrete, where local interaction rules to global dynamic behavior in time.

Cellular automata models

Basic cellular automata models have actors fixed in particular locations, one actor per cell. These models can be extended in a number of useful ways. An extension, which is valuable for models that involve movement, is to allow the actors to move over the grid. This means that we now have to distinguish the actors from the cells in which they happen to be placed, and we also have to consider whether or not more than one actor can occupy a cell at any particular moment. A second extension allows actors to be influenced by more than their immediate neighbors; state changes in such models might depend on the aggregate effect of the states of all other actors in the model, or some proportion of them.

For instance, cellular automata models for road traffic have received a great deal of interest during the ninetieths. A road traffic cellular automata model seemed suitable to an urban environment. Based on the Nagel-Schreckenberg model the dynamics of cellular automata models are investigated. This is done in order to model a variety of effects known in real traffic scenarios. An example may be the so-called 'velocity dependent rules' - models, where the focus is on the occurrence of metastable states or the synchronized traffic (Barlovic *et al.*, 1998). This simulation model can be used for large-scale networks and because of the speed capability of the model even for traffic assignment and traffic forecast purposes (Esser and Schreckenberg, 1997).

Cellular automata works for traffic flow as follows. The road is divided into cells, each 7.5 meters long. Every cell is either vacant or occupied by a vehicle with a discrete velocity v that takes values from 0 to a maximum velocity v-max. The gap is the number of empty cells between two consecutive vehicles.

Fig. 2. Cellular automata model of traffic flow

To simulate the transportation system of a large region dynamically, three things have to known and modeled: who wants to go where at what departure time (destination choice), which route to the destination is selected (route choice), and finally how the locomotion along this route is performed (travelling).

We think, that the principles of this approach are applicable as well to the modeling and simulation of user behavior in buildings and public spaces, although the specific mechanisms need to be changed. For example, the behavior in buildings such as enclosed malls and in public spaces could be evaluated or simulated to better assess whether a design meets its goals in terms of comprehensibility, and navigation.

Agent characteristics

The term agent came to be widely discussed within the Distributed Artificial Intelligence (DAI) field. A central issue of DAI is how to allow autonomous agents to model each other to reason about the activities of other agents. The research effort focuses on answering the question of the suitability of an agent based approach to design, starting from a domain dependant description of tasks, development of agents for different functions, finding a communication protocol or common language and applying the developed environment on specific domain problems. The dynamic characteristics of agent systems present the opportunity to create new types of applications that can integrate several approaches in application development.

What exactly is an agent? In agent research there are a variety of definitions, almost as many opinions on this as there are agents themselves. There is no real consensus on what an agent is. In the opinion of Russel and Norvig (1995), an agent is just something that perceives and acts. Dependent of their roles, skills and environment, an agent has his own capacity. Here is one of the definitions:

Agents are computational systems that inhabit some complex dynamic environment, sense and act autonomously in this environment, and by doing so realize a set of goals or tasks for which they are designed (Maes, 1994).

Wooldridge and Jennings (1995) establish that, if many people are successfully developing interesting and useful applications, then it hardly matters that they do not agree on potentially trivial terminological details. They distinguish two general usage's of the term agent: the first is weak and relatively uncontentious; the second is stronger, and potentially more contentious. The weak notion of agent is often used as a reference.

Wooldridge and Jennings (1995): an agent is a hardware or (more usually) software-based computer system that enjoys the following properties:

Autonomy: agents operate without the direct intervention of humans or others, and having direct control over their actions and internal state;

Social ability: agents interact with other agents (and possibly humans) via some kind of agent-communication language;

Reactivity: agents perceive their environment, (which may be the physical world, a user via a graphical user interface, a collection of other agents, the Internet, or a simulated world with other agents), and respond in a timely fashion to changes that occur in it;

Pro-activeness: as well as reacting to their environment, agents are also able to exhibit goal-directed behavior by taking the initiative.

Wooldridge and Jennings (1995) point out that for some researchers the term agent has a stronger and more specific meaning. These researchers mean an agent to be a computer system that, in addition to having the properties identified above is either conceptualized or implemented using concepts that are more usually applied to humans. For example, you can have in mind an agent using mentalistic notions, such as knowledge, belief, intention, obligation and even emotion.

Multi-agent systems are designed as a collection of interacting autonomous agents, each having their own capacities and goals that are situated to a common environment. This interaction might involve communication, i.e. the passing of information, from one agent to another and their environment. Research here is concerned with coordinating intelligent behaviors among a collection of autonomous agents; how these agents coordinate their knowledge, goals, skills, and plans to take action and to solve problems. All agents' actions are derived from rules embodied into the agent, which depend on local information accessible to the agent. An agent possesses some sensors to perceive the environment within it moves, and some effectors to act in this environment. In the given architecture of an agent (Figure 3.), the Production System and the intrinsic State determine its behavior.

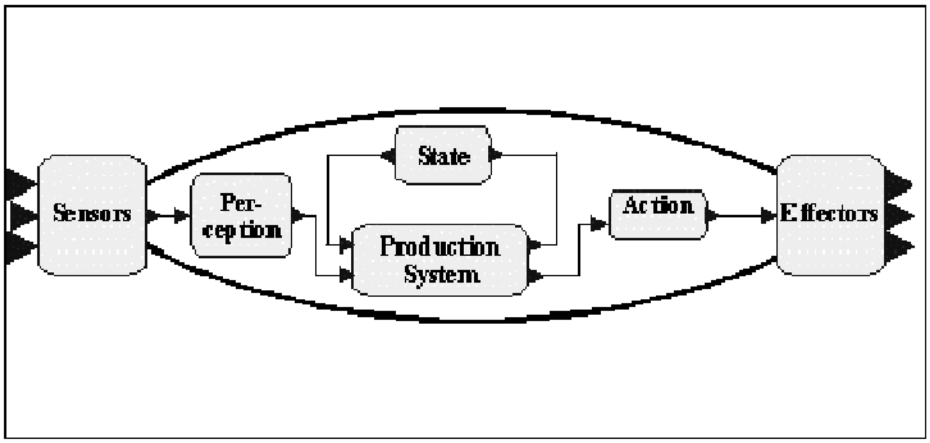


Figure 3. Architecture of an agent (adapted from Chantemargue et al, 1996)

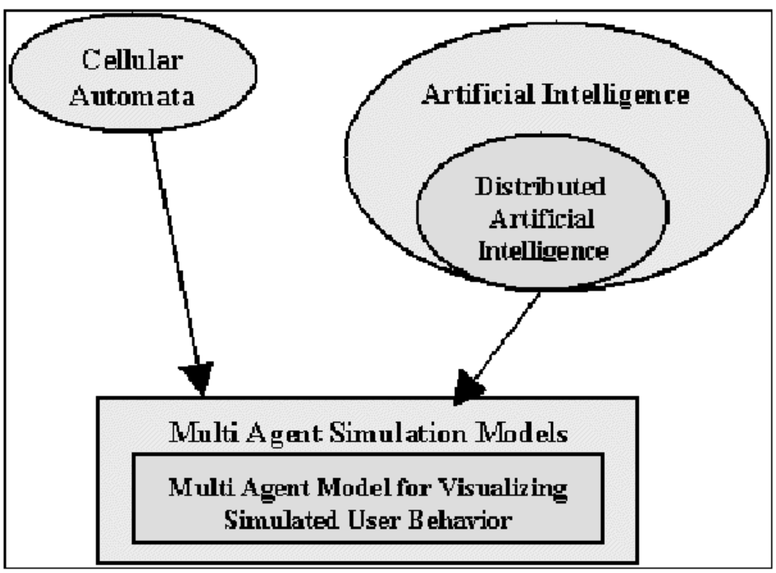


Figure 4. Deduction of multi agent simulation models from the primary research fields

Multi agent simulation models

The development of multi-agent systems offers the promise of simulating autonomous agents and the interaction between them. Simulations with complex behavior can be built using the ideas of cellular automata, and such simulations can model social dynamics where the focus is on the emergence of properties of local interactions. Therefore, in our opinion, cellular automata form a useful framework for a multi-agent simulation model that can be used for network decision analysis.

We will use simulation as a particular type of modeling; building a model is a well-recognized way of understanding the world. The uses of simulation are (i) to obtain a better understanding of some features of the world, and (ii) we can develop a model that truly reproduces the dynamics of some behavior. With the development of a multi agent model is it possible to simulate autonomous individuals and the interaction between them. For example, to simulate people with different perspectives on their world.

One of the characteristics of the (complex) system is that behaviors evolve dynamically during the simulation. Evolution capabilities should then be given to behavior-agents when designing the system, such as:

• *evolution of the agent's environment (neighborhood)*; reflects the emergence of structures (also called self-organization)

• *evolution of the agent's behavior during the simulation,* decomposed in:

• Adaptation of the behavior according to knowledge and environment evolution, i.e. improvement and adjustment to the environment (self-adaptation or anticipated behavior)

• Description of non-predictable behaviors (unplanned behavior). Sometimes, from the analysis of the best actions of the system, some rules can be generalized that lead to prediction of behavior.

Towards a multi agent model for visulizing simulated user behavior

Motivation

In this section, we describe how cellar automata and multi-agent technology can be combined to develop a model of how people move in a particular 3D (or 2D) environment. People are represented by agents, and the cellular automata model is used to simulate their behavior across the network. In this environment, agents can have particular targets such as a starting point and destination point, or a series of stops, but also the route of shortest duration or the most attractive route. Interaction between agents is also an issue: for example, more agents will decrease the speed of movement. There are also opportunities to stop for window-shopping and/or to start a conversation. Thus, the application of cellular automata implies the possibility to simulate how an 'agent'-user moves in a given environment, dependent of the behavior of other agents in the system.

An example of an application is the design of a shopping center. Critical performance indicators related to user behavior include the distribution of visitors across the center, easy of navigation, pedestrian expenditures as a function of layout, and functional characteristics of the center and its shops, etc. A simulation model would allow the designer to assess how its design decisions influence pedestrian movement, and hence these performance indicators. To conceptualize this problem, on might assume that pedestrians have a list of activities they want to do while visiting the shopping center. They will try to realize these goals by navigating through the center. In terms of a cellular automata model, this means that they will move one or more cells forward in the network (grid of cells), dependent of the speed of the pedestrian flow. Their behavior can also be affected by avoiding activity or by unplanned circumstances such as signage and window-shopping.

In developing this system, it is useful to differentiate between the cellular automata model and the distributed artificial intelligence-agents model. The agents model part involves the different agents with their respective roles.

The cellular automata model part

The network is the three-dimensional cellular automata model represented by the graphical representation of a state at a certain time. A closed box represents the occupation of a cell. The refinement of the network will be expressed by the format of the network, for example a cube of size one-meter. If a user-agent moves over the network, the left behind occupied cell changes into an empty cell and another cell will be occupied.

A user-agent can occupy a number of cells. The navigation speed v is the number of cells that are crossed during an update time-step Dt. The speed can be influenced by the occupation of other cells in the network. The population of crowded cells could result in emergence behavior of the crowded neighborhood.

We define a cell *x* to be on *(s(x)=1)* if it is occupied, otherwise it is *off(s(x)=0)*. Also we define a density size dr(x) which shows the activity around cell x; it shows the number of neighbors in an on state in relation to the total number of neighbors in the *Moore* neighborhood of cell x with radius r. In a d-dimensional grid with a

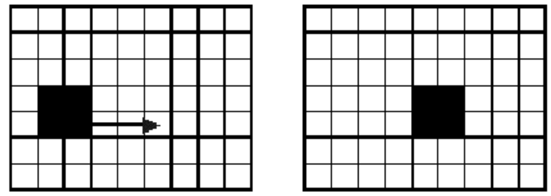


Figure 5. Navigation speed v = 2 cells/?t in a 2D representation

Moore radius r, the number of cells n in the neighborhood of cell *x*(*x included*) = *(2r+1)*^{d}. The updated cell x depends on the on states of all cells in the neighborhood *N* of *x(N(x))*. To summarize the transition of a state of a cell,

$$s^t(x) = 0 \rightarrow s^{t+1}(x) = 1 \text{ if hit by an object or an user-agent;}$$

$$s^t(x) = 1 \rightarrow s^{t+1}(x) = \begin{cases} 1 & \text{if cell activity remains} \\ 0 & \text{if an object or a user-agent left the cell behind} \end{cases}$$

$$\delta_r\,(s^{t+1}(x)) = \left(\sum_{i=0}^{n} (s^{t+1}(x+y_i)) \;/\; n\right); \quad y_i \in N(x),\ y_0=0,\ n=(2r+1)^d$$

The Agent Model Part

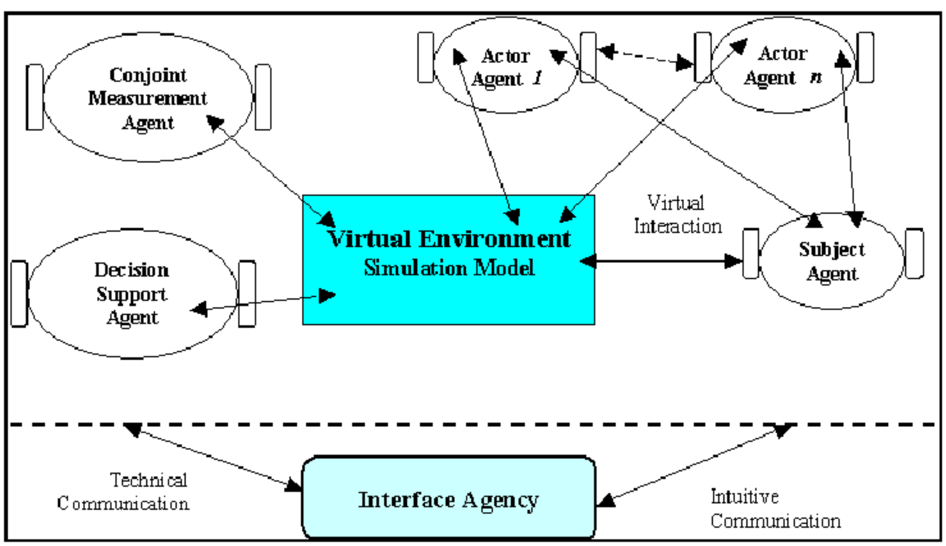


Figure 6. Framework of the agent model

We will distinguish various agent types in the model. There are user-agents that represent people in the simulation. The one, who is part of the simulation, is called the subject-agent. Actor-agents can simulate humans. Thus, subject-agent and actor-agents are user-agents that navigate in the virtual environment network, each with their own behavior, beliefs and intentions. A belief is the internal, imperfect representation of the virtual environment including the state of other user-agents, on which their decisions are based. We must view behavior as the interaction between the user-agent and the environment. For the subject-agent, this behavior is not an attribute of the agent, but rather lies in the mind of the subject alone. The researcher will determine an actor-agent's behavior, which is draw up by a behavior-agent. We could consider styles of behavior like anticipated behavior and unplanned behavior. Besides a behavior-agent, we also distinguish an intra-task-agent. An intra-task-agent fulfills the intentions of a user-agent to reach a destination (goal) and/or to carry out a list of activities (plan). Concerning inter-task-agents, we distinguish among others an interface-agent for assisting the subject-agent in the virtual environment, a conjoint-measurement-agent for subject's preference measurement and a decision-support-agent to assist the researcher or designer in a decision process.

A framework for the agent model is given in Figure 6, which focuses on the interaction with a virtual environment. There is an intuitive communication between the subject-agent and the interface-agent. The interaction between actor-agents and inter-agents with the interface-agency concerns technical communication.

The integration of cellular automata and multi-agent technology

In 'modeling and simulation of pedestrian traffic flow' (Løvås, 1994) a simulation tool is presented to estimate the relevant performance measures of the pedestrian traffic system. Also, a stochastic model is presented based on the assumptions that (i) any pedestrian facility can be modeled as a network of walkway sections, and (ii) pedestrian flow in this network can be modeled as a queuing network process, where each pedestrian is treated as a separate flow object, interacting with other objects. An examination of the literature studies in relation to pedestrian traffic flow indicates the greater part of studies pay attention on car-users and user of transport systems. In some studies various temporal and spatial choice heuristics that pedestrian may apply, are examined just like space syntax models.

In our proposed model, we incorporate features like the dynamic aspects of pedestrian choice behavior, and the relationship between individual choice process and emergent aggregate patterns. We think that our proposed model is of importance for many different design and decision problems. Particularly, the prediction of pedestrian behavior in buildings such as enclosed malls and in pubic spaces reflects the importance of this approach. Architects, and also urban planners need to predict or analyze pedestrian movement to better assess whether their design meet their goals in terms of comprehensibility, and obviously navigation.

A cellular automata model is used to simulate pedestrian movement along the network of the system. Cellular automata present the possibility of using individual behavioral rules to recreate the behavior of pedestrians. Actor agents represent pedestrians with individually assigned characteristics; a subject agent is a particular actor agent which represent the user / subject in question that will be part of the simulation. The pedestrian walkway is modeled as a regular grid of some width and length, and density that represents the mesh of the network. At the start of the simulation, actor agents are created and assigned randomly to the network. The multi-agent technology is used to develop individual actor behaviors and their activity agenda. This technology is also used to develop aggregate patterns from individual behavior and to simulate the feedback from the status of the system. Otherwise, agents are used to retrieve information about the system that is relevant for assessing design parameters in supporting design performance.

In the research progress, we will successively visualize the simulation in a 2D environment and by a graphic means of presentation to get a better understanding of our proposed model. Next, we will take this one step further by using virtual reality techniques in the VR-DIS (Virtual Reality - Design Information System) context (Achten *et al*, 1998). This should allow subjects to experience building designs to bring them in a state of mind that better resembles their actual decision-making in the real world.

Point of departure is a shopping mall where pedestrians are walking in. In general, pedestrian behavior in a shopping mall depends on their knowledge about shops, establishments, the walkway network, the distribution of shops, and the choice mechanisms that are involved where to stop, in what order, and which route to take. In previous studies gravity models have typically been used to predict pedestrian movement. Researchers have assumed that pedestrian destination and route choice can be viewed as the result of utility-maximizing behavior, in which pedestrians trade-off the attractiveness of stores or shopping walkways and the distance or time it takes to visit that store. Suppose that a pedestrian visits this mall. We assume this visit is motivated by the desire to realize particular goals by conducting particular activities. This set of activities or activity agenda represents the activities that a pedestrian plans to conduct during the visit; a priority hierarchy may be part of the activity agenda. We assume that the activity agenda is time-dependant to allow changes in the agenda during the visit at the shopping mall. Given the activity agenda, the pedestrian is faced with the multi-faced problem of deciding where to conduct the activities, in what sequence, and which route to take.

In our simulation model, we will get insight in this pedestrian behavior in shopping malls, not yet existing. This will be of great importance in the assessment of design performance. Not only in the realization of new building designs but also in the revitalization of existing buildings. In the basic design cycle defined as a sequence of stages that describe the various phases of design (Roozenburg and Eekels, 1996), our simulation model is very useful in the simulation of

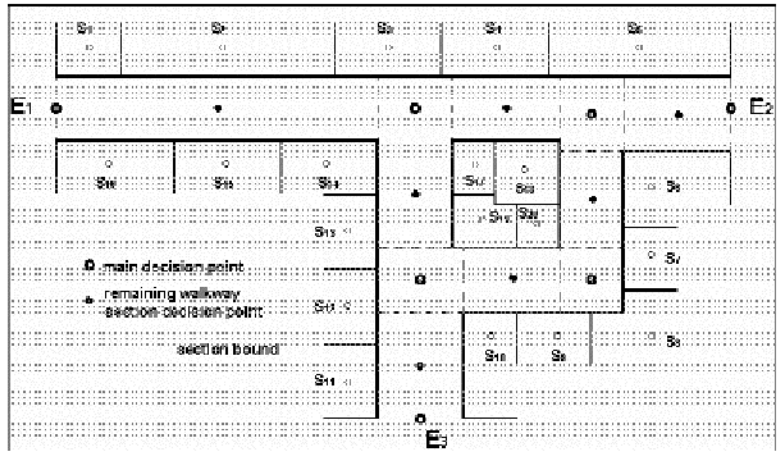


Figure 7. Network grid and decision points

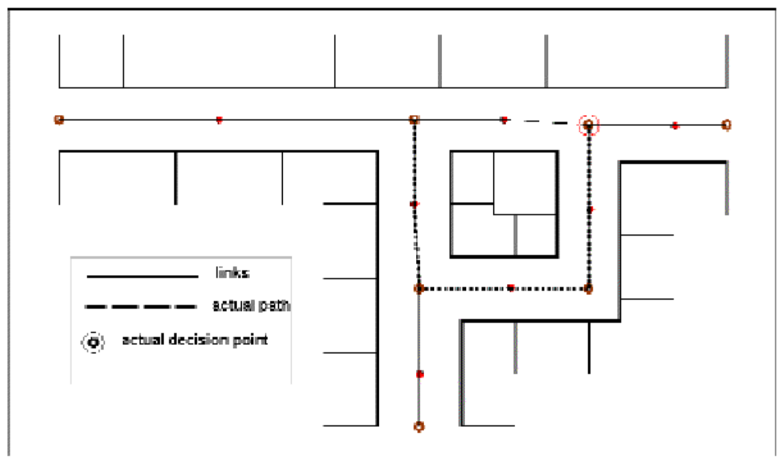
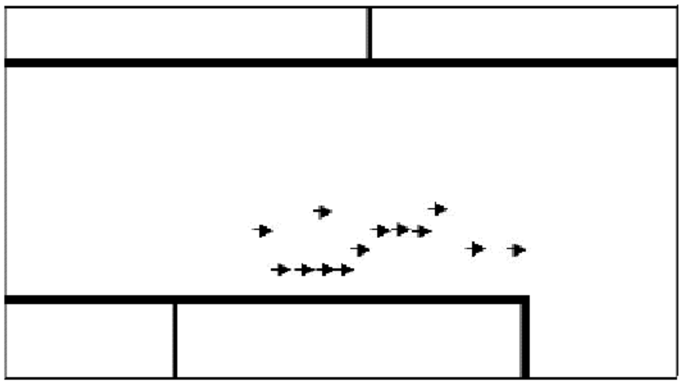


Figure 8. A main node-based view to represent the main decision points

preliminary designs to see what its performance will be. As an evaluation, the simulation outcome can be compared with the design criteria. A choice can be made which alternative of a preliminary design is satisfactory. This decision results in an approved design.

Initially, we will realize different graphic representations of our simulation: (i) an actor-based view to represent the pedestrians in the simulation, (ii) a network-based view to represent the density size of occupied cells in the network,



Fiure. 9. An example of an actor-based view

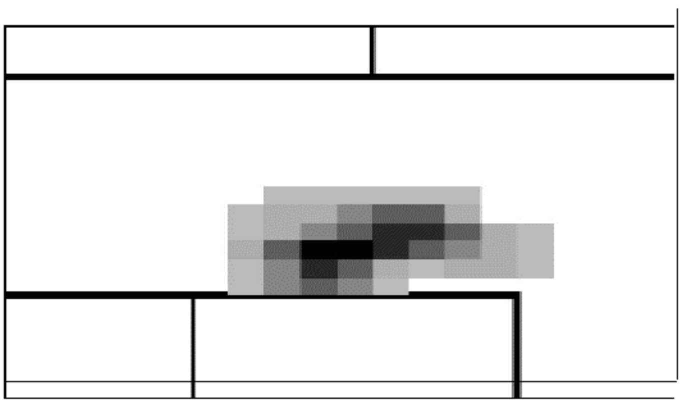


Figure 10. An example of a network-based view to represent the density size.

and (iii) a main node-based view to represent the main decision points in the network and the decision points which are arrived.

To simplify these representations, we introduce the following definitions (partially adapted from Løvås, 1994): the pedestrian environment is called building. A section of the building is called a room. The rooms {R} are divided in four subsets: stores or establishments {S}, entries or departures {E} that are rooms outside the building, walkway intersections or bends {W} and remaining walkway sections {O}. There is one decision point in each room; if the room is large, it may be modeled as several sub-rooms. A decision point is called a node in the network; the main nodes; the main decision points are situated in {E} and {W}. A line between two decision points represents a link between these points; i.e a walkway between these points. Each walkway is dived in two parts; one part belongs to each of the two remaining rooms. For example the walkway between rooms i and j has the length $d(i,j) = d_i(j) + d_j(i)$. Figure 7 and 8 shows an example of a part of a mall and figures 9 and 10 some (zoomed in) views.

Discussion

In this paper, we have argued that complex behavior can be simulated by using the concept of cellular automata in the context of multi-agent technology. The development of multi-agent models offers the promise of simulating autonomous individuals and the interaction between them. In the present paper, we have discussed the concept of a multi-agent model for visualizing simulated user behavior to support the assignment of design performance based on this notion. We think that the proposed concept potentially has a lot to offer in architecture and urban planning when visual and active environments may impact user behavior and decision-making processes.

The ultimate test of the relevancy of such a system depends on empirical evaluation. Initially, we plan to build a simple model with a limited number of user-agents with restricted behavior and learn from using this system to simulate user behavior. Based on the experiences with such a system, we then plan to develop, test and apply a full-blown system. We hope to report on such developments in the near future.

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