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Pedestrian Logistics Simulation – Crowd Management in Stadiums

Simulation von Fußgängerströmen – Lenkung der Menschenmassen in Stadien

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Abstract: The interest in simulation in the field of pedestrian logistics is growing. Simulation models can show results about quality and safety of the facility, by evaluating normal operation and performing evacuation scenario's. Simulation of pedestrian flows on a mesoscopic level is very suitable for evaluating large-scale infrastructures with many simultaneously moving pedestrians. In the case of the Philips soccer stadium the benefit of using simulation for crowd management has proved its value.

1 Introduction

Since the nineties of the last century there has been a fast growing interest in understanding and modelling pedestrian behaviour. In all kinds of environments the importance of analyzing and quantifying pedestrian flows is acknowledged. These range from urban design in public areas to effective product placement in a store to evacuation dynamics. Major reasons for this increased attention is that the quality of pedestrian flow and particularly the safety in pedestrian environments are more important than ever before.

Especially during emergency situations crowd management is an important aspect. Public facilities are getting bigger and bigger and still pedestrians have to be routed and evacuated through the building in a fast and efficient manner. Classical, qualitative manners of flow analysis are no longer sufficient. Therefore, simulation models are used to optimize proposed infrastructural designs and to test and improve the crowd management inside an existing or planned infrastructure.

Different approaches have been developed to model and simulate this pedestrian behaviour. In chapter 2 some general insight is created in the different models and approaches of pedestrian dynamics. In this article one of these approaches is discussed in detail, as it is the basis for the development of the stadium simulation model. Chapter 3 describes how this behaviour is captured in the pedestrian simulation tool. Using this simulation tool the Philips soccer stadium in Eindhoven, the Netherlands, is modelled to analyze the pedestrian dynamics inside and outside this stadium. This case study is presented in chapter 4. Finally, in chapter 5 conclusions and recommendations for further research are summarized.

2 Pedestrian modelling and approaches

The research of pedestrian behaviour is mainly based on observations and empirical studies. The focus in this research lies on observing human behaviour and capturing pedestrian movements. In this way existing theories are extended and new theories are developed. The basic properties of pedestrian movements and its research are:

- Speed (m/s)
- Density (person/m^2)
- Flow rate (persons/s)
- Throughput time (s)
- Inter-arrival time (s)

Figure 1: *Crowded train station*

In order to be able to model pedestrian movements the most important challenge is to capture the human behaviour, as result of the encountered circumstances. The most characteristic aspects of behaviour in pedestrian movements seem to be (HELBING et al. 2001):

- People select the quickest route to their destination and dislike taking alternative (slower) routes even if congestion arises on the initial route
- Each pedestrian has its own desired walking speed. This speed is dependent on both individual properties (e.g. age, gender, physical state, purpose of travel) as environmental properties (e.g. crowdedness, time, temperature)
- Pedestrians keep a certain distance to other pedestrians, walls and other obstacles. Dependant on the crowdedness in the area this distance between the pedestrian will differ.

These aspects are important to include in simulation models of pedestrian environments and can be found in almost every simulation tool used for research about pedestrian flows.

Approaches to model pedestrian dynamics can be classified into three main levels (TAUBÖCK 2005):

- **Microscopic level:** In the microscopic approach, each pedestrian is represented individually. The individual entities have a unique behaviour. Also the mutual behaviour of pedestrians, like collision avoidance, is taken into account. The microscopic models can be described in two main approaches, either continuous (e.g. social force, HELBING et al. 1995) or discrete (e.g. cellular automata, BLUE et al. 2001).
- **Macroscopic level:** This approach describes the flow of pedestrians as a fluid through space. The main subject of this approach lies with the behaviour of the combined pedestrians in a group. The corresponding mathematical models are partial differential sometimes similar to fluid equations (e.g. BAUER et al. 2007)
- **Mesoscopic level:** In a mesoscopic approach the individuality of each particle is maintained. During each time step, particles are aggregated to field quantities such as density, the velocities are computed from these densities, and then each individual particle is moved according to these macroscopic velocities (TAUBOCK et al. 2005).

3 Simulation

The simulation application that forms the basis for this study uses a mesoscopic approach and is developed with the discrete event simulation software Enterprise Dynamics. The basic concept of the application is the controlled movement of individual entities (pedestrians) between locations over a node network.

The position of the nodes in this network is determined by the infrastructure (e.g. train station, airport, and stadium) that is analyzed. In this infrastructure all relevant areas with their corresponding sizes are created by the user. Dependant to the infrastructure, the areas are connected by placing nodes in the area and connect them to each other. These nodes can represent either network intersections, passages or links to processes (see figure 2). Stairs and escalators are special types of nodes with adjusted speeds and capacities.

The application's purpose is to analyse the "performance" of a functional infrastructure, for example a train station, airport, exhibition hall or stadium. Based on the purpose and destination of the pedestrian it will have (multiple) sequential destinations inside the infrastructure. A traveller will for example go to a ticket machine first and then to the train platform. Based on the defined destination sequence of the pedestrian it will follow the shortest and or fastest route to fulfil its purpose within the infrastructure. At every node in the network (graph) the pedestrian passes, the next node in the route is determined by the Dijkstra Algorithm (DIJKSTRA 1959). This algorithm calculates the shortest routes over nodes in a graph network.

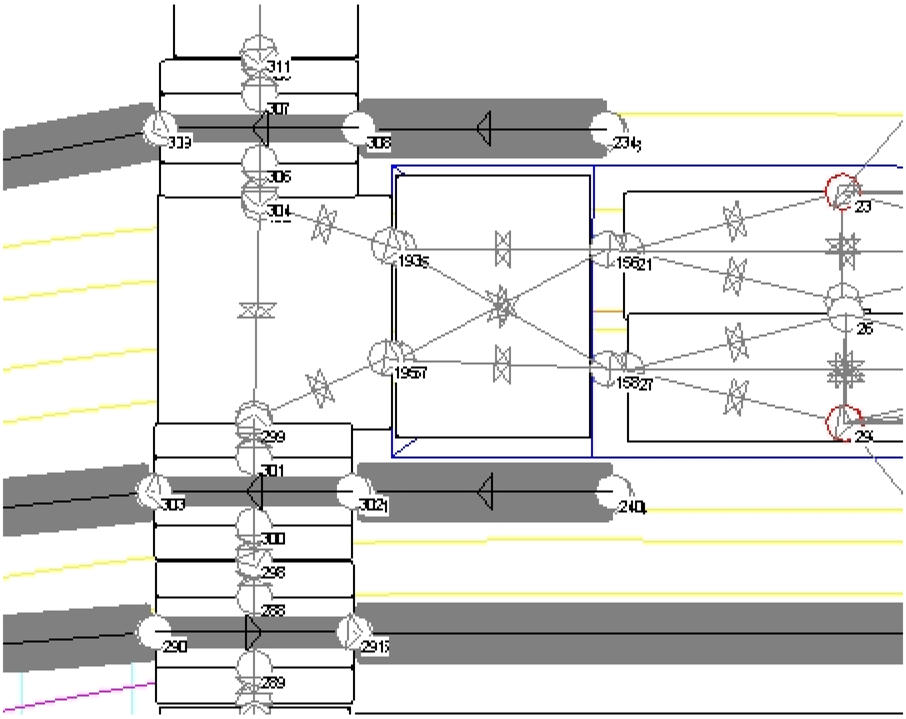

Figure 2: *Areas and node network*

Dependant to the properties (e.g. age, purpose, gender) of the pedestrian, it will have a desired walking speed. Based on the density in the area and the desired walking speed the pedestrian will have a certain walking speed, while travelling from one node to the next. Each time the pedestrian enters a node its walking speed is adapted according to the density of the area the pedestrian is in.

The degree of increase or decrease of the travel speed is a result of the speed-density relation, researched by FRUIN (1971). In figure 3 a graph is presented that shows the relation between desired walking speed and density.

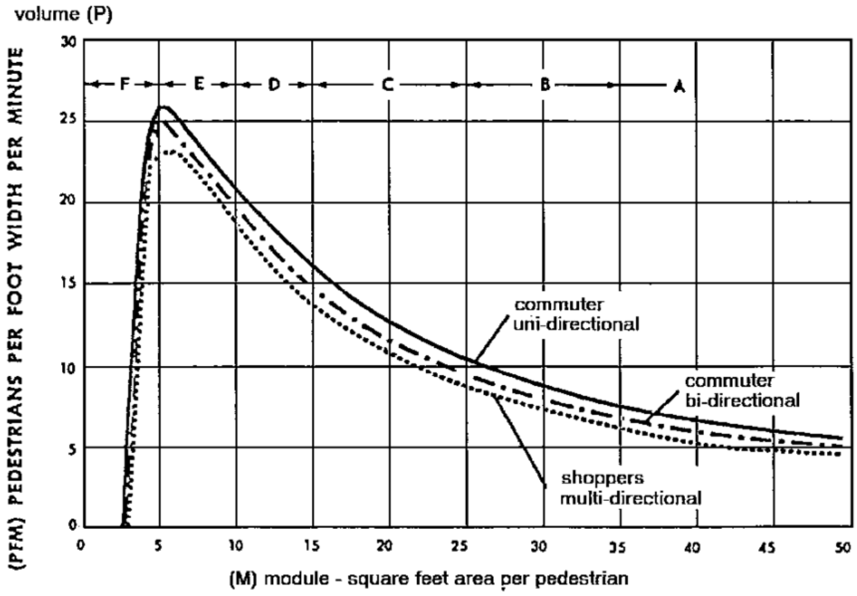

Figure 3: *Speed vs. Density*

Apart from the network and the walking behaviour also functional processes (e.g. ticket sales desks, ID check gates, shops) are taken into account. These processes are modelled as "servers" with corresponding properties (e.g. capacities, cycle times). As a result of the finite capacity, the cycle times and the distributed inter-arrival time of the pedestrians, queuing and congestion can arise.

Event-based simulation tools are very suitable for the mesoscopic simulation approach. Every time a pedestrian enters a process or node, an event is created for determining the current state (e.g. density) of the area. Based on this state, the pedestrian will act in accordance with certain pre-defined behaviour. This behaviour is extracted from microscopic research of pedestrian flows. For this study the discrete event simulation software Enterprise Dynamics has been applied.

Microscopic models often use forms of continues simulation. In these simulations the surrounding of a pedestrian (also called agent in this manner) is monitored continuously and the behaviour of the pedestrian is adapted instantly. Microscopic research is often used to validate a model that represents the exact behaviour of pedestrians in small areas. Due to the continuous monitoring of all the pedestrians in the model the required computer processor capacity of these models is very high.

Therefore large-scale microscopic simulation models are rare. Since the discussed mesoscopic simulation application is very well capable of dealing with large numbers of pedestrians and large scale routing networks, it is very suitable for modelling large infrastructures such as train stations, airports and soccer stadiums. Several simulation models have already reached a simultaneous content of over 70,000 pedestrians.

In the next chapter a practical application of the large scale pedestrian simulation tool is discussed.

4 Stadium Case study

The case study concerns the pedestrian dynamics in and around the Philips soccer stadium, home of the soccer team PSV Eindhoven in the Netherlands.

The goal of the stadium case was to develop a customized simulation model of this soccer stadium with over 35,000 seats. With this model, the security managers, who are responsible for safety and visitor protocols, must be able to perform:

- Analysis of pedestrian crowd flows, both inside and outside the stadium,
- Analysis on changing infrastructure and protocols,
- Development and analysis of evacuation scenarios, and
- Capacity planning of processes and personnel.

The security managers are the end-users of the application and must be able to modify settings and perform their analysis autonomous. Therefore the constraints for the application and its model were not just functionality, but also ease of use and adjustability.

Important performance indicators in this application are the densities in the different areas of the stadium and the waiting times at the different processes (e.g. entrance gates, ticket sales etc.) before, during and after a match and off course the evacuation time of the visitors.

Figure 4: *Philips Stadium, Eindhoven*

The main aspects that influence this performance in the stadium are:

- the lay-out of the stadium and its surroundings,
- the arrival intensities of the visitors,
- visitor properties,
- the entrance & exit gate distribution, and
- the use of processes (facilities).

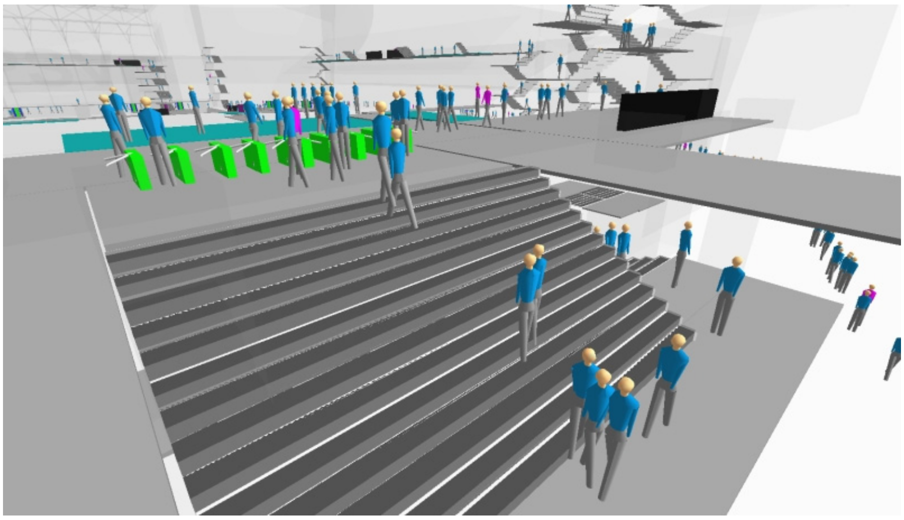

Figure 5: *3D Visualization simulation model*

The model is constructed exactly on scale by using a CAD drawing of the infrastructure with all relevant floors taken into account and is visualized in both 2D as 3D. The model structure is created by defining all relevant walking areas and intersections (nodes). Within this node network links to processes are indicate, so that the pedestrians can go to the several (sub)destinations. In figure 5 a 3D screenshot of a stadium staircase area is presented.

4.1 Functionality

The following functionality was implemented in the routing management of the pedestrians both to simulate a truthful model and to allow the security team to evaluate alternative scenario's.

- **Arrival:** Visitors enter according to a Poisson distribution defined per time interval. In this way the effect of changing the intensity per time window before the game can be analyzed.
- **Entrance allocation:** Due to the internal infrastructure of the stadium on a general level the stadium is divided into four main sections (North, South, East, and West). In these sections several entrances (with turnstiles) and tribune areas are located. In the application the user is able to allocate turnstile entrances based on the tribune of destination and in that way to select an optimal allocation strategy for assigning pedestrians to one or more entrances.
- **Facility usage:** Based on user settings each pedestrian is assigned a random combination of facility properties. Examples are visiting a bar before the game or visiting the toilet during the break. Owing to these properties and the game status (before the match, during break or at the end) pedestrians walk to the local sub destination which represents the facility. After the process time and potentially a waiting time, the pedestrian can walk to a next process and finally

to its end destination, the tribune seat (during start-up and break) or the exit (at game end). By changing these facility usage properties the model user is able to analyze the effects of changing facility behaviour of the pedestrian on stadium performance.

- **Evacuation:** At any moment during the simulation run the user is able to start up an evacuation. At that point each visitor will receive an end destination node which is the closest available (emergency) exit. Also the desired walking speed of the pedestrian will be adapted according to a pre-defined distribution of emergency walking speeds. In order to evaluate a wide range of emergency situations, the user is able to close different sections or exits during an evacuation (e.g. to simulate a fire) and thus analyze the effect of this situation on the infrastructure usage and the selected protocols.

4.2 Performance

To analyze the "performance" – the quality and safety - of the selected crowd management decisions, several performance indicators are monitored within the simulation. In this case the most important indicators are area densities, travel times (including evacuation times) and waiting times.

- **Densities:** The density is stated as the m^2 per person. This density shows the level of comfort in this area. Based on the "level of service" concept (FRUIN 1971) six levels of comfort are stated in the output. This density is monitored per defined area per time interval. In this way the user is able to discover bottlenecks and their duration in the proposed pedestrian flow.

- **Travel and evacuation times:** The travel times between origin and final destination is monitored. This is especially important for the evacuation scenario. Since there are governmental guidelines for the maximum time needed to travel to a safe area, the user is able to test the available or proposed evacuation and emergency protocols. In figure 6 an example of the evacuation time distribution of a certain tribune is shown.

- **Waiting times:** The waiting times are monitored at both the entrance gates as the several facilities in the stadium in order to determine the "service" level of these processes. Results are presented in histogram classes for comparison with standards as dictated by the authorities.

This business case discusses the development of an application that is used by external users for operational analysis. They make crowd management decisions based on the results of experiments as expressed in these performance indicators.

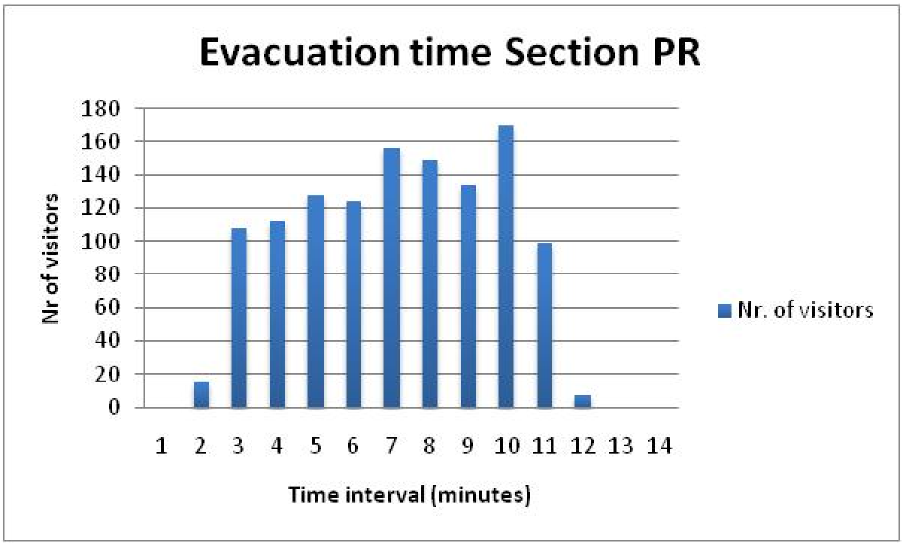

Figure 6. *Output Example; Section evacuation duration*

5 Final remarks

The benefit of simulation for the analysis of pedestrian flow was evident in this project. The user was able to perform scenarios which were never evaluated before, simply because it was practically to complex to attempt these scenarios in reality.

In general, it can be stated that due to the physical scale of the infrastructures in combination with the complexity and (financial) consequences of testing in reality, the developed simulation tool is very suitable to deal with these logistical pedestrian questions. The security managers of the Philips stadium use the model on operational basis to test and evaluate scenario's.

In relation to the majority of other simulators the main difference is that a mesoscopic approach is used instead of a macroscopic or microscopic approach. The application using this approach enables large scale pedestrian systems with huge numbers of moving entities (e.g. 70.000 visitors), while treating them as individuals with personal characteristics.

Regarding the mesoscopic approach some recommendations for further development and extensions of the model are stated.

- **Route selection:** In the current selection algorithm the shortest route is selected, disregarding the crowdedness on this route. In the current application the Dijkstra Algorithm is used to calculate the minimum distances between al network nodes. The cost of a route in this manner is only dependant on the distance. Suggested is to develop for example a dynamic Dijkstra algorithm that can be executed during a simulation run. Using this dynamic algorithm a pedestrian can select the optimal route to his destination based on a cost function. This cost calculation is then a function of variables such as distance, pedestrian preferences and crowdedness on the route.

- **Evacuation:** Although the application allows several variants, in the current evacuation scenario the pedestrians in the model will select the shortest emergency exit as destination. In reality this selection of an exit is very complex. From research (SOOMEREN 2007) it is concluded that the selection of an emergency exit is dependent on many factors such as pedestrian properties, crowdedness, signing, familiarity with the building and the used entrance. It is proposed to develop a more complex selection algorithm that can take all these factors into account.

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