Modeling and Simulation of Pedestrian Behaviour
As Planning Support for Building Design

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Abstract: Major challenges in the simulation of pedestrians are the realistic behaviour of agents, realistic appearance and variety, and how to conveniently define larger crowds of pedestrians. In this paper, pedestrian behaviour in buildings is analysed and structured in order to develop a behavioural model for buildings with high pedestrian flows. Observing pedestrians at a larger train station is used as a basis for the creation of a three-level behavioural model. The model follows a multi-agent-based approach and consists of a strategic, tactical, and operational level. A strategy indicates why a person visits a building and is broken down into activities on the tactical level. In this model, the strategy remains constant for an agent during its lifetime, while activities and associated areas are chosen and prioritized dynamically. This results in a coarse route through the facility. The operational level consists of path planning and obstacle avoidance. The suggested behavioural model has been implemented with the Unity framework and was tested using a 3D model of an existing train station. The purpose of the simulation is to provide building planners with feedback about space utilisation by its users.

1 INTRODUCTION

Simulation of pedestrian behaviour is used in urbanism (traffic planning) and architecture, film and computer game production, as well as safety science. Depending on the application area, major challenges occur: realistic behaviour of agents, realistic appearance and variety, and how to conveniently define larger crowds of pedestrians. Application areas of pedestrian simulation include evacuation dynamics, efficiency evaluation of planned layouts, and validation of dimensions.

The planning of complex buildings is a multi-criteria optimization process which is done in stages, ranging from sketching design concepts over 3D modelling to a detailed building information model (BIM). The design process typically includes the simulation of several aspects at different levels. Traditional simulation methods include the simulation of the load-bearing structure, the energy consumption of a building, as well as light simulation. A still under-represented aspect of simulation in building planning is concerned with the space utilisation and especially the dynamic behaviour of people inside the building.

Taking a major train station as an example, it has to handle over a thousand passengers within a few minutes, which constitutes a substantial pedestrian flow. In addition to being infrastructure for transport, it provides functions for the city by being a hub for other means of transport, and by integrating other types of infrastructure like shops, hotels, or entertainment.

Our focus is on the simulation of pedestrian flow as a visual feedback in the planning phase of buildings as part of a design prototyping system. These types of buildings which are frequented by a large number of people include airports, bus or railway stations, educational institutions, shopping malls, museums, theatres, cinemas, or stadiums.

For the planning phase of such a building, the simulation of pedestrian flow has to provide feedback for layout and dimensions regarding floor space, maximum capacities, unused and congested space, possible high collision areas, and general organisation of space.

In order to simulate the flow of pedestrians in these infrastructure buildings, a purpose-built behavioural model was devised. We address the research question: Which features should a

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behavioural model offer in order to provide feedback in the planning phase for complex buildings with a substantial flow of pedestrians?

To answer this question, a case study was conducted where people inside a major train station were observed. An analysis of the gathered observations led to a behavioural model which was then implemented as a proof-of-concept prototype. The model was devised in a modular form so that it lends itself to easy adaptation and alteration for further use cases. Similarly, the implementation was designed for expansion and reuse. Thus, the employed research methods are: observation at an existing train station, analysis of observed data in order to derive a behavioural model, implementation of a proof-of-concept prototype.

The following section summarizes aspects of crowd simulation that pertain to pedestrian simulation within buildings. Section 3 describes the case study and provides an analysis of the gathered observations. Section 4 presents the devised model and its prototype implementation. Section 5 concludes with a discussion of the results.

2 CROWD SIMULATION

2.1 Overview

In their recent book, (Thalmann and Musse, 2013) provide an extensive overview of crowd simulation methods and techniques. Most behavioural models are based on autonomous agents, or particle systems that define position and velocity for each particle using an equation.

For motion planning, navigation meshes (Cui and Shi, 2012) and the A* algorithm (Hart et al., 1968; Hart et al., 1972) are commonly used techniques. For collision avoidance among moving agents the technique of reciprocal velocity obstacle (Van den Berg et al, 2008) proved useful.

An analysis of real crowd behaviour is provided by (Schadschneider et al., 2009; Narahara, 2007; Still, 2000; Helbing and Mukerji, 2012, Henderson, 1971, Song and Ma, 2016), also in order to understand the reasons for crowd disasters. Empirical values for transportation buildings and pedestrian space utilization can be found in (Neufert, 2005, Illera et al., 2009).

Performance can be enhanced by giving agents a “mental map” of the geometry instead of simulating its perception. For rendering large crowds, impostors and level-of-detail (LOD) techniques increase the performance (Aubel et al., 2000).

2.2 Crowds and Self-organization

According to the principle of least effort, people seem to choose the shortest path to their goal (Still, 2000). Additionally, crowds exhibit certain emergent behaviours (Schadschneider et al., 2009, Narahara, 2007): Lane formation and intersection patterns allow people to move faster; Jamming and clogging appear in bottleneck and counter-flow situations. They can lead to oscillations, i.e. changes in direction of the flow; Density waves can be compared to stop-and-go car traffic and occur at high crowd densities. In some circumstances, these waves can pose a threat to people in the crowd.

2.3 Crowd Model

Modelling the behaviour of a crowd has been done in several ways, e.g. through behavioural models, force-field models, or data-driven models.

In behavioural models, crowds are composed of individual agents whose behaviour with respect to other agents or the environment is controlled by diverse techniques (e.g. rules, reasoning). Actual models vary according to the knowledge about other agents’ motion data. In force-field models, attractive and repulsive forces control the simulation. Those forces are calculated for each cell of the grid that represents the simulation world (e.g. Helbing and Molnar, 1995). In data-driven models, the simulation is controlled by statistical data which was gathered through real-world observations.

While behavioural models allow better individual modelling, force-field models provide easier control of the crowd as a whole. A disadvantage of the force-field approach lies in the possibility of “stalled” motion due to local minima. Data-driven models by design offer a higher realism for specific aspects. A combination of these approaches within a hybrid crowd model (often designed in a hierarchical manner) aims at exploiting the respective advantages of the different approaches at the cost of increased complexity.

Complex behavioural models are not yet feasible for most real-time implementations. For the enhancement of performance, LOD techniques are applied so that the calculation of behaviour is restricted to the most important agents (Thalmann and Musse, 2013).

2.4 Motion Planning

Motion planning is necessary for autonomous movements of agents, with path finding as an essential aspect. For performance reasons, motion planning is calculated on graphs as abstract representations of the simulation world as opposed to geometric models of this very world which are used for rendering.

These graphs can be used as an input to path finding algorithms. In virtual environments the following algorithms are often used: breadth-first search (BFS) and depth-first search (DFS) (Schrijver, 2012), Dijkstra's algorithm (Dijkstra, 1959), and the A* algorithm (Hart et al., 1968; Hart et al., 1972). For the obvious reason of taking advantage of the respective strengths of different algorithms, they are combined into hybrid approaches.

2.5 Collision Avoidance

In motion planning, paths are calculated on walkable areas where dynamic objects (such as the simulated agents) constitute obstacles. For preventing a collision, so-called collision avoidance (CA) methods are used to determine local avoidance strategies without recalculating the entire path.

Figure 2: Observation of pedestrian movements.

A major challenge in CA lies in an agent's lack of access to the velocity vectors of dynamic obstacles at the (future) time of collision. Assuming linear movement for each obstacle to predict its motion and plan collision avoidance accordingly is done by an approach called velocity obstacle. Reciprocal velocity obstacle expects the obstacle to use similar collision avoidance strategies.

3 OBSERVATION

In order to be able to devise a behavioural model for pedestrians, observations have been made at a major train station in Vienna, the Westbahnhof (see Figure 2). It was used to handle commute and long-distance westbound traffic until the end of the year 2015. It is connected to local trains, underground and tram lines, and regional buses. It offers parking for cars and bicycles. It is integrated with a shopping mall, a food court, and connected to hotels and offices. A schematic floor plan is depicted in Figure 1.

3.1 Data Collection

The observation of pedestrians inside the station was done in a non-intrusive way by a person on-site who took notes. It consisted of the following parts:

- Pedestrians were observed in different areas of the station for a short period of time to find a list of activities and parameters.
- Selected pedestrians were followed through the station to find typical trajectories and activity patterns.
- At specific areas in the station pedestrians were

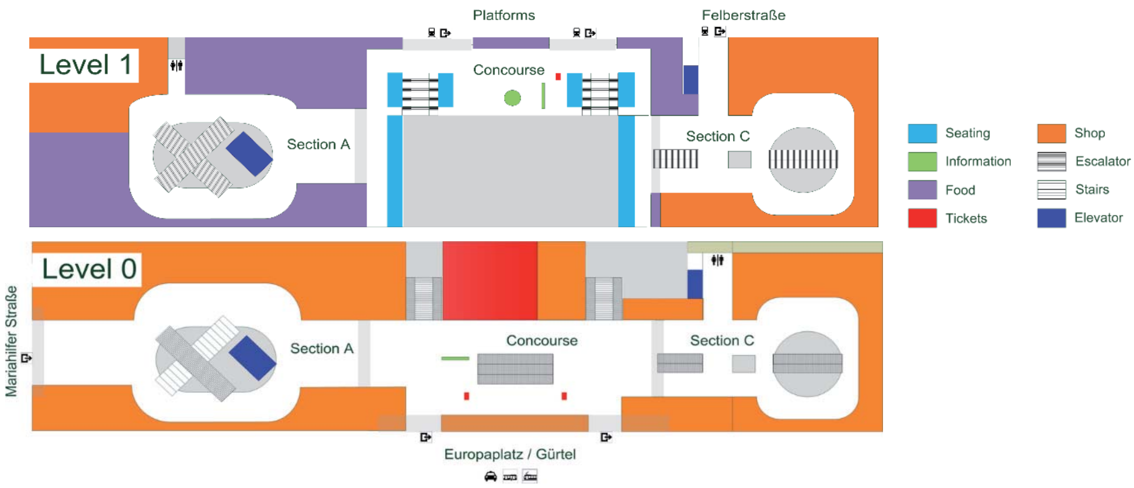

Figure 1: Schematic floor plan of the main parts of the train station Westbahnhof in Vienna.

counted in order to estimate numbers regarding passenger flows.
- Additionally, video and photo material was collected.

3.2 Observation Analysis

3.2.1 Pedestrian Activities

Observation data was categorized into known activity patterns. Some activities are restricted to specific motion types. Motion types include *stand, sit, walk, use escalator, arrive, and depart.* The observed activities for the motion type stand can be found in Table 1.

Table 1: Activities for the motion type *stand*.

activity	parameters	notes
talk to . . .	(person)	
hug . . .	(person)	
kiss . . .	(person)	
look at . . .	(person or object)	
look around		
orient		
wait for . . .	(person)	
in queue / wait for . . .	(object)	(AA)
buy . . .	(object)	(AA)
enter toilet		(AA)
consume . . .	(object)	
throw away . . .	(object)	(AA)
inspect exhibits		(AA)
inspect shop window		(AA)
use cell phone (talk)		
use cell phone (look at screen)		
read		
ask for . . .	directions	
	money	
work (at kiosk, information desk)		(AA)
take pictures		
watch baggage		
sort baggage		

Activities that can only be performed at specific activity areas are marked “(AA)”. A full list of activities for all motion types can be found in (Jaros, 2015).

3.2.2 Pedestrian Parameters

In addition to the motion types, the parameters listed in Table 2 could be identified. Parameters with the scope “agent + activity” can change between activities for the same agent.

Table 2: Additional parameters.

Name	Scope	Domain
Social form	agent + activity	single
		couple
		small group (3-10)
		large group (>10)
Associate entity type	agent + activity	none
		baby buggy
		bicycle
		baby/infant
		dog/pet
		suitcase/trolley/bag
Preferred walking speed	agent	]0; 10] m/s
Gender	agent	male
		female
Age	agent	]0; 130] years
Appearance	agent	(complex)
Time left until departure	agent	[0;∞[s

3.2.3 Activity Patterns

Strategies in the behavioural model are described as activity graphs, where activities are represented as nodes and edges are weighted by the probability of transition. A strategy can be associated with a large set of possible activity patterns. Each agent is assigned one specific activity pattern (activity list).

Table 3: Exemplary activity patterns.

Departure with food arrive (city side), taxi → walk to (escalator) → use escalator → walk to (kiosk) → buy (food) → walk slowly, eat (platform) → depart (train side)
Departure with ticket arrive (city side), public transport → walk to (arrivals/departures monitor) → look at (arrivals/departures monitor) → walk to (ticket machine) → buy (ticket) → walk to (escalator) → use escalator → walk to (platform) → depart (train side)
Arrival arrive (train side) → walk to (escalator) → use escalator → walk (outside) → depart (city side), taxi
Shopping arrive (city side), public transport → REPEAT (walk to (shop) → buy (product)) → walk (outside) → depart (city side), public transport

The activity patterns described in Table 3 were identified through observation. This list is of exemplary nature due to the difficulty of observing activity patterns. Only one pedestrian was observed at a time. Transition probabilities and the set of available activities for each strategy are largely based on subjective experience.

3.2.4 Pedestrian Flows

Pedestrians have been counted at various points of interest inside the concourse in order to estimate pedestrian flows. Figure 3 illustrates pedestrian streams coming via the escalators from the ground level onto the platform level. Destinations are colour-coded.

4 RESULTS

The presented modelling of pedestrian behaviour is based on the idea of pedestrian behavioural levels according to (Hoogendoorn and Bovy, 2004): On the strategic level, a pedestrian picks an activity pattern and sets the departure time. On the tactical level, the pedestrian selects a list of activities, activity areas, and a route connecting them. On the operational level, the necessary steps to actually reach that position are decided.

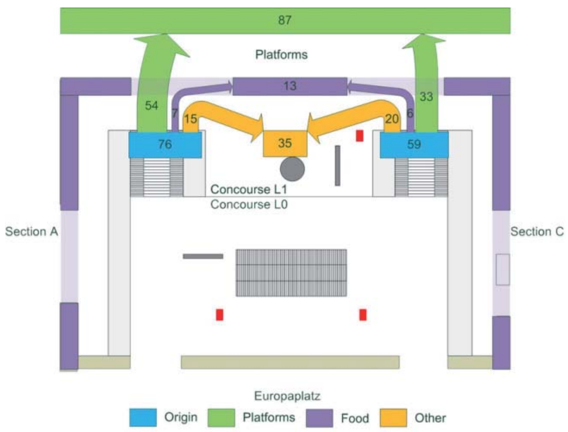

Figure 3: Pedestrian streams onto the platform level.

The presented model is derived from pedestrian observation at a major train station. It is designed to be easily expanded to other building types with substantial pedestrian flow. It focuses on task scheduling, motion planning, and collision avoidance. The employed methods are navigation meshes and A* algorithm, as well as reciprocal velocity obstacle.

4.1 Behavioural Model

The following subsections outline a behavioural model for a multi-agent simulation concept.

4.1.1 Agents

In the model people are represented by agents. Each agent follows one of the possible strategies for its entire simulation lifetime (i.e. its stay at the facility). This strategy expands into a dynamic list of activities and respective path finding information.

In addition, agents have the parameters *Gender, Age, Baggage type, Appearance, Preferred walking speed*, and *Time left until departure*. They act autonomously and appear in different social forms, which can change during their stay at the facility: Single, Couple, Small group or family (3–10), Large group (>10).

4.1.2 Behaviour

Figure 4 illustrates the agent behaviour for the (level 1) strategy depart: Level 2 adds a list of activities, while level 3 adds high-level path finding, and level 4 adds low-level path finding. Broken lines mark the partition of the list displayed for the next level.

Strategic Level. A strategy can be considered as use case and indicates why a pedestrian stays at the facility. The strategy is generally predetermined and does not change during the pedestrian's stay. The chosen strategy determines a set of activities on the tactical level. Examples for strategies are: Arrive via train, Depart via train, Shop, Pick up an arriving passenger, Escort a departing passenger, Work.

Tactical Level. On the tactical level, a set of activities is chosen which is necessary and sufficient to fulfil the strategy. The selected activities are ordered to minimize the walking distances, unless there are specific requirements (e.g. using the toilet just before departure). Depending on the situation, both the order and elements of the activity list can change during the agent's stay at the facility. The activity list is modelled as a queue following the principle of first-in-first-out (FIFO). The next activity in the queue determines the next destination on the operational level. An exemplary list of activities for the strategy *Depart* is: Arrive via public transport, Buy flowers at the florist, Buy food at a food stall, Consume food in the sitting area, Talk to a friend on the phone, Use the toilet, Enter the train for departure.

Most activities are parametrized concerning objects, people involved, or the exact location of the activity. Many activities are restricted to certain activity areas (e.g. Buying a ticket), while other activities do not have such a restriction (e.g. Talking on the phone). Activity areas can be associated with specific motion types (e.g. stand, sit).

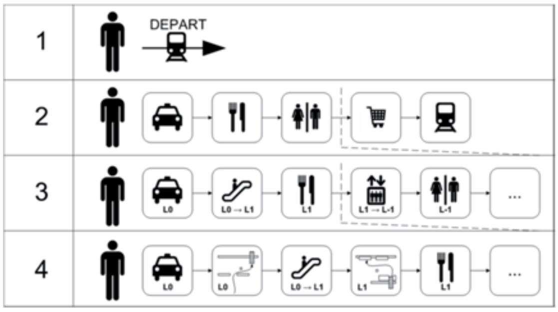

Figure 4: Exemplary agent behaviour on the (1) strategic, (2) tactical, and (3, 4) operational level.

Operational Level. An activity on the tactical level determines the next destination on the operational level. This level is responsible for path planning (from the current position to the next activity area) and for actually reaching that position. Available operations on this level are the navigation on the graph representing the simulation world, local collision avoidance, and teleportation (e.g. when using a lift).

4.2 Implementation

A proof-of-concept prototype has been implemented with the Unity framework. It provides a real-time visualization and simulation environment with extension possibilities in C# and Javascript, based on the Mono framework.

The development of the pedestrian simulation was aided by available packages, e.g. for the A* algorithm and navigation mesh structures. Support for high-level navigation between separate parts of navigation meshes was not included.

To ease the implementation for the prototype, the following simplifications were made:

- Social forms other than “single” were not considered, as well as interactions between agents.
- Only the strategies *Arrive, Depart, Shop* were implemented.
- From the list of activities the following were selected: Sit, Buy food, Buy something, Use toilet, Use elevator/escalator/stairs, Get information, Buy ticket, Orient, Appear (by leaving a train or city-side transport), Leave (by entering a train or city-side transport)
- All motion types were reduced to Walking or Standing.

A 3D model of the train station Westbahnhof was created, as well as additional models for removable objects like ticket machines, information walls, etc. The models were created using SketchUp and imported into Unity via the open Collada file format (.DAE).

Artwork was obtained from the city’s open data repository (pictograms of local transport), other public domain artwork, Unity standard assets, SketchUp standard materials, or own creations.

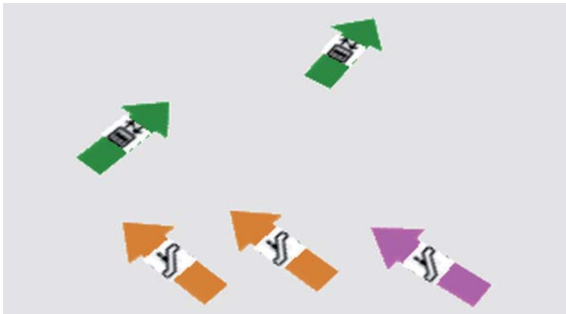

Figure 5: Footprints indicate the agent’s strategy in colour codes and the target activity area with icons.

For the implementation the following functional requirements were considered:

Behaviour

- Agents must be created in plausible arrival patterns on the city side and the train side. Agents must be destroyed as soon as the execution of their activity list is completed.
- Agents must have a constant general strategy and follow a list of activities accordingly.
- The motion of agents in the virtual environment should approximate the motion of pedestrians in the real station.
- Agents must form a queue in the appropriate direction if the activity is configured to have a queue (e.g. a ticket machine).
- Agents must wait in the activity area while performing an activity that has such an area.
- Agent speed should be randomly distributed within a reasonable range.

Information system

- Information about the strategy and next activity must be accessible at all times for each agent.
- Each agent must display: direction, velocity, next activity, strategy (see Figure 6, 8)
- Walking agents must leave a trail symbol

(“footprints”, see Figure 5) at their position periodically.

- Stopped agents must leave a trail symbol at their position periodically.
- A representation of traffic density (e.g. heatmap, see Figure 7) must be available.

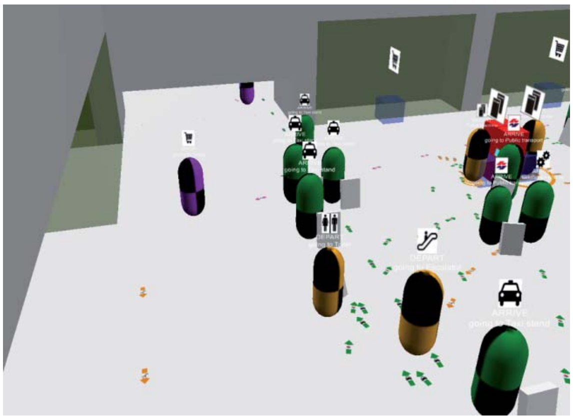

Figure 6: Agents leaving trails (footprints), displaying strategy (colour of capsule and footsteps) and activity (icon above capsule).

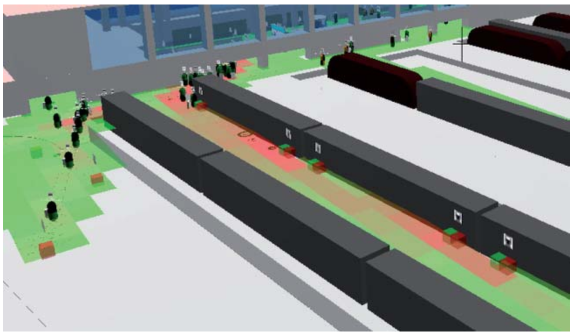

Figure 7: Heatmap view displaying used areas in colour. Low density is represented in green, high density in red.

5 DISCUSSION

A behavioural model based on observations at a major train station has been presented. The model consists of hierarchical behavioural levels. The highest level determines the agent’s purpose (strategy) in the simulation. At the next level, a set of activities is selected accordingly. The lowest level controls the agent’s movements including pathfinding and collision avoidance.

Our prototype integrates pedestrian simulation and visualization into a real-time 3D application that provides interactive feedback for planning.

In order to identify problem areas in the planning phase of building design, the prototype provides visual feedback for chosen layout and dimensions by indicating problem areas, possible jam areas, and intersection patterns. To that end the behavioural model has been furnished with an information system that visualizes an agent's position, trajectory (footprints), strategy (colour), and activities (icons), as well as traffic densities (heatmap). Both, agents and environment are represented in an abstract way to minimize distraction and rendering effort.

The pedestrian simulation has been implemented using the Unity framework which provides support for the operational level with built-in motion planning and collision avoidance capabilities. Task scheduling and high-level navigation between parts of the navigation meshes have been implemented, as well as the information system.

On current office hardware, performance is not yet sufficient to simulate plausible passenger numbers for an entire train station in real-time with multiple trains departing and arriving concurrently, but acceptable results have been shown for passenger numbers below 800.

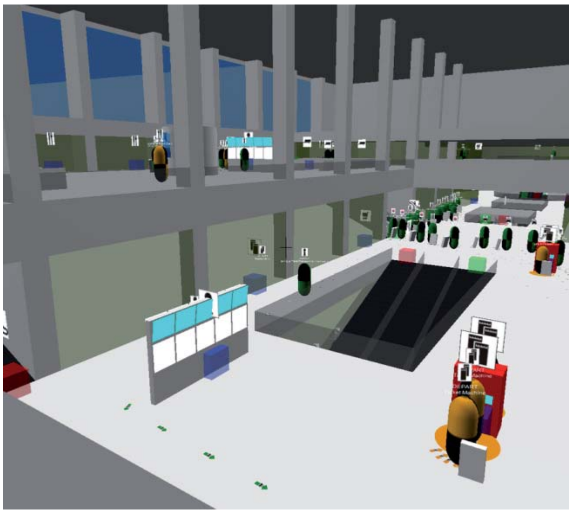

Figure 8: Pedestrian simulation at Westbahnhof showing platform level and street level.

From discussions with planners using the presented prototype we consider the following features essential for such a behavioural model:

- Provide specification for separate walkable areas (navigation meshes) including the link between them (e.g. lift, escalator).
- Provide specification of activity areas (e.g. ticket machine, shop, toilet)
- Provide queueing for realistic space utilisation (incl. specification)

- Handle realistic number of agents moving simultaneously (determined by train frequency and capacity)
- Use realistic spatial and temporal values for agents (e.g. walking speed, space consumption, time for activity)
- Collect statistical data for feedback on usage patterns (e.g. congestion areas)
- Be extensible for new activities

The presented behavioural model is generally applicable for various indoor situations and can be easily adapted to other building types.

For an improved feedback for planning purposes, an export of simulation results should be provided. This could be in terms of a model textured with the generated heatmap including the positions and types of footprint trails. A separate export should be oriented towards statistical data in a spreadsheet format.

Further cooperation with building operators in combination with video analysis could lead to a better verification and improvement of the simulation.

A significant improvement of the proposed behavioural model would be the integration of a visual perception system for the agent's orientation.

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