



Eidgenössische Technische Hochschule Zürich
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Lecture with Computer Exercises: Modelling and Simulating Social Systems with MATLAB

Project Report

Modeling of a passenger ship evacuation

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1 Abstract

The evacuation of a passenger liner is problematic due to a big mass of passengers wanting to reach the rescue boats. Real data can just be gained on accidents. Another way is to simulate such scenarios using computer models. Our approach was to take a common ship shape with real floor plans and run simulations on it with a continuous space social force model as introduced by Helbling et al [?]. A implementation of this has already been done by a former MSSSM group [1] on building structures. We took this C based code with a MATLAB interface and changed it to our needs.

Several scenarios were simulated. As a standard we took a simplified floor plan of the passenger liner Costa Serena, a 290 meter long ship with up to more than 4000 passengers. We compared it to modifications in the stair placement as well as rescue boat capacity adjustments. Another idea was to implement the leading and controlling influence of staff on the passengers.

Our simulations clarified that there is a potential to decrease the overall evacuation time. The most weightily influence had the stair displacement with up to 20% faster evacuation. on the other hand, the crew influence model seemed to be to simplified. We did not see a lot of improvement in this scenario. However, a more detailed model would probably lead to better results.

In a future work one could merge our modifications to get an even safer evacuation. The potential exists.

2 Individual contributions

The whole project was completed as a team. For sure we took into consideration all the personal backgrounds and knowledge. That is the reason why Raphael and Manuela focused on implementing the computer code. Whereas Andreas and Fabian concentrated on providing background information, compared the results with the reality and doing its verification. A more detailed breakdown can be seen by looking at the GitHub time line of our project.

3 Introduction and Motivations

3.1 Introduction

The evacuation of a passenger liner due to fire, sinking or other issues leads to several problems. A large amount of passengers try to save their lives and get to a rescue boat. Narrow and branched floors, smoke, inflowing water, the absence of illumination, rude passengers and so forth can make the evacuation difficult and reduce the number of survivors. There are a lot of norms how to minimize the harm of such an evacuation. For example there are rules on the number of rescue boats dependent on the amount of passengers [2]. With dry runs the staff is prepared for the case of emergency et cetera. In real life ship corridor reproductions, the behavior of distressed people is studied. Another approach is to model such ship evacuations numerically on the computer. As an example the software maritimeEXODUS by a development team from the University of Greenwich is a computer based evacuation and pedestrian dynamics model that is capable of simulating individual people, behavior and vessel details. The model includes aspects of people-people, people-structure and people-environment interaction. It is capable of simulating thousands of people in very large ship geometries and can incorporate interaction with fire hazard data such as smoke, heat, toxic gases and angle of heel [5]. Our approach is similarly to model a passenger ship with a common geometrical outline and ground view. In an optimization process we will thereafter look for an ideal ground view, rescue boat distribution and their size to minimize the time needed for evacuation. Finally we will make a statement on possible improvements.

3.2 Motivation

Even though modern ocean liners are considered to be safe, the latest occasions attested that there is still potential for evacuation and safety improvements [6]. Certainly we know that this science is very advanced and practiced since the sinking of the Titanic. Nevertheless knowing that there are still bottlenecks on the ships we are very motivated to detect and eliminate them with our mathematical models.

3.3 Fundamental Questions

To find these bottlenecks we run a mathematical model of a ship structure with several decks and its passengers [4]. After we localized these places we are interested in the answers of the following questions:

How much time can be saved by varying the dependent variables mentioned below:

- How much people can be saved by changing the disposition of the specific room types?
- Where are the bottlenecks during the evacuation? How can they be avoided?

What is the influence of the rescue boats?

- Are small or bigger boats better?
- Where do they have to be positioned?

We analyze the difference between uncontrolled and controlled passenger flow:

- Is the crew able to prevent chaos in the evacuation process?
- What is the best way to lead the passengers out of the ship?

In addition we are keen to know if our model is a good abstraction of the reality.

3.4 Expected Results

Before making computer simulations we discussed, what we expect as results out of the simulation:

- Even though modern ships are quite optimized in regard to evacuation time, they are always a compromise between safety and luxury. Therefore we are convinced to find a superior adjustment of the decks geometries to increase the survival rate.
- Since the rescue boats can not be averaged but are rather concentrated over one or two decks, we consider the staircases as the bottlenecks.
- In aligning this variables we are persuaded of a reduction of the overall evacuation time.
- We suppose that smaller and evenly spread rescue boats combined with a higher quantity will scale the evacuation time down. Certainly there is going to be an optimum in size which we are willing to find.
- By controlling the rescue we assume to detect a huge decrease in evacuation time. Further we have the hypothesis that disorder can be minimized. The crew who is familiar with the decks and the emergency exits is able to guide the passengers in minimum time to the rescue boats.

- There are many parameters we do not model in our simulation. For example fire and smoke, the tilt of the ship or handicapped and petrified passengers are disregarded. By leaving out this details we get a very simplified model. However, by starting the optimization process by data of a nowadays passenger liner we hope to see some real evacuation dynamics in this system and therefore make conclusion on the fundamental questions.

4 Description of the model

We base our model on the work done by a group of former MSSSM students, by name Hans Hardmeier, Andrin Jenal, Beat Kueng and Felix Thaler [1]. In their work "Modeling Situations of Evacuation in a Multi-level Building" they wrote a computer program in in the language C with a MATLAB interface to rapidly simulate the evacuation of multi-level buildings.

4.1 Social force model

Our approach is the social force model described by Helbling, Farkas and Vicsek [?], as summarised below. In order to observe an escape panic situation and especially bottlenecks, they built up a continuous-space model. In mathematical terms they took Newtons second law and introduced a mix of socio psychological and physical forces for each so called pedestrian.

$$m_i \frac{d\mathbf{v}_i}{dt} = m_i f_D + \sum_{j(\neq i)} f_{ij} + \sum_W f_{iW} \quad (1)$$

Each pedestrian has his own mass and a direction e_i^0 in which he wants to move with a certain velocity v_i^0 . He tries to adapt his own velocity to the wanted velocity with a given characteristic time τ_i .

$$f_D = \frac{v_i^0(t)\mathbf{e}_i^0(t) - \mathbf{v}_i(t)}{\tau_i} \quad (2)$$

There are additionally interaction forces f_{ij} between the pedestrian and other people including an exponential part for the tendency of two pedestrians to stay away from each other. The second and third term are zero if the two pedestrians are not in touch. Elsewise there is a force in tangential direction t and in radial direction away from each other.

$$f_{ij} = \{A_i \exp[(r_{ij} - d_{ij})/B_i] + kg(r_{ij} - d_{ij})\} \mathbf{n}_{ij} + \kappa g(r_{ij} - d_{ij}) \Delta v_{ji}^t \mathbf{t}_{ij} \quad (3)$$

To be able to handle with walls there is another forces f_{iW} introduced. Its direction is away from the surrounding walls and the structure is similar to the one for the interaction between pedestrians.

$$f_{iW} = \{A_i \exp[(r_i - d_{iW})/B_i] + kg(r_i - d_{iW})\} \mathbf{n}_{iW} - \kappa g(r_i - d_{iW})(\mathbf{v}_i \cdot \mathbf{t}_{iW}) \mathbf{t}_{iW} \quad (4)$$

4.2 Ship structure

To apply the force model on a realistic situation a ship has to be implemented as well. Floor plans from the Costa Serena were taken [4]. In order to make strong conclusions we want to keep the following variables independent:

- Number of passengers (4400 agents)
- Overall capacity of the rescue boats (4680 seats)
- Ship size (290 meters long) and outer shape

In order to optimize the evacuation time, we change the following dependent variables:

- Stairs and their positions
- Rescue boat size, number and position
- Control of the passenger flow by crew members (e.g. is there staff to lead the passengers and how are they doing it?)

5 Implementation

As mentioned above our code is based on the work of a previous project. Working on a different problem statement we had to make several adjustments and adapt it to our simulation model. In this chapter we will explain the most significant modifications we made. For the exact understanding of the original code and the process of optimization, please refer to the documentation of the previous project group [1], especially chapter five and nine or our code in the Appendix.

5.1 Basic code

The builders of the code we base on created a flexible model to simulate building structures. The floors can be feed as graphic data into the system where different colors stand for different areas. Black are walls, red stairs up, blue stairs down, green exits and purple agent spawning areas. The data is evaluated in MATLAB in matrices. Information on parameters such as timestep, simulation time, force characteristics et cetera can be read in using a config file which is evaluated on simulation start.

With a fast sweeping algorithm in C a vector field is created for every floor pointing in direction of the shortest way towards stairs and exits. In a loop over all passengers the acting forces on them are calculated and via forward Euler converted into velocities.

$$\mathbf{v}_{i,new} = \mathbf{v}_{i,previous} + \frac{\sum f}{m_i} dt \quad (5)$$

Again with the forward Euler scheme positions are calculated that were reached in a finite timestep.

$$\mathbf{r}_{i,new} = \mathbf{r}_{i,previous} + \mathbf{v}_{i,new} dt \quad (6)$$

5.2 Code adjustments

This subsection is intended to illustrate the modifications in the code. We explain the difference between our model and the one used in [1] and the reason why a modification was necessary. Further we define the assumptions we made to minimize the modifications. Finally we specify the modifications and where they take place. Those parts are however not essential for the results of our research. They are meant to be an assistance for following projects.

5.2.1 Exits

Reason:

The first change which was necessary was due to the fact that the exits in our simulation are not simply on the lowest floor.

Assumption:

In case of an emergency all agents are keen to leave the ship as fast as possible. Therefore in our simulation all passengers above the exits floor are only enabled to move down and passengers lower than the exit floor move upstairs.

Function:

applyForcesAndMove.m

New variables:

To define the floor in which the exits are we introduced a new variable *floor_exit* in the config file.

Modifications:

Since we defined our exit, we are able to easily modify the code by splitting the loop, in which the force-calculation and the movement of the agents take place, in two parts. First we loop over all floors higher than the exit floor. In those the agents are only allowed to move down. Secondly we do the same for all people in the floors lower than the exit floor where the passengers only can move up. The only floor left is the exit floor where the agents only move towards exits.

Because of this modification it is not necessary to loop twice over all floors. Consequently our code remains fast and efficient. We also kept the simple concept of vectors out of booleans. This means for each agent there is one number set:

- If the agent reaches a staircase and therefore changes the floor 1 is stored in the logical array *floorchange*
- otherwise a 0 is stored

The assumption is also a very helpful simplification for the pictures since we do not have to mess with the problem of stairs overlapping.

5.2.2 Different exits

Reason:

In our model the exits are the rescue boats, which can only hold a limited number of agents. Therefore we had to find a way how to differ the exits from each other and to assign a specific number to every exit. This number defines how many agents can stay on that rescueboat.

Function:

loadConfig.m

New variables:

- *exit_count*, to define the number of exits.
- For each exit k a variable *exit_k_nr*, to define the number of agents it can hold.
- To store how many agents can exit in one specific exit, we introduced a matrix *exit_nr matrix*, where the number of agents that can exit is indicated for each pixel.

Modifications:

Some changes in the decoding of the pictures were necessary. The aim was to change as little as possible to the original code. It was clear that we are going to need as many different colors as we have different exits, to be able to distinguish them during the simulation.

We define every pixel which has red to value=0, blue value=0 and green value unequal to zero a "exit-pixel". Now we can specify a lot of different colored exits by using green values between 256 and 256-*exit_count*.

We implemented the matrix *exit_nr* similar to the already existing one *img_exit*, in which we store a count to number the different exits. The number is defined by the green value of the pixel that belongs to this exit.

```
%make a zeros matrix as big as img_exit
config.exit_nr=zeros(size(config.floor(config.floor_exit).img_exit));
% build the exit_nr matrix
config.exit_nr = config.exit_nr + e*( img_build(:, :, 1) == 0 & img_build(:, :, 2) ==
(256-e) & img_build(:, :, 3) == 0 ) ;
```

Figure 1: Implementation of the exit_nr matrix

5.2.3 Closing exits during simulation

Reason:

To close an exit as soon as it let a specific number of agents in, we have to keep track of the number of agents that already used this exit.

Function:

loadConfig.m and *applyForcesAndMove.m*

New variables:

exit_left

Modifications:

For this purpose, we defined the matrix *exit_left*, in which we store the number of agents who can exit for every exit.

```
%make a zeros vector as long as exit_count
config.exit_left = zeros(1,config.exit_count);
%loop over all exits
for e=1:config.exit_count
%build the exit_nr matrix
config.exit_nr = config.exit_nr + e*( img_build(:, :, 1) == 0 & img_build(:, :, 2) ==
(256-e) & img_build(:, :, 3) == 0 );
%build the exit_left matrix and save the number of agents the exit can hold
config.exit_left(1,e) = config.(sprintf('exit_%d_nr', e));
end
```

Figure 2: Implementation of the exit_left matrix

In the loop where the forces and velocities are updated, (*applyForcesandMove.m*) we added a piece of code, which updates the exit_left matrix at every timestep. First, we get the number of the current exit.

```
%save current exit nr
data.current_exit = data.exit_nr(round(newp(1)), round(newp(2)));
```

Figure 3: Implementation to get the current exit number

Then we update the *exit_left* matrix by counting down the number of agents allowed to exit by 1. If the allowed number of agents exited the number is 0. Now we have

```
%update exit_left
data.exit_left(1,data.current_exit) = data.exit_left(1,data.exit_nr(round(newp(1)),
round(newp(2)))) - 1;
```

Figure 4: Implementation to update the exit_left

to close the current exit, by changing it into a wall. Therefore we have to update the *img_wall* matrix.

```
%close exit if there is no more free space
if data.exit_left(1,data.current_exit) < 1
%change current exit to wall
data.floor(data.floor_exit).img_wall = data.floor(data.floor_exit).img_wall == 1 ...
— (data.exit_nr == (data.current_exit));
data.floor(data.floor_exit).img_exit = data.floor(data.floor_exit).img_exit == 1 ...
& (data.exit_nr = (data.current_exit));
```

Figure 5: Implementation to close filled boats

5.3 Crew command simulation

Reason:

In reality an evacuation is coordinated. Loudspeaker announcements and crew members lead the people to the exit floor. In some cases there are even assembly points on the deck where people meet. Afterward they go with crew members to the rescue boats. In our first simulations we saw, that the last passengers escaping the ship have to walk all the way along the ship to get into a rescue boat in the middle of the deck. Those boats are the only ones that are not fully loaded at this time. To counteract, we tried to implement somehow the interaction of the passengers and the crew members.

Assumption:

In order not to change too much the structure of our standard evacuation code, we tried to implement the scenario in two steps. First just some rescue boats in the middle of the ship are available what can be interpreted as a crew leading people to those boats because they know that the boats near to the stairs should be left unalloyed for the last passengers to be evacuated rapidly. In a second step, all rescue boats are opened when a certain number of passengers already left the ship.

Function:

The whole basic code has been copied and adjusted in several positions, mainly in loadConfig.m and applyForcesAndMove.m.

5.4 Video creation

Reason:

In the basic code there was a graphical output into eps-formated files possible on every timestep. The images then had to be converted into a video file in a postprocessing part. This is not an optimal implementation for a fast system. Furthermore

it turned out that we could increase the simulation speed by factor two just by saving not on every single timestep but only on every 10th or 100th. Another issue was the conversion from eps to a video file. To simplify the handling, we used a MATLAB function to create directly a video out of the figures instead of making a detour via images.

Function:

simulate.m, initialize.m

New variables:

save_frame

5.5 System output

Reason:

Storing the simulation output is important to be able to analyze and optimize the system. The output of the basic code was just a plot with agents left the building over time and the above mentioned graphical output of the floor plans over time. We extended the output and created a dump struct where all the important variables are listed over time. That struct is the system output at simulation end and it can be used in a postprocessing part to generate meaningful graphs and data.

Function:

simulate.m

New variables:

output

5.6 Postprocessing

Reason:

To analyze the gathered data in a systematic way and to create consistent plots we created a postprocessing file. The output file can be loaded in MATLAB using the load command and is thereafter automatically evaluated. Plots with agents per floor over time, left space in rescue boats over time and agents that left the ship over time are created with proper axis label and so on. Additionally there is an output in the MATLAB command window with timestep, number of steps, total simulation time, agents on ship on start, agents on ship on simulation end, agents deleted due to Not-a-Number-positions and the characteristic t_{10} , t_{50} , t_{90} and t_{95} times.

Function:

postprocessing.m

New variables:

none of relevance

Modification:

We created the whole script ourself. It can be found in the annex.

5.7 Parameter input and config file

The social force model can be adjusted using different parameters e.g. to weight the importance of different forces among each other or to define the decay rate of these forces over the distance. Also the mass and radii of the passengers as well as their maximum velocity can be set. The parameters are written down in the config files that are passed to the MATLAB interface on simulation start. For sake of simplicity we adopted the force model parameters from the previous group. The parameters concerning the ship shape were adjusted so that they represent reality as far as possible.

In the annex a typical simulation input of the config file and some explanations can be found.

5.8 Ship Decks

The Costa Concordia has 14 decks which are all different from each other. They are connected by stairs and elevators in different configurations and they fulfil different purposes. There are decks for entertainment, eating, shopping, sports and so on. Due to the big differences of each deck, it is enormous time consuming to implement all these decks with all details in a model. So it is necessary to simplify the decks in a reasonable manner. Further the picture source is not perfect in size and data type so there is a manual conversion needed. In this chapter it is shown what assumptions were made and with which conversion techniques the decks were implemented into the model.

5.8.1 Conversion

First of all the decks have to match each other in pixel size and position to allow a flawless connection of the decks. So the size of some decks has to be adjusted and the stair overlay has to be matched as good as possible. Secondly doors, numbers, names and symbols are removed to have one connected surface without unreal obstacles.

Now that the surfaces are clean and connected, the colors have to be replaced by predefined colors of the code (purple for spawn of agents, black for walls, red for upstairs, blue for downstairs and different green type for each rescue boat).

In figures 6 and 7 a small portion of a deck with stairs, rooms, doors and elevators is

shown before and after conversion. In the converted picture is a blue block included for the stairs, which conversion will just be explained in the next part.

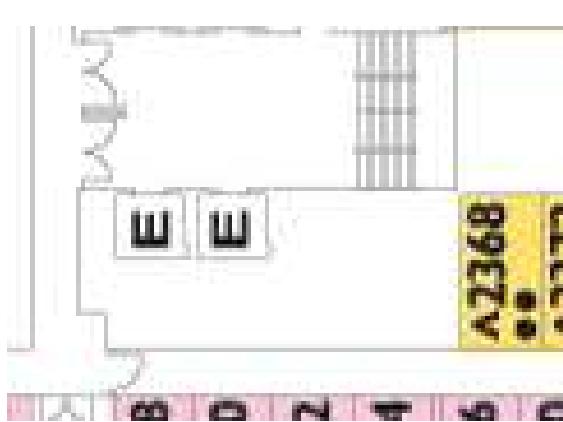


Figure 6: Deck before conversion

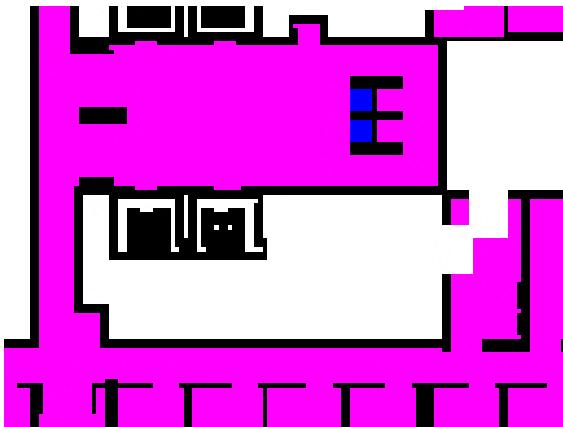


Figure 7: Deck after conversion

In most of the cases stairs from one to another floor are designed in a spiral way to minimize the consumed space. That leads to a problem by implementing the stairs into the model. It is not possible to make a clean transition from one floor to another without using some tricks.

There are special additional floors to overcome the mentioned problem in the work "Modeling Situations of Evacuation in a Multi-level Building" [1]. These additional floors which represents the stairs, are a fine method to create an infinite amount of floors and connections without any trouble. But it needs an additional floor for each connection.

While the agents on the ship march only in the direction of the rescue floor the connection can be simplified. So there is a new technique used to get rid of these additional floors.

In figure 8 a spiraling stairs connection between floor 01 and floor 02 is shown as example. The arrows in light blue are used to clarify the technique.

The agents arrive from the left on floor 11 and go into the direction of the arrow until they reach the blue box. There they are skipped down on the floor 10 and try to go to the blue box again. So they have to go around to be skipped down again on floor 09 and go around in the other direction. That continues until they reach floor 04 which is the floor with the rescue boats.

With that technique no additional floors are needed and we get very close to the real spiraling stairs. For the ship in that project this is sufficient, because the modeling fault will be in a lower degree than the one of other assumptions.

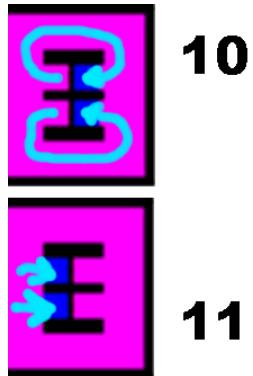


Figure 8: Stairs connection between floor 10 and floor 11

5.8.2 Similarities and reduction

The most important floor for the simulation is of course floor 04 because it holds all the rescue boats as seen in figure 10. There all agents have to pass and it is reasonable to have it very detailed. Floor 05 and 03 are the ones just above and beyond and will also have a non negligible influence on the agents movement.

The further we move the less important the deck configuration gets, because it is assumed that the stairs will be the bottlenecks. As long as the stair setup corresponds good to reality, the further decks can differ more. So we decided to convert deck 02, 03, 04 and 05 in detail and make a copy with adjusted stairs for each other floor. Floor 02 is used for the copy because it gets the closest to floor 01, 06 and 07 and is by that still a good approximation.

Floor 08 until 14 differ more from floor 02 but as long as they are far away from floor 04 it will not have a big influence. These last floors are also smaller than floor 02 and therefore the amount of floors is reduced to only 11 with approximately the same area as the original 14 floors.

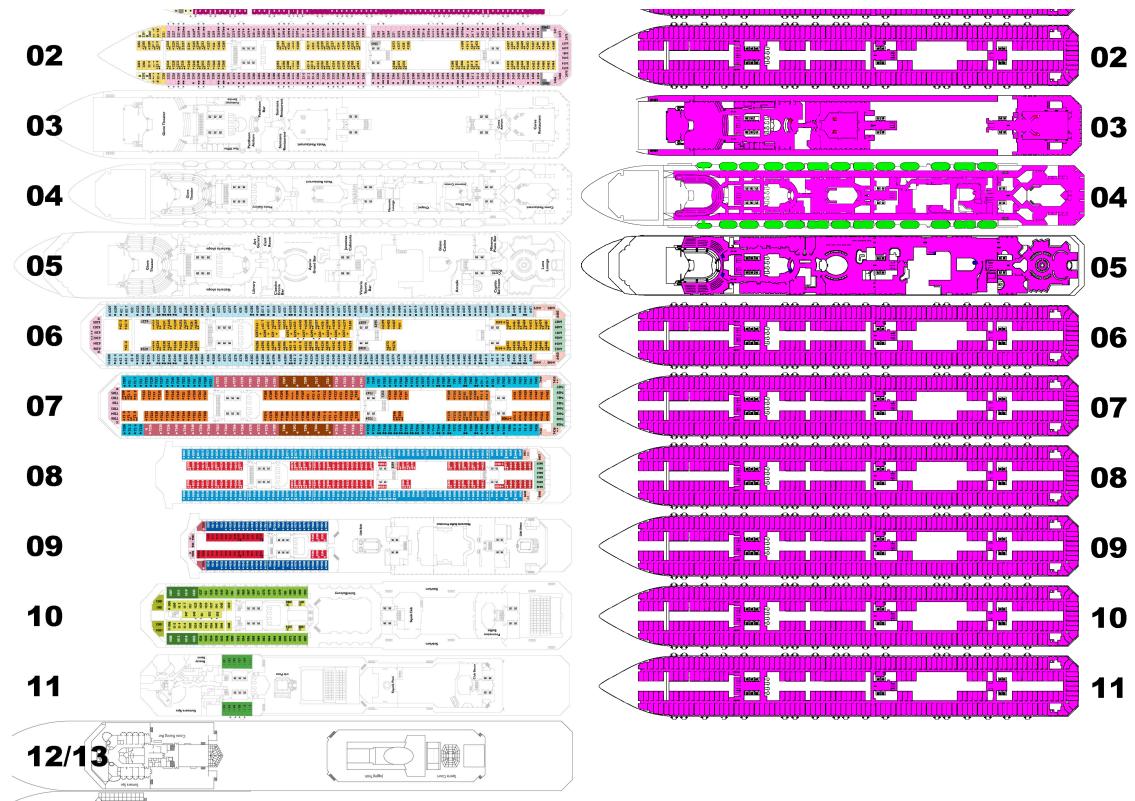


Figure 9: Original decks before conversion

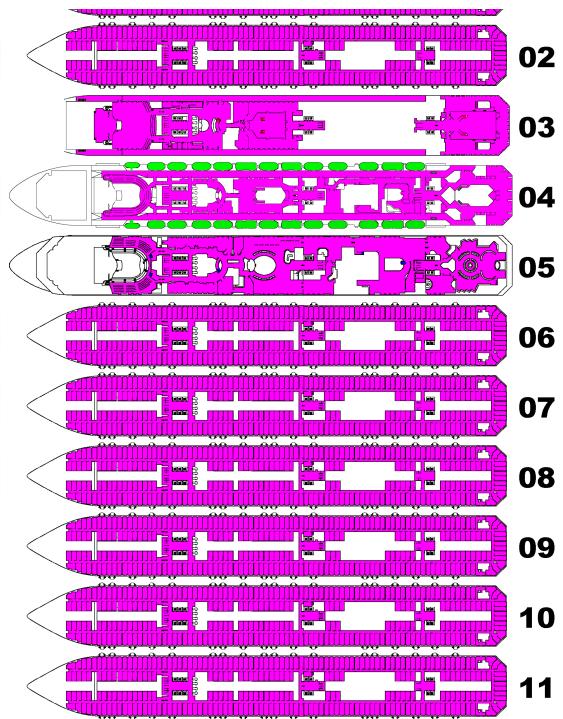


Figure 10: Deck approximated and converted

6 Results and Discussion

6.1 Simulation issues

Some agents always stuck in the walls near the stairways. Those agents did not reach the exits. This is why we could not get a t_{100} time but just saved about 98% of all passengers. The frequency of this issue was especially high in small areas and with a high total passenger amount. However, there was a trade off between realistic clogging in stairways and good ratio of rescued people out of all passengers. We decided not to decrease the number of passengers or expand the stairs because we did not want to eliminate the realistic clogging behavior which is important for the simulation.

6.2 Simulation Results

6.2.1 Standard ship

As listed above we were interested in the time in which a certain percentage of all agents was evacuated:

percentage of agents	10%	50%	90%	95%
evacuation time run1	16s	69s	167s	214s
evacuation time run2	16s	69s	164s	238s
averaged evacuation time	16s	69s	166s	226s

Table 1: Standard simulation: Needed time to evacuate a certain percentage of all agents.

Further our standard ship simulation showed the following performance:

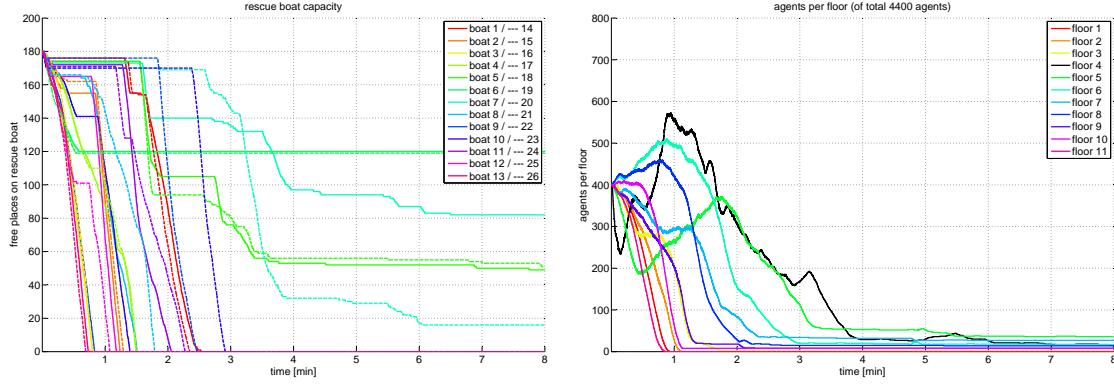


Figure 11: Standard simulation: Boat capacities during first simulation

Figure 12: Standard simulation: Number of agents per floor in first simulation

6.2.2 Modified room disposition

As we expected the standard simulation revealed that hold-up problems occur because of the staircases. As the flow everywhere else was quite dynamic we abstained from adjusting the room disposition but instead we inserted an additional staircase. This simulation yielded the following results:

percentage of agents	10%	50%	90%	95%
evacuation time	16s	67s	145s	182s

Table 2: Added stairs simulation: Needed time to evacuate a certain percentage of all agents.

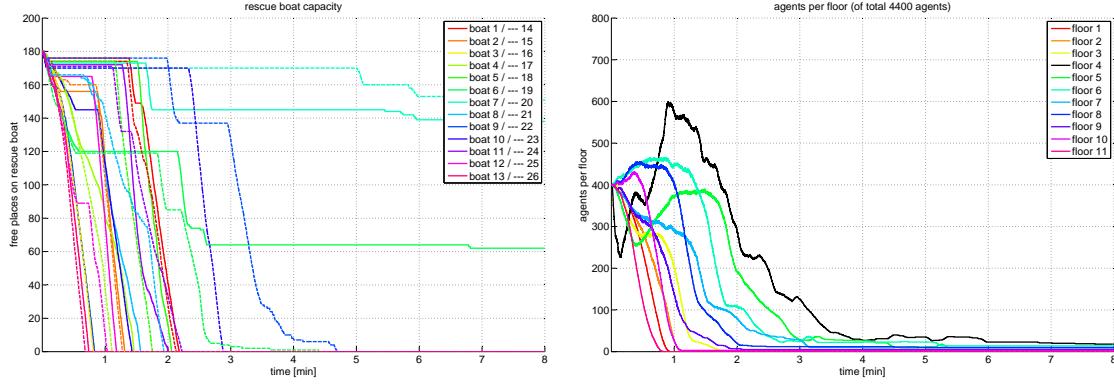


Figure 13: Added stairs simulation: Boat capacities during simulation

Figure 14: Added stairs simulation: Number of agents per floor

6.2.3 Modified rescueboat size

As we could see in the simulations with the standard ship, the rescue boats which are nearest to the stairs are filled first. This behavior is very intuitive. As soon as the nearest lifeboats are full, the agents continue to fill the other lifeboats. The greatest extension of the evacuation time occurs as follows: Towards the end of the simulation, not all lifeboats are still open. Therefore leftover agents, which walked in the direction of a lifeboat that closed in the meantime, have to cross a big distance to reach a lifeboat with free space.

We tried to avoid this delay by increasing the capacity of lifeboats near the stairs and removed some, which are the farthest away for the agents left over towards the end of the evacuation.

percentage of agents	10%	50%	90%	95%
evacuation time	17s	70s	154s	203s

Table 3: Varied boatsize simulation: Needed time to evacuate a certain percentage of all agents.

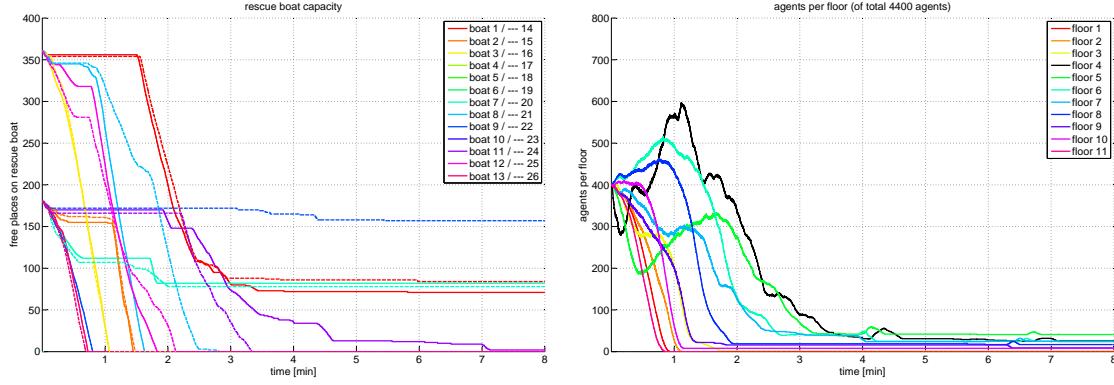


Figure 15: Varied boatsize simulation: Boat capacities during simulation

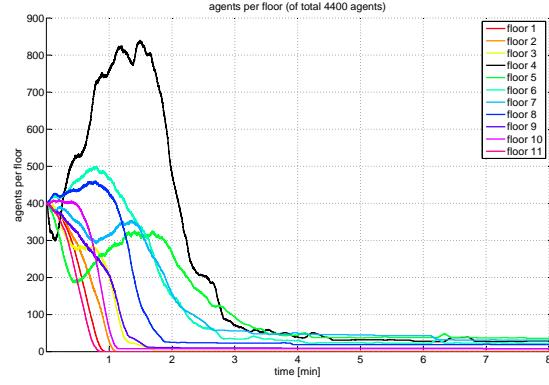
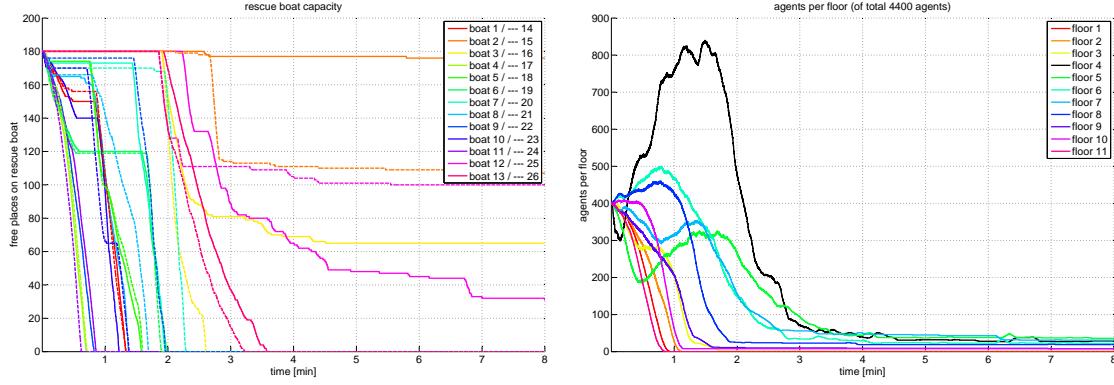
Figure 16: Varied boatsize simulation: Number of agents per floor

6.2.4 Crew command

As already mentioned in the implementation part, we changed our code in order to simulate staff controlling the rescue situation. The results of that extension can be seen below.

percentage of agents	10%	50%	90%	95%
evacuation time	20s	78s	162s	219s

Table 4: Crew command implementation: Needed time to evacuate a certain percentage of all agents.



6.3 Comparison

6.3.1 Standard - Modified room disposition

The Analysis of the simulation results showed that there is a huge potential in saving evacuation time. By adding just one additional staircase we were able to reduce the overall evacuation time by 42 seconds. Further 50% of all agents entered the exits approximately 2 seconds earlier compared to the standard model. In contrast to that the rescueboat capacity utilization remains basically the same.

6.3.2 Standard - Modified rescueboat size

As the results above show, there is no significant acceleration in the first part of the evacuation achieved by changing the distribution of the lifeboats. But, there is clearly a difference in the second half of the evacuation. The last 5% of agents are evacuated 23 seconds faster what is a huge speed up. This decrease in evacuation time is an effect of the reduced time the last agents need to leave the exit-deck.

6.3.3 Standard - Crew command

The results of the crew command extension are rather disappointing. On the one hand it was clear, that the first part of the simulation would become slower because the agents do not use the nearest boat. But on the other hand it was mentioned that the last part of the simulation has a significant speed up what is not the case. By looking at the video output the reason can be seen: The opening of the rescue boats near the stairs is useless at the point when only a few passengers are left because

then they are already on the exit floor and walked towards the middle of the ship. However, the idea has not to be thrown away. An implementation with a continuous opening of the next outer boat when the midmost ones are filled would eliminate our problem and a faster total evacuation time could be reached.

6.4 General discussion

During our project we revealed a lot of adjustments which could make cruise ships safer. Definitely we are aware of the simplicity of our model. Nevertheless we achieved to decrease the evacuation time with our improvements as shown above. Further we were able to attest that the staircases are the bottlenecks and it is possible to save time by adapting the ship geometry. Due to lack of time and simulation problems we unfortunately did not manage to find the optimal rescueboat size. However we proved that there is a capability to save further time by varying its size and position.

7 Outlook

During our work, we found a lot of possibilities to improve the model. The target of an ongoing project could be to make the model more realistic. There are a lot of possibilities to achieve this goal.

Some suggestions:

- To take into account that not all people automatically know where exactly the nearest exit is, the initialization of the escape routes should be modified.
- In our model the agents are evenly distributed over the floors and decks at the beginning of the simulation. This is however a very unrealistic scenario. In reality the agents will be unevenly spread. The evacuation time would depend very much on the form of this distribution.
- Different scenarios like night, dinner-time etc. that would change the distribution of the agents significantly could be compared.
- In reality there are a lot of effects that could occur like fire, tilt of the ship, flooded areas, power failure, mass panic etc.

There are a lot of other interesting effects that could be looked at as well.

Some ideas:

- In the ideal case, the evacuations on a ship are planned well. A good idea would be to define specific control points at which agents gather first. From

those points the agents would be led in small groups to the rescue boats by a crew member. It would be interesting to analyze the effect of such a efficient control.

- The optimal combination of the different modifications we analyzed in this project could be found and therefore a minimal evacuation time.

For sure further interesting outcomes could be made by simply merging our results, means for example varying rescueboat size and geometries.

8 References

References

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- [3] SHIP EVACUATION: <http://www.shipevacuation.com/>
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- [5] University of Greenwich (2011): maritimeEXODUS. http://fseg.gre.ac.uk/fire/marine_evac_model.html
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9 Appendix

9.1 Code

9.1.1 *standard code*

```

1 function data = addAgentRepulsiveForce(data)
%ADDAGENTREPULSIVEFORCE Summary of this function goes here
3 % Detailed explanation goes here

5 % Obstruction effects in case of physical interaction

7 % get maximum agent distance for which we calculate force
r_max = data.r_influence;
9 tree = 0;

11 for fi = 1:data.floor_count
    pos = [arrayfun(@(a) a.p(1), data.floor(fi).agents);
13         arrayfun(@(a) a.p(2), data.floor(fi).agents)];
15
    % update range tree of lower floor
    tree_lower = tree;
17
    agents_on_floor = length(data.floor(fi).agents);
19
    % init range tree of current floor
21 if agents_on_floor > 0
        tree = createRangeTree(pos);
23 end

25 for ai = 1:agents_on_floor
    pi = data.floor(fi).agents(ai).p;
27    vi = data.floor(fi).agents(ai).v;
    ri = data.floor(fi).agents(ai).r;
29
    % use range tree to get the indices of all agents near agent ai
31 idx = rangeQuery(tree, pi(1) - r_max, pi(1) + r_max, ...
                      pi(2) - r_max, pi(2) + r_max)';
33
    % loop over agents near agent ai
35 for aj = idx

        % if force has not been calculated yet...
        if aj > ai
            pj = data.floor(fi).agents(aj).p;
            vj = data.floor(fi).agents(aj).v;
41            rj = data.floor(fi).agents(aj).r;

43            % vector pointing from j to i
            nij = (pi - pj) * data.meter_per_pixel;
45
            % distance of agents
47 d = norm(nij);

49            % normalized vector pointing from j to i

```

```

51         nij = nij / d;
52         % tangential direction
53         tij = [-nij(2), nij(1)];
54
55         % sum of radii
56         rij = (ri + rj);
57
58         % repulsive interaction forces
59         if d < rij
60             T1 = data.k*(rij - d);
61             T2 = data.kappa*(rij - d)*dot((vj - vi),tij)*tij;
62         else
63             T1 = 0;
64             T2 = 0;
65         end
66
67         F = (data.A * exp((rij - d)/data.B) + T1)*nij + T2;
68
69         data.floor(fi).agents(ai).f = ...
70             data.floor(fi).agents(ai).f + F;
71         data.floor(fi).agents(aj).f = ...
72             data.floor(fi).agents(aj).f - F;
73     end
74
75     % include agents on stairs!
76     if fi > 1
77         % use range tree to get the indices of all agents near agent ai
78         if ~isempty(data.floor(fi-1).agents)
79             idx = rangeQuery(tree_lower, pi(1) - r_max, ...
80                               pi(1) + r_max, pi(2) - r_max, pi(2) + r_max)';
81
82             % if there are any agents...
83             if ~isempty(idx)
84                 for aj = idx
85                     pj = data.floor(fi-1).agents(aj).p;
86                     if data.floor(fi-1).img_stairs_up(round(pj(1)),
87                         round(pj(2)))
88
89                         vj = data.floor(fi-1).agents(aj).v;
90                         rj = data.floor(fi-1).agents(aj).r;
91
92                         % vector pointing from j to i
93                         nij = (pi - pj) * data.meter_per_pixel;
94
95                         % distance of agents
96                         d = norm(nij);
97
98                         % normalized vector pointing from j to i
99                         nij = nij / d;

```

```

99          % tangential direction
101         tij = [-nij(2), nij(1)];
103
105         % sum of radii
106         rij = (ri + rj);
107
108         % repulsive interaction forces
109         if d < rij
110             T1 = data.k*(rij - d);
111             T2 = data.kappa*(rij - d)*dot((vj -
112                                         vi),tij)*tij;
113         else
114             T1 = 0;
115             T2 = 0;
116         end
117
118         F = (data.A * exp((rij - d)/data.B) + T1)*nij
119             + T2;
120
121         data.floor(fi).agents(ai).f = ...
122             data.floor(fi).agents(ai).f + F;
123         data.floor(fi-1).agents(aj).f = ...
124             data.floor(fi-1).agents(aj).f - F;
125
126     end
127
128 end

```

Listing 1: addAgentRepulsiveForce.m

```

1 function data = addDesiredForce(data)
2 %ADDDESIREDFORCE add 'desired' force contribution (towards nearest exit or
3 %staircase)
4
5 for fi = 1:data.floor_count
6
7     for ai=1:length(data.floor(fi).agents)
8
9         % get agent's data
10        p = data.floor(fi).agents(ai).p;
11        m = data.floor(fi).agents(ai).m;
12        v0 = data.floor(fi).agents(ai).v0;
13        v = data.floor(fi).agents(ai).v;
14
15        % get direction towards nearest exit
16        ex = lerp2(data.floor(fi).img_dir_x, p(1), p(2));
17

```

```

19     ey = lerp2(data.floor(fi).img_dir_y, p(1), p(2));
20     e = [ex ey];

21     % get force
22     Fi = m * (v0*e - v)/data.tau;
23
24     % add force
25     data.floor(fi).agents(ai).f = data.floor(fi).agents(ai).f + Fi;
26   end
27 end

```

Listing 2: addDesiredForce.m

```

function data = addWallForce(data)
%ADDWALLFORCE adds wall's force contribution to each agent

for fi = 1:data.floor_count

  for ai=1:length(data.floor(fi).agents)
    % get agents data
    p = data.floor(fi).agents(ai).p;
    ri = data.floor(fi).agents(ai).r;
    vi = data.floor(fi).agents(ai).v;

    % get direction from nearest wall to agent
    nx = lerp2(data.floor(fi).img_wall_dist_grad_x, p(1), p(2));
    ny = lerp2(data.floor(fi).img_wall_dist_grad_y, p(1), p(2));

    % get distance to nearest wall
    diW = lerp2(data.floor(fi).img_wall_dist, p(1), p(2));

    % get perpendicular and tangential unit vectors
    niW = [ nx ny];
    tiW = [-ny nx];

  end

  % calculate force
  if diW < ri
    T1 = data.k * (ri - diW);
    T2 = data.kappa * (ri - diW) * dot(vi, tiW) * tiW;
  else
    T1 = 0;
    T2 = 0;
  end
  Fi = (data.A * exp((ri-diW)/data.B) + T1)*niW - T2;

  % add force to agent's current force
  data.floor(fi).agents(ai).f = data.floor(fi).agents(ai).f + Fi;
end
end

```

Listing 3: addWallForce.m

```
function data = applyForcesAndMove(data)
%APPLYFORCESANDMOVE apply current forces to agents and move them using
%the timestep and current velocity
n_velocity_clamps = 0;
% loop over all floors higher than exit floor
for fi = data.floor_exit:data.floor_count

    % init logical arrays to indicate agents that change the floor or exit
    % the simulation
    floorchange = false(length(data.floor(fi).agents),1);
    exited = false(length(data.floor(fi).agents),1);

    % loop over all agents
    for ai=1:length(data.floor(fi).agents)
        % add current force contributions to velocity
        v = data.floor(fi).agents(ai).v + data.dt * ...
            data.floor(fi).agents(ai).f / data.floor(fi).agents(ai).m;

        % clamp velocity
        if norm(v) > data.v_max
            v = v / norm(v) * data.v_max;
            n_velocity_clamps = n_velocity_clamps + 1;
        end

        % get agent's new position
        newp = data.floor(fi).agents(ai).p + ...
            v * data.dt / data.meter_per_pixel;

        % if the new position is inside a wall, remove perpendicular
        % component of the agent's velocity
        if lerp2(data.floor(fi).img_wall_dist, newp(1), newp(2)) < ...
            data.floor(fi).agents(ai).r

            % get agent's position
            p = data.floor(fi).agents(ai).p;

            % get wall distance gradient (which is off course perpendicular
            % to the nearest wall)
            nx = lerp2(data.floor(fi).img_wall_dist_grad_x, p(1), p(2));
            ny = lerp2(data.floor(fi).img_wall_dist_grad_y, p(1), p(2));
            n = [nx ny];

            % project out perpendicular component of velocity vector
            v = v - dot(n,v)/dot(n,n)*n;
        end
    end
end
```

```

48         % get agent's new position
50         newp = data.floor(fi).agents(ai).p + ...
51             v * data.dt / data.meter_per_pixel;
52     end
53
54     % check if agents position is ok
55     % repositioning after 50 times clogging
56     % deleting if agent has a NaN position
57     if ~isnan(newp)
58         if data.floor(fi).img_wall(round(newp(1)), round(newp(2)))
59             newp = data.floor(fi).agents(ai).p;
60             v = [0 0];
61             data.floor(fi).agents(ai).clogged =
62                 data.floor(fi).agents(ai).clogged + 1;
63             fprintf('WARNING: clogging agent %i on floor %i (%i).
64                 Position
65                 (%f,%f).\n',ai,fi,data.floor(fi).agents(ai).clogged,newp(1),newp(2))
66         if data.floor(fi).agents(ai).clogged >= 40
67             nx = rand(1)*2 - 1;
68             ny = rand(1)*2 - 1;
69             n = [nx ny];
70             v = n*data.v_max/2;
71             fprintf('WARNING: agent %i on floor %i velocity set
72                 random to get out of wall. Position
73                 (%f,%f).\n',ai,fi,newp(1),newp(2))
74
75         % get agent's new position
76         newp = data.floor(fi).agents(ai).p + ...
77             v * data.dt / data.meter_per_pixel;
78         if isnan(newp)
79             % get rid of disturbing agent
80             fprintf('WARNING: position of an agent is NaN!
81                 Deleted this agent.\n')
82             exited(ai) = 1;
83             data.agents_exited = data.agents_exited +1;
84             data.output.deleted_agents=data.output.deleted_agents+1;
85             newp = [1 1];
86         end
87     end
88 else
89     % get rid of disturbing agent
90     fprintf('WARNING: position of an agent is NaN! Deleted this
91         agent.\n')
92     exited(ai) = 1;
93     data.agents_exited = data.agents_exited +1;
94     data.output.deleted_agents=data.output.deleted_agents+1;
95     newp = [1 1];
96 end

```

```

92      % update agent's velocity and position
93      data.floor(fi).agents(ai).v = v;
94      data.floor(fi).agents(ai).p = newp;

96      % reset forces for next timestep
97      data.floor(fi).agents(ai).f = [0 0];

98      % check if agent reached a staircase down and indicate floor change
99      if data.floor(fi).img_stairs_down(round(newp(1)), round(newp(2)))
100         floorchange(ai) = 1;
101     end

104      % check if agent reached an exit
105      if data.floor(fi).img_exit(round(newp(1)), round(newp(2)))
106         exited(ai) = 1;
107         data.agents_exited = data.agents_exited +1;
108
109      %fprintf('agent exited from upper loop\n');

110      %save current exit nr
111      data.current_exit = data.exit_nr(round(newp(1)),
112                                         round(newp(2)));

113      %fprintf(int2str(data.current_exit));

114      %update exit_left
115      data.exit_left(1,data.current_exit) =
116          data.exit_left(1,data.exit_nr(round(newp(1)),
117                               round(newp(2)))) - 1;

118      %close exit if there is no more free space
119      if data.exit_left(1,data.current_exit) < 1

120          %change current exit to wall
121          data.floor(data.floor_exit).img_wall =
122              data.floor(data.floor_exit).img_wall == 1 ...
123                  | (data.exit_nr == (data.current_exit));
124          data.floor(data.floor_exit).img_exit =
125              data.floor(data.floor_exit).img_exit == 1 ...
126                  & (data.exit_nr ~= (data.current_exit));

127          %redo initEscapeRoutes and initWallForces with new exit
128          % and wall parameters
129          data = initEscapeRoutes(data);
130          data = initWallForces(data);

131      %fprintf('new routes from upper loop\n');

132      end

```

```

        end
136    end

138    % add appropriate agents to next lower floor
139    if fi > data.floor_exit
140        data.floor(fi-1).agents = [data.floor(fi-1).agents
141            data.floor(fi).agents(floorchange)];
142    end
143
144    % delete these and exited agents
145    data.floor(fi).agents = data.floor(fi).agents(~(floorchange|exited));
146
147
148
149
150    % loop over all floors lower than exit floor
151    for fi = 1:data.floor_exit
152
153        % init logical arrays to indicate agents that change the floor or exit
154        % the simulation
155        floorchange = false(length(data.floor(fi).agents),1);
156        exited = false(length(data.floor(fi).agents),1);
157
158        % loop over all agents
159        for ai=1:length(data.floor(fi).agents)
160            % add current force contributions to velocity
161            v = data.floor(fi).agents(ai).v + data.dt * ...
162                data.floor(fi).agents(ai).f / data.floor(fi).agents(ai).m;
163
164            % clamp velocity
165            if norm(v) > data.v_max
166                v = v / norm(v) * data.v_max;
167                n_velocity_clamps = n_velocity_clamps + 1;
168            end
169
170            % get agent's new position
171            newp = data.floor(fi).agents(ai).p + ...
172                v * data.dt / data.meter_per_pixel;
173
174            % if the new position is inside a wall, remove perpendicular
175            % component of the agent's velocity
176            if lerp2(data.floor(fi).img_wall_dist, newp(1), newp(2)) < ...
177                data.floor(fi).agents(ai).r
178
179            % get agent's position
180            p = data.floor(fi).agents(ai).p;
181
182            % get wall distance gradient (which is of course perpendicular

```

```

184         % to the nearest wall)
185         nx = lerp2(data.floor(fi).img_wall_dist_grad_x, p(1), p(2));
186         ny = lerp2(data.floor(fi).img_wall_dist_grad_y, p(1), p(2));
187         n = [nx ny];
188
189         % project out perpendicular component of velocity vector
190         v = v - dot(n,v)/dot(n,n)*n;
191
192         % get agent's new position
193         newp = data.floor(fi).agents(ai).p + ...
194             v * data.dt / data.meter_per_pixel;
195     end
196
197
198         % check if agents position is ok
199         % repositioning after 50 times clogging
200         % deleting if agent has a NaN position
201         if ~isnan(newp)
202             if data.floor(fi).img_wall(round(newp(1)), round(newp(2)))
203                 newp = data.floor(fi).agents(ai).p;
204                 v = [0 0];
205                 data.floor(fi).agents(ai).clogged =
206                     data.floor(fi).agents(ai).clogged + 1;
207                 fprintf('WARNING: clogging agent %i on floor %i (%i).
208                         Position
209                         (%f,%f).\n',ai,fi,data.floor(fi).agents(ai).clogged,newp(1),newp(2))
210             if data.floor(fi).agents(ai).clogged >= 40
211                 nx = rand(1)*2 - 1;
212                 ny = rand(1)*2 - 1;
213                 n = [nx ny];
214                 v = n*data.v_max/2;
215                 fprintf('WARNING: agent %i on floor %i velocity set
216                         random to get out of wall. Position
217                         (%f,%f).\n',ai,fi,newp(1),newp(2))
218
219                 % get agent's new position
220                 newp = data.floor(fi).agents(ai).p + ...
221                     v * data.dt / data.meter_per_pixel;
222                 if isnan(newp)
223                     % get rid of disturbing agent
224                     fprintf('WARNING: position of an agent is NaN!
225                         Deleted this agent.\n')
226                     exited(ai) = 1;
227                     data.agents_exited = data.agents_exited +1;
228                     data.output.deleted_agents=data.output.deleted_agents+1;
229                     newp = [1 1];
230                 end
231             end
232         end
233     else

```

```

228         % get rid of disturbing agent
229         fprintf('WARNING: position of an agent is NaN! Deleted this
230             agent.\n')
231         exited(ai) = 1;
232         data.agents_exited = data.agents_exited +1;
233         data.output.deleted_agents=data.output.deleted_agents+1;
234         newp = [1 1];
235     end
236
237     % update agent's velocity and position
238     data.floor(fi).agents(ai).v = v;
239     data.floor(fi).agents(ai).p = newp;
240
241     % reset forces for next timestep
242     data.floor(fi).agents(ai).f = [0 0];
243
244     % check if agent reached a staircase up and indicate floor change
245     if data.floor(fi).img_stairs_up(round(newp(1)), round(newp(2)))
246         floorchange(ai) = 1;
247     end
248
249     % check if agent reached an exit
250     if data.floor(fi).img_exit(round(newp(1)), round(newp(2)))
251         exited(ai) = 1;
252         data.agents_exited = data.agents_exited +1;
253
254         % agent exited from lower loop
255
256         %save current exit nr
257         data.current_exit = data.exit_nr(round(newp(1)),
258                                         round(newp(2)));
259
260         %update exit_left
261         data.exit_left(1,data.current_exit) =
262             data.exit_left(1,data.exit_nr(round(newp(1)),
263                           round(newp(2)))) - 1;
264
265             %close exit if there is no more free space
266             if data.exit_left(1,data.current_exit) < 1
267
268                 %change current exit to wall
269                 data.floor(data.floor_exit).img_wall =
270                     data.floor(data.floor_exit).img_wall == 1 ...
271                         | (data.exit_nr == (data.current_exit));
272                 data.floor(data.floor_exit).img_exit =
273                     data.floor(data.floor_exit).img_exit == 1 ...
274                         & (data.exit_nr ~= (data.current_exit));
275
276                 %redo initEscapeRoutes and initWallForces with new exit
277                 % and wall parameters

```

```

272         data = initEscapeRoutes(data);
273         data = initWallForces(data);

274 %             fprintf('new routes from lower loop\n');

275         end

276     end
277 end

278 % add appropriate agents to next lower floor
279 if fi < data.floor_exit
280     data.floor(fi+1).agents = [data.floor(fi+1).agents ...
281                               data.floor(fi).agents(floorchange)];
282 end

283 % delete these and exited agents
284 data.floor(fi).agents = data.floor(fi).agents(~(floorchange|exited));
285 end

286 % if n_velocity_clamps > 0
287 %     fprintf(['WARNING: clamped velocity of %d agents, ' ...
288 %              'possible simulation instability.\n'], n_velocity_clamps);
289 % end

```

Listing 4: applyForcesAndMove.m

```

function val = checkForIntersection(data, floor_idx, agent_idx)
% check an agent for an intersection with another agent or a wall
% the check is kept as simple as possible
%
% arguments:
%   data           global data structure
%   floor_idx      which floor to check
%   agent_idx      which agent on that floor
%   agent_new_pos  vector: [x,y], desired agent position to check
%
% return:
%   0            for no intersection
%   1            has an intersection with wall
%   2            with another agent

val = 0;

p = data.floor(floor_idx).agents(agent_idx).p;
r = data.floor(floor_idx).agents(agent_idx).r;
%
% check for agent intersection
for i=1:length(data.floor(floor_idx).agents)
    if i~=agent_idx

```

```

24     if norm(data.floor(floor_idx).agents(i).p-p)*data.meter_per_pixel
25         ...
26             <= r + data.floor(floor_idx).agents(i).r
27             val=2;
28             return;
29         end
30     end
31
32 % check for wall intersection
33 if lerp2(data.floor(floor_idx).img_wall_dist, p(1), p(2)) < r
34     val = 1;
35 end

```

Listing 5: checkForIntersection.m

```

1 mex 'fastSweeping.c'
2 mex 'getNormalizedGradient.c'
3 mex 'lerp2.c'
4 mex 'createRangeTree.c'
5 mex 'rangeQuery.c'

```

Listing 6: compileC.m

```

1 function data = initAgents(data)
2
3 % place agents randomly in desired spots, without overlapping
4
5
6
7 function radius = getAgentRadius()
8     %radius of an agent in meters
9     radius = data.r_min + (data.r_max-data.r_min)*rand();
10    end
11
12    data.agents_exited = 0; %how many agents have reached the exit
13    data.total_agent_count = 0;
14
15    floors_with_agents = 0;
16    agent_count = data.agents_per_floor;
17    for i=1:data.floor_count
18        data.floor(i).agents = [];
19        [y,x] = find(data.floor(i).img_spawn);
20
21        if ~isempty(x)
22            floors_with_agents = floors_with_agents + 1;
23            for j=1:agent_count
24                cur_agent = length(data.floor(i).agents) + 1;
25

```

```

27     % init agent
28     data.floor(i).agents(cur_agent).r = getAgentRadius();
29     data.floor(i).agents(cur_agent).v = [0, 0];
30     data.floor(i).agents(cur_agent).f = [0, 0];
31     data.floor(i).agents(cur_agent).m = data.m;
32     data.floor(i).agents(cur_agent).v0 = data.v0;
33     data.floor(i).agents(cur_agent).clogged = 0; %to check if
34         agent is hanging in the wall
35
36     tries = 10;
37     while tries > 0
38         % randomly pick a spot and check if it's free
39         idx = randi(length(x));
40         data.floor(i).agents(cur_agent).p = [y(idx), x(idx)];
41         if checkForIntersection(data, i, cur_agent) == 0
42             tries = -1; % leave the loop
43         end
44         tries = tries - 1;
45     end
46     if tries > -1
47         %remove the last agent
48         data.floor(i).agents = data.floor(i).agents(1:end-1);
49     end
50
51     data.total_agent_count = data.total_agent_count +
52         length(data.floor(i).agents);
53
54     if length(data.floor(i).agents) ~= agent_count
55         fprintf(['WARNING: could only place %d agents on floor %d , ...
56                 instead of the desired %d.\n'], ...
57                 length(data.floor(i).agents), i, agent_count);
58     end
59 end
60 if floors_with_agents==0
61     error('no spots to place agents!');
62 end
63

```

Listing 7: initAgents.m

```

function data = initEscapeRoutes(data)
%INITESCAPEROUTES Summary of this function goes here
% Detailed explanation goes here
for i=1:data.floor_count
    boundary_data = zeros(size(data.floor(i).img_wall));
    boundary_data(data.floor(i).img_wall) = 1;

```

```

10 if i<data.floor_exit
    boundary_data(data.floor(i).img_stairs_up) = -1;
12
13 elseif i>data.floor_exit
    boundary_data(data.floor(i).img_stairs_down) = -1;
14
15 else
    boundary_data(data.floor(i).img_exit) = -1;
16
17 end
18
19 exit_dist = fastSweeping(boundary_data) * data.meter_per_pixel;
20 [data.floor(i).img_dir_x, data.floor(i).img_dir_y] = ...
21     getNormalizedGradient(boundary_data, -exit_dist);
22
23 end

```

Listing 8: initEscapeRoutes.m

```

function data = initialize(config)
% initialize the internal data from the config data
%
4 % arguments:
%   config      data structure from loadConfig()
6 %
% return:
8 %   data      data structure: all internal data used for the main loop
%
10 %           all internal data is stored in pixels NOT in meters

12
13 data = config;
14
15 %for convenience
16 data.pixel_per_meter = 1/data.meter_per_pixel;

18 fprintf('Init escape routes...\n');
19 data = initEscapeRoutes(data);
20 fprintf('Init wall forces...\n');
21 data = initWallForces(data);
22 fprintf('Init agents...\n');
23 data = initAgents(data);
24
25 % maximum influence of agents on each other
26
27 data.r_influence = data.pixel_per_meter * ...
28     fzero(@(r) data.A * exp((2*data.r_max-r)/data.B) - 1e-4, data.r_max);

30 fprintf('Init plots...\n');
31 %init the plots
32 %exit plot

```

```

    data.figure_exit=figure;
34 hold on;
axis([0 data.duration 0 data.total_agent_count]);
36 title(sprintf('agents that reached the exit (total agents: %i)', data.total_agent_count));

38 % floors plot
    data.figure_floors=figure;
40 % figure('units','normalized','outerposition',[0 0 1 1])
    data.figure_floors_subplots_w = data.floor_count;
42 data.figure_floors_subplots_h = 4;
    for i=1:config.floor_count
        data.floor(i).agents_on_floor_plot =
            subplot(data.figure_floors_subplots_h,
                    data.figure_floors_subplots_w, 3*data.floor_count - i+1 +
                    data.figure_floors_subplots_w);
        if i == config.floor_exit - 1
            data.floor(i).building_plot =
                subplot(data.figure_floors_subplots_h,
                        data.figure_floors_subplots_w,
                        [(2*config.floor_count+1):3*config.floor_count]);
        elseif i == config.floor_exit
            data.floor(i).building_plot =
                subplot(data.figure_floors_subplots_h,
                        data.figure_floors_subplots_w,
                        [(config.floor_count+1):2*config.floor_count]);
        elseif i == config.floor_exit + 1
            data.floor(i).building_plot =
                subplot(data.figure_floors_subplots_h,
                        data.figure_floors_subplots_w, [1:config.floor_count]);
        end
52 end

54 % init output matrizes
    data.output = struct;
56 data.output.config = config;
    data.output.agents_per_floor =
        ones(data.floor_count,data.duration/data.dt).*(-1);
58 data.output.exit_left = zeros(data.exit_count,data.duration/data.dt);

60 % prepare output file name
    data.output_file_name = ['output_' data.frame_basename];
62 % prepare video file name
64 data.video_file_name = ['video_' data.frame_basename '.avi'];

66 % set deleted_agents to zero
    data.output.deleted_agents = 0;

```

Listing 9: initialize.m

```

1 function data = initWallForces(data)
2 %INITWALLFORCES init wall distance maps and gradient maps for each floor
3
4 for i=1:data.floor_count
5
6     % init boundary data for fast sweeping method
7     boundary_data = zeros(size(data.floor(i).img_wall));
8     boundary_data(data.floor(i).img_wall) = -1;
9
10    % get wall distance
11    wall_dist = fastSweeping(boundary_data) * data.meter_per_pixel;
12    data.floor(i).img_wall_dist = wall_dist;
13
14    % get normalized wall distance gradient
15    [data.floor(i).img_wall_dist_grad_x, ...
16     data.floor(i).img_wall_dist_grad_y] = ...
17     getNormalizedGradient(boundary_data, wall_dist-data.meter_per_pixel);
18 end

```

Listing 10: initWallForces.m

```

1 function config = loadConfig(config_file)
2 % load the configuration file
3 %
4 % arguments:
5 % config_file      string, which configuration file to load
6 %
7
8 % get the path from the config file -> to read the images
9 config_path = fileparts(config_file);
10 if strcmp(config_path, '') == 1
11     config_path = '.';
12 end
13
14 fid = fopen(config_file);
15 input = textscan(fid, '%s=%s');
16 fclose(fid);
17
18 keynames = input{1};
19 values = input{2};
20
21 %convert numerical values from string to double
22 v = str2double(values);
23 idx = ~isnan(v);
24 values(idx) = num2cell(v(idx));
25
26 config = cell2struct(values, keynames);
27
28
29

```

```

% read the images
31 for i=1:config.floor_count

33     %building structure
34     file = config.(sprintf('floor_%d_build', i));
35     file_name = [config_path '/' file];
36     img_build = imread(file_name);

37     % decode images
38     config.floor(i).img_wall = (img_build(:, :, 1) == 0 ...
39                                 & img_build(:, :, 2) == 0 ...
40                                 & img_build(:, :, 3) == 0);

43     config.floor(i).img_spawn = (img_build(:, :, 1) == 255 ...
44                                 & img_build(:, :, 2) == 0 ...
45                                 & img_build(:, :, 3) == 255);

47 %second possibility:
48 %pixel is exit if 1-->0, 3-->0, and if 2 is between 255 and 230 or if no
49 %red or blue

51     config.floor(i).img_exit = (img_build(:, :, 1) == 0 ...
52                                 & img_build(:, :, 2) ~= 0 ...
53                                 & img_build(:, :, 3) == 0);

55     config.floor(i).img_stairs_up = (img_build(:, :, 1) == 255 ...
56                                     & img_build(:, :, 2) == 0 ...
57                                     & img_build(:, :, 3) == 0);

59     config.floor(i).img_stairs_down = (img_build(:, :, 1) == 0 ...
60                                     & img_build(:, :, 2) == 0 ...
61                                     & img_build(:, :, 3) == 255);

63

65     if i == config.floor_exit

67         %make the exit_nr matrix where the number of exit is indicated in
68         %each
69         %pixel

71         %make a zeroes matrix as big as img_exit
72         config.exit_nr=zeros(size(config.floor(config.floor_exit).img_exit));

73         %make a zeros vector as long as floor_exit
74         config.exit_left = zeros(1,config.exit_count);

75         %loop over all exits
76         for e=1:config.exit_count

```

```

79         %build the exit_nr matrix
80     config.exit_nr = config.exit_nr + e*( img_build(:, :, 1) == 0
81         & img_build(:, :, 2) == (256-e) & img_build(:, :, 3) == 0 )
82         ;
83
84         %build the exit_left matrix
85     config.exit_left(1,e) = config.(sprintf('exit_%d_nr', e));
86
87     end
88
89     %init the plot image here, because this won't change
90     config.floor(i).img_plot = 5*config.floor(i).img_wall ...
91         + 4*config.floor(i).img_stairs_up ...
92         + 3*config.floor(i).img_stairs_down ...
93         + 2*config.floor(i).img_exit ...
94         + 1*config.floor(i).img_spawn;
95     config.color_map = [1 1 1; 0.9 0.9 0.9; 0 1 0; 0.4 0.4 1; 1 0.4 0.4; 0
96         0 0];
97 end

```

Listing 11: loadConfig.m

```

function plotAgentsPerFloor(data, floor_idx)
%plot time vs agents on floor

h = subplot(data.floor(floor_idx).agents_on_floor_plot);

set(h, 'position', [0.05+(data.floor_count -
    floor_idx)/(data.figure_floors_subplots_w+0.2), ...
    0.05, 1/(data.figure_floors_subplots_w*1.2), 0.3-0.05 ]);

if floor_idx~=data.floor_count
    set(h, 'ytick', []) %hide y-axis label
end

axis([0 data.time+data.dt 0 data.agents_per_floor*2]);
%axis([0 data.duration 0 data.agents_per_floor*2]);

hold on;
plot(data.time, length(data.floor(floor_idx).agents), 'b-');
hold off;

title(sprintf('%i', floor_idx));

```

Listing 12: plotAgentsPerFloor.m

```

function plotExitedAgents(data)
%plot time vs exited agents

```

```

4 hold on;
plot(data.time, data.agents_exited, 'r-');
6 hold off;

```

Listing 13: plotExitedAgents.m

```

function plotFloor(data, floor_idx)
2
if floor_idx == data.floor_exit-1 || floor_idx == data.floor_exit ||
   floor_idx == data.floor_exit+1
4 h=subplot(data.floor(floor_idx).building_plot);
6 set(h,
      'position',[0,0.35+0.65/3*(floor_idx-data.floor_exit+1),1,0.65/3-0.005]);
8 hold off;
% the building image
10 imagesc(data.floor(floor_idx).img_plot);
hold on;
12
%plot options
14 colormap(data.color_map);
axis equal;
16 axis manual; %do not change axis on window resize
18 set(h, 'Visible', 'off')
% title(sprintf('floor %i', floor_idx))
20
% plot agents
22 if ~isempty(data.floor(floor_idx).agents)
    ang = [linspace(0,2*pi, 10) nan];
24    rmul = [cos(ang) sin(ang)] * data.pixel_per_meter;
    draw = cell2mat(arrayfun(@(a) repmat(a.p,length(ang),1) + a.r*rmul, ...
26        data.floor(floor_idx).agents, 'UniformOutput', false));
    line(draw(:,2), draw(:,1), 'Color', 'r');
28 end
30 hold off;
end
32 end

```

Listing 14: plotFloor.m

```

% post processing of output.mat data from simulation
2 % to run, you need to load the output first:
% load('output_FILENAME');
4
% tabula rasa
6 clc

```

```

8 % read in data from output
agents_per_floor = output.agents_per_floor;
10 config = output.config;
exit_left = output.exit_left;
12 simulation_time_real = output.simulation_time;
dt = config.dt;
14 deleted_agents = output.deleted_agents;

16
% get users screen size
18 screenSize = get(0, 'ScreenSize');

20 % agents on boat
agents_on_boat = sum(agents_per_floor(:,1:1:length(agents_per_floor)));
22
% check if whole simulation was performed
24 steps=config.duration/dt-1;
for i=1:steps
26    if agents_on_boat(i)<0
        steps=i-2;
        break
    end
30 end

32 simulation_time_sim = steps*dt;

34 % recalculate agents on boat
agents_on_boat = sum(agents_per_floor(:,1:1:steps));
36 agents_start = agents_on_boat(1);
agents_left = agents_start-agents_on_boat;
38
% find out t10, t50, t90, t100
40 t10=0;
for i=1:steps
42    if agents_left(i)<agents_start/10
        t10=t10+dt;
    end
44 end
46 if t10~=0
    t10=t10+dt;
48 end

50 t50=0;
for i=1:steps
52    if agents_left(i)<agents_start/2
        t50=t50+dt;
    end
54 end
56 if t50~=0

```

```

        t50=t50+dt;
58 end

60 t90=0;
for i=1:steps
    if agents_left(i)<agents_start*0.9
        t90=t90+dt;
    end
end
66 if t90~=0
    t90=t90+dt;
68 end

70 t95=0;
for i=1:steps
    if agents_left(i)<agents_start*0.95
        t95=t95+dt;
    end
end
76 if t95~=0
    t95=t95+dt;
78 end

80 t100=0;
if agents_left==agents_start
    for i=1:steps
        if agents_left(i)<agents_start
            t100=t100+dt;
        end
    end
end
88
% create time axis
90 if t100~=0
    time = [0:dt:t100];
92 else
    time = [0:dt:simulation_time_sim];
94 end
steps = length(time);
96
% recalculate agents on boat
98 agents_on_boat = sum(agents_per_floor(:,1:1:steps));
agents_start = agents_on_boat(1);
100 agents_left = agents_start-agents_on_boat;
agents_per_floor = agents_per_floor(:,1:1:steps);
102 exit_left = exit_left(:,1:1:steps);

104 % plot agents left over time
f1 = figure;
106 hold on

```

```

grid on
108 set(gca,'XTick',[1:1:8], 'FontSize',16)
109 plot(time/60,agents_left/agents_start*100, 'LineWidth', 2)
110 axis([0 8 0 100])
111 title(sprintf('rescued agents (of total %i agents)',agents_start));
112 xlabel('time [min]')
113 ylabel('rescued agents out of all agents [%]')
114
115 % plot agents_per_floor over time
116 f2 = figure;
117 hold on
118 grid on
119 set(gca,'XTick',[1:1:8], 'FontSize',16)
120 list = cell(config.floor_count,1);
121 color = hsv(config.floor_count);
122 color(config.floor_exit,:)= [0 0 0];
123 for i=1:config.floor_count
124     plot(time/60,agents_per_floor(i,:), 'LineWidth', 2, 'color',color(i,:))
125     list{i} = [sprintf('floor %i',i)];
126 end
127 legend(list)
128
129 axis([0 8 0 800])
130 title(sprintf('agents per floor (of total %i agents)',agents_start));
131 xlabel('time [min]')
132 ylabel('agents per floor')
133
134 % plot free places in rescue boats over time
135 f3 = figure;
136 hold on
137 grid on
138 set(gca,'XTick',[1:1:8], 'FontSize',16)
139 list = cell(config.exit_count/2,1);
140 color = hsv(config.exit_count/2);
141 for i=1:config.exit_count/2
142     plot(time/60,exit_left(i,:), 'LineWidth', 2, 'color',color(i,:))
143     list{i} = [sprintf('boat %i / --- %i',i,i+13)];
144 end
145 for i=config.exit_count/2+1:config.exit_count
146     plot(time/60,exit_left(i,:), '--', 'LineWidth',
147           2, 'color',color(i-config.exit_count/2,:))
148 end
149 legend(list)
150
151 axis([0 8 0 200])
152 title('rescue boat capacity');
153 xlabel('time [min]')
154 ylabel('free places on rescue boat')
155
156 % scale plots up to screen size

```

```

156 set(f1, 'Position', [0 0 screen_size(3) screen_size(4)] );
157 set(f2, 'Position', [0 0 screen_size(3) screen_size(4)] );
158 set(f3, 'Position', [0 0 screen_size(3) screen_size(4)] );

160
% print out
162 fprintf('Timestep: %f s\n', dt)
163 fprintf('Steps simulated: %i\n', steps)
164 fprintf('Simulation time: %f min\n', simulation_time_sim/60)
165 fprintf('Agents on ship on start: %i\n', agents_start)
166 fprintf('Agents on ship on simulation end: %i\n', agents_on_boat(end))
167 fprintf('Agents deleted due to NaN-positions: %i\n', deleted_agents)

168 fprintf('t_10: %f\n', t10)
169 fprintf('t_50: %f\n', t50)
170 fprintf('t_90: %f\n', t90)
171 fprintf('t_95: %f\n', t95)
172 fprintf('t_100: %f\n', t100)

```

Listing 15: plotFloor.m

```

1 function simulate(config_file)
% run this to start the simulation
3
% start recording the matlab output window for debugging reasons
5 diary log

7 if nargin==0
    config_file='../../data/config1.conf';
9 end

11 fprintf('Load config file...\n');
config = loadConfig(config_file);
13
data = initialize(config);

15
data.step = 1;
16 data.time = 0;
17 fprintf('Start simulation...\n');

19
% tic until simulation end
20 simstart = tic;

22 %make video while simulation
23 if data.save_frames==1
    vidObj=VideoWriter(data.video_file_name);
    open(vidObj);
24
end

```

```

29 while (data.time < data.duration)
    % tic until timestep end
31     tstart=tic;
32     data = addDesiredForce(data);
33     data = addWallForce(data);
34     data = addAgentRepulsiveForce(data);
35     data = applyForcesAndMove(data);

37     % dump agents_per_floor to output
38     for floor=1:data.floor_count
39         data.output.agents_per_floor(floor,data.step) =
40             length(data.floor(floor).agents);
41     end

42     % dump exit_left to output
43     data.output.exit_left(:,data.step) = data.exit_left';

44     if mod(data.step,data.save_step) == 0

45         % do the plotting
46         set(0,'CurrentFigure',data.figure_floors);
47         for floor=1:data.floor_count
48             plotAgentsPerFloor(data, floor);
49             plotFloor(data, floor);
50         end

51         if data.save_frames==1
52             print('-depsc2',sprintf('frames/%s_%04i.eps', ...
53             data.frame_basename,data.step), data.figure_floors);
54
55             % make video while simulate
56             currFrame=getframe(data.figure_floors);
57             writeVideo(vidObj,currFrame);
58
59         end

60     end

61     set(0,'CurrentFigure',data.figure_exit);
62     plotExitedAgents(data);

63     if data.agents_exited == data.total_agent_count
64         fprintf('All agents are now saved (or are they?). Time: %.2f
65             sec\n', data.time);
66         fprintf('Total Agents: %i\n', data.total_agent_count);

67         print('-depsc2',sprintf('frames/exited_agents_%s.eps', ...
68             data.frame_basename), data.figure_floors);
69         break;
70     end

71     % toc of timestep

```

```

77     data.telapsed = toc(tstart);
    % toc of whole simulation
79     data.output.simulation_time = toc(simstart);

81     % save output
82     output = data.output;
83     save(data.output_file_name,'output')
84     fprintf('Frame %i done (took %.3fs; %.3fs out of %.3gs
85             simulated).\n', data.step, data.telapsed, data.time,
86             data.duration);

87 end

88 % update step
89 data.step = data.step+1;

90 % update time
91 if (data.time + data.dt > data.duration)
92     data.dt = data.duration - data.time;
93     data.time = data.duration;
94 else
95     data.time = data.time + data.dt;
96 end

97 end

98 %make video while simulation
99 close(vidObj);

100 % toc of whole simulation
101 data.output.simulation_time = toc(simstart);

102 % save complete simulation
103 output = data.output;
104 save('output','output')
105 fprintf('Simulation done in %i seconds and saved data to output file.\n',
106         data.output.simulation_time);

107 % save diary
108 diary
109
```

Listing 16: simulate.m

9.1.2 C code

```

1 #include <mex.h>
3 #include <string.h>
```

```

5 #include "tree_build.c"
6 #include "tree_query.c"
7 #include "tree_free.c"

9 void mexFunction(int nlhs, mxArray *plhs[], int nrhs, const mxArray
    *prhs[])
{
11     point_t *points;
12     tree_t *tree;
13     int m, n;
14     uchar *data;
15     int *root_index;

17     if (nlhs < 1)
18         return;
19
20     points = (point_t*) mxGetPr(prhs[0]);
21     m = mxGetM(prhs[0]);
22     n = mxGetN(prhs[0]);
23
24     if (m != 2)
25         mexErrMsgTxt("...");

27     tree = build_tree(points, n);

29     plhs[0] = mxCreateNumericMatrix(tree->first_free + sizeof(int), 1,
30         mxUINT8_CLASS, mxREAL);
31     data = (uchar*) mxGetPr(plhs[0]);
32
33     root_index = (int*) data;
34     *root_index = tree->root_index;
35     memcpy(data + sizeof(int), tree->data, tree->first_free);
36
37     free_tree(tree);
}

```

Listing 17: createRangeTree.c

```

1 #include "mex.h"

3 #include <math.h>

5 #if defined __GNUC__ && defined __FAST_MATH__ && !defined __STRICT_ANSI__
#define MIN(i, j) fmin(i, j)
7 #define MAX(i, j) fmax(i, j)
#define ABS(i)      fabs(i)
9 #else
#define MIN(i, j) ((i) < (j) ? (i) : (j))
#define MAX(i, j) ((i) > (j) ? (i) : (j))
#define ABS(i)      ((i) < 0.0 ? -(i) : (i))
11

```

```

13 #endif

15
16 #define SOLVE_AND_UPDATE    udiff = uxmin - uymmin; \
17     if (ABS(udiff) >= 1.0) \
18     { \
19         up = MIN(uxmin, uymmin) + 1.0; \
20     } \
21     else \
22     { \
23         up = (uxmin + uymmin + sqrt(2.0 - udiff * \
24             udiff)) / 2.0; \
25         up = MIN(uij, up); \
26     } \
27     err_loc = MAX(ABS(uij - up), err_loc); \
28     u[ij] = up;

29 #define I_STEP(_uxmin, _uymmin, _st) if (boundary[ij] == 0.0) \
30     { \
31         uij = un; \
32         un = u[ij + _st]; \
33         uxmin = _uxmin; \
34         uymmin = _uymmin; \
35         SOLVE_AND_UPDATE \
36         ij += _st; \
37     } \
38     else \
39     { \
40         up = un; \
41         un = u[ij + _st]; \
42         ij += _st; \
43     }
44
45
46
47 #define I_STEP_UP(_uxmin, _uymmin)    I_STEP(_uxmin, _uymmin, 1)
48 #define I_STEP_DOWN(_uxmin, _uymmin)   I_STEP(_uxmin, _uymmin, -1)

50 #define UX_NEXT un
51 #define UX_PREV up
52 #define UX_BOTH MIN(UX_PREV, UX_NEXT)

54 #define UY_RIGHT u[ij + m]
55 #define UY_LEFT u[ij - m]
56 #define UY_BOTH MIN(UY_LEFT, UY_RIGHT)

58
59

```

```

61 static void iteration(double *u, double *boundary, int m, int n, double
62   *err)
63 {
64     int i, j, ij;
65     int m2, n2;
66     double up, un, uij, uxmin, uymin, udifff, err_loc;
67
68     m2 = m - 2;
69     n2 = n - 2;
70
71     *err = 0.0;
72     err_loc = 0.0;
73
74     /* first sweep */
75     /* i = 0, j = 0 */
76     ij = 0;
77     un = u[ij];
78     I_STEP_UP(UX_NEXT, UY_RIGHT)
79
80     /* i = 1->m2, j = 0 */
81     for (i = 1; i <= m2; ++i)
82         I_STEP_UP(UX_BOTH, UY_RIGHT)
83
84     /* i = m-1, j = 0 */
85     I_STEP_UP(UX_PREV, UY_RIGHT)
86
87     /* i = 0->m-1, j = 1->n2 */
88     for (j = 1; j <= n2; ++j)
89     {
90         I_STEP_UP(UX_NEXT, UY_BOTH)
91
92         for (i = 1; i <= m2; ++i)
93             I_STEP_UP(UX_BOTH, UY_BOTH)
94
95         I_STEP_UP(UX_PREV, UY_BOTH)
96     }
97
98     /* i = 0, j = n-1 */
99     I_STEP_UP(UX_NEXT, UY_LEFT)
100
101    /* i = 1->m2, j = n-1 */
102    for (i = 1; i <= m2; ++i)
103        I_STEP_UP(UX_BOTH, UY_LEFT)
104
105    /* i = m-1, j = n-1 */
106    I_STEP_UP(UX_PREV, UY_LEFT)
107
108    /* sweep 2 */
109    /* i = 0, j = n-1 */

```

```

    ij = (n-1)*m;
111   un = u[ij];
    I_STEP_UP(UX_NEXT, UY_LEFT)

113
/* i = 1->m2, j = n-1 */
115   for (i = 1; i <= m2; ++i)
      I_STEP_UP(UX_BOTH, UY_LEFT)

117
/* i = m-1, j = n-1 */
119   I_STEP_UP(UX_PREV, UY_LEFT)

121
/* i = 0->m-1, j = n2->1 */
122   for (j = n2; j >= 1; --j)
{
123     ij = j*m;
124     un = u[ij];
      I_STEP_UP(UX_NEXT, UY_BOTH)

127
      for (i = 1; i <= m2; ++i)
        I_STEP_UP(UX_BOTH, UY_BOTH)

131
      I_STEP_UP(UX_PREV, UY_BOTH)
}

133
/* i = 0, j = 0 */
134   ij = 0;
135   un = u[ij];
    I_STEP_UP(UX_NEXT, UY_RIGHT)

139
/* i = 1->m2, j = 0 */
140   for (i = 1; i <= m2; ++i)
      I_STEP_UP(UX_BOTH, UY_RIGHT)

143
/* i = m-1, j = 0 */
144   I_STEP_UP(UX_PREV, UY_RIGHT)

145
/* sweep 3 */
146
/* i = m-1, j = n-1 */
147   ij = m*n - 1;
148   un = u[ij];
    I_STEP_DOWN(UX_NEXT, UY_LEFT)

151
/* i = m2->1, j = n-1 */
152   for (i = m2; i >= 1; --i)
      I_STEP_DOWN(UX_BOTH, UY_LEFT)

155
/* i = 0, j = n-1 */
156   I_STEP_DOWN(UX_PREV, UY_LEFT)

159
/* i = m-1->0, j = n2->1 */

```

```

161     for (j = n2; j >= 1; --j)
162     {
163         I_STEP_DOWN(UX_NEXT, UY_BOTH)
164
165         for (i = m2; i >= 1; --i)
166             I_STEP_DOWN(UX_BOTH, UY_BOTH)
167
168             I_STEP_DOWN(UX_PREV, UY_BOTH)
169         }
170
171         /* i = m-1, j = 0 */
172         I_STEP_DOWN(UX_NEXT, UY_RIGHT)
173
174         /* i = m2->1, j = 0 */
175         for (i = m2; i >= 1; --i)
176             I_STEP_DOWN(UX_BOTH, UY_RIGHT)
177
178         /* i = 0, j = 0 */
179         I_STEP_DOWN(UX_PREV, UY_RIGHT)
180
181         /* sweep 4 */
182         /* i = m-1, j = 0 */
183         ij = m - 1;
184         un = u[ij];
185         I_STEP_DOWN(UX_NEXT, UY_RIGHT)
186
187         /* i = m2->1, j = 0 */
188         for (i = m2; i >= 1; --i)
189             I_STEP_DOWN(UX_BOTH, UY_RIGHT)
190
191         /* i = 0, j = 0 */
192         I_STEP_DOWN(UX_PREV, UY_RIGHT)
193
194         /* i = m-1->0, j = 1->n2 */
195         for (j = 1; j <= n2; ++j)
196         {
197             ij = m - 1 + j*m;
198             un = u[ij];
199             I_STEP_DOWN(UX_NEXT, UY_BOTH)
200
201             for (i = m2; i >= 1; --i)
202                 I_STEP_DOWN(UX_BOTH, UY_BOTH)
203
204             I_STEP_DOWN(UX_PREV, UY_BOTH)
205         }
206
207         /* i = m-1, j = n-1 */
208         ij = m*n - 1;
209         un = u[ij];
210         I_STEP_DOWN(UX_NEXT, UY_LEFT)

```

```

211 /* i = m2->1, j = n-1 */
212 for (i = m2; i >= 1; --i)
213     I_STEP_DOWN(UX_BOTH, UY_LEFT)

215 /* i = 0, j = n-1 */
216 I_STEP_DOWN(UX_PREV, UY_LEFT)

217 *err = MAX(*err, err_loc);
218 }

221 void mexFunction(int nlhs, mxArray *plhs[], int nrhs, const mxArray
222 *prhs[])
223 {
224     double *u, *boundary;
225     double tol, err;
226     int m, n, entries, max_iter, i;

227     /* Check number of outputs */
228     if (nlhs < 1)
229         return;
230     else if (nlhs > 1)
231         mexErrMsgTxt("At most 1 output argument needed.");

233     /* Get inputs */
234     if (nrhs < 1)
235         mexErrMsgTxt("At least 1 input argument needed.");
236     else if (nrhs > 3)
237         mexErrMsgTxt("At most 3 input arguments used.");
238

241     /* Get boundary */
242     if (!mxIsDouble(prhs[0]) || mxIsClass(prhs[0], "sparse"))
243         mexErrMsgTxt("Boundary field needs to be a full double precision
244 matrix.");

245     boundary = mxGetPr(prhs[0]);
246     m = mxGetM(prhs[0]);
247     n = mxGetN(prhs[0]);
248     entries = m * n;

249     /* Get max iterations */
250     if (nrhs >= 2)
251     {
252         if (!mxIsDouble(prhs[1]) || mxGetM(prhs[1]) != 1 ||
253             mxGetN(prhs[1]) != 1)
254             mexErrMsgTxt("Maximum iteration needs to be positive
255 integer.");
256         max_iter = (int) *mxGetPr(prhs[1]);
257     }

```

```

257     if (max_iter <= 0)
258         mexErrMsgTxt("Maximum iteration needs to be positive
259                     integer.");
260     }
261     else
262         max_iter = 20;
263
264     /* Get tolerance */
265     if (nrhs >= 3)
266     {
267         if (!mxIsDouble(prhs[2]) || mxGetM(prhs[2]) != 1 ||
268             mxGetN(prhs[2]) != 1)
269             mexErrMsgTxt("Tolerance needs to be a positive real number.");
270         tol = *mxGetPr(prhs[2]);
271         if (tol < 0)
272             mexErrMsgTxt("Tolerance needs to be a positive real number.");
273     }
274     else
275         tol = 1e-12;
276
277
278     /* create and init output (distance) matrix */
279     plhs[0] = mxCreateDoubleMatrix(m, n, mxREAL);
280     u = mxGetPr(plhs[0]);
281
282     for (i = 0; i < entries; ++i)
283         u[i] = boundary[i] < 0.0 ? 0.0 : 1.0e10;
284
285     err = 0.0;
286     i = 0;
287     do
288     {
289         iteration(u, boundary, m, n, &err);
290         ++i;
291     } while (err > tol && i < max_iter);
292 }

```

Listing 18: fastSweeping.c

```

1 #include "mex.h"
2
3 #include <math.h>
4
5 #define INTERIOR(i, j)  (boundary[(i) + m*(j)] == 0)
6
7 #define DIST(i, j)    dist[(i) + m*(j)]
8 #define XGRAD(i, j)   xgrad[(i) + m*(j)]
9 #define YGRAD(i, j)   ygrad[(i) + m*(j)]

```

```

11 void mexFunction(int nlhs, mxArray *plhs[], int nrhs, const mxArray
*prhs[])
{
13     double *xgrad, *ygrad, *boundary, *dist;
14     double dxp, dxm, dyp, dyM, xns, yns, nrm;
15     int m, n, i, j, nn;

17     /* Check number of outputs */
18     if (nlhs < 2)
19         mexErrMsgTxt("At least 2 output argument needed.");
20     else if (nlhs > 2)
21         mexErrMsgTxt("At most 2 output argument needed.");

23     /* Get inputs */
24     if (nrhs < 2)
25         mexErrMsgTxt("At least 2 input argument needed.");
26     else if (nrhs > 2)
27         mexErrMsgTxt("At most 2 input argument used.");
28

29

31     /* Get boundary */
32     if (!mxIsDouble(prhs[0]) || mxIsClass(prhs[0], "sparse"))
33         mexErrMsgTxt("Boundary field needs to be a full double precision
matrix.");
34

35     boundary = mxGetPr(prhs[0]);
36     m = mxGetM(prhs[0]);
37     n = mxGetN(prhs[0]);

39     /* Get distance field */
40     if (!mxIsDouble(prhs[1]) || mxIsClass(prhs[1], "sparse") ||
41         mxGetM(prhs[1]) != m || mxGetN(prhs[1]) != n)
42         mexErrMsgTxt("Distance field needs to be a full double precision
matrix with same dimension as the boundary.");
43

44     dist = mxGetPr(prhs[1]);
45     m = mxGetM(prhs[1]);
46     n = mxGetN(prhs[1]);

47     /* create and init output (gradient) matrices */
48     plhs[0] = mxCreateDoubleMatrix(m, n, mxREAL);
49     plhs[1] = mxCreateDoubleMatrix(m, n, mxREAL);
50     xgrad = mxGetPr(plhs[0]);
51     ygrad = mxGetPr(plhs[1]);
52

53

55     for (j = 0; j < n; ++j)
56         for (i = 0; i < m; ++i)

```

```

57         if (INTERIOR(i,j))
58     {
59         if (i > 0)
60             dxm = INTERIOR(i-1,j) ? DIST(i-1,j) : DIST(i,j);
61         else
62             dxm = DIST(i,j);
63
64         if (i < m-1)
65             dxp = INTERIOR(i+1,j) ? DIST(i+1,j) : DIST(i,j);
66         else
67             dxp = DIST(i,j);
68
69         if (j > 0)
70             dyd = INTERIOR(i,j-1) ? DIST(i,j-1) : DIST(i,j);
71         else
72             dyd = DIST(i,j);
73
74         if (j < n-1)
75             dyp = INTERIOR(i,j+1) ? DIST(i,j+1) : DIST(i,j);
76         else
77             dyp = DIST(i,j);
78
79         XGRAD(i, j) = (dxm - dyp) / 2.0;
80         YGRAD(i, j) = (dyd - dyp) / 2.0;
81         nrm = sqrt(XGRAD(i, j)*XGRAD(i, j) + YGRAD(i, j)*YGRAD(i,
82                         j));
83         if (nrm > 1e-12)
84         {
85             XGRAD(i, j) /= nrm;
86             YGRAD(i, j) /= nrm;
87         }
88     else
89     {
90         XGRAD(i, j) = 0.0;
91         YGRAD(i, j) = 0.0;
92     }
93
94     for (j = 0; j < n; ++j)
95         for (i = 0; i < m; ++i)
96             if (!INTERIOR(i, j))
97             {
98                 xns = 0.0;
99                 yns = 0.0;
100                nn = 0;
101                if (i > 0 && INTERIOR(i-1,j))
102                {
103                    xns += XGRAD(i-1,j);
104                    yns += YGRAD(i-1,j);
105                    ++nn;

```

```

107         }
108     if (i < m-1 && INTERIOR(i+1,j))
109     {
110         xns += XGRAD(i+1,j);
111         yns += YGRAD(i+1,j);
112         ++nn;
113     }
114     if (j > 0 && INTERIOR(i,j-1))
115     {
116         xns += XGRAD(i,j-1);
117         yns += YGRAD(i,j-1);
118         ++nn;
119     }
120     if (j < n-1 && INTERIOR(i,j+1))
121     {
122         xns += XGRAD(i,j+1);
123         yns += YGRAD(i,j+1);
124         ++nn;
125     }
126     if (nn > 0)
127     {
128         XGRAD(i, j) = xns / nn;
129         YGRAD(i, j) = yns / nn;
130     }
131 }

```

Listing 19: getNormalizedGradient.c

```

2 #include <mex.h>

4 void mexFunction(int nlhs, mxArray *plhs[], int nrhs, const mxArray
*prhs[])
{
6     int m, n, i0, i1, j0, j1, idx00;
7     double *data, *out, x, y, wx0, wy0, wx1, wy1;
8     double d00, d01, d10, d11;

10    if (nlhs < 1)
11        return;
12    else if (nlhs > 1)
13        mexErrMsgTxt("Exactly one output argument needed.");
14
15    if (nrhs != 3)
16        mexErrMsgTxt("Exactly three input arguments needed.");
17
18    m = mxGetM(prhs[0]);
19    n = mxGetN(prhs[0]);

```

```

20     data = mxGetPr(prhs[0]);
21     x = *mxGetPr(prhs[1]) - 1;
22     y = *mxGetPr(prhs[2]) - 1;
23
24     plhs[0] = mxCreateDoubleMatrix(1, 1, mxREAL);
25     out = mxGetPr(plhs[0]);
26
27     x = x < 0 ? 0 : x > m - 1 ? m - 1 : x;
28     y = y < 0 ? 0 : y > n - 1 ? n - 1 : y;
29     i0 = (int) x;
30     j0 = (int) y;
31     i1 = i0 + 1;
32     i1 = i1 > m - 1 ? m - 1 : i1;
33     j1 = j0 + 1;
34     j1 = j1 > n - 1 ? n - 1 : j1;
35
36     idx00 = i0 + m * j0;
37     d00 = data[idx00];
38     d01 = data[idx00 + m];
39     d10 = data[idx00 + 1];
40     d11 = data[idx00 + m + 1];
41
42     wx1 = x - i0;
43     wy1 = y - j0;
44     wx0 = 1.0 - wx1;
45     wy0 = 1.0 - wy1;
46
47     *out = wx0 * (wy0 * d00 + wy1 * d01) + wx1 * (wy0 * d10 + wy1 * d11);
48 }

```

Listing 20: lerp2.c

```

2 #include <mex.h>
3 #include <string.h>
4
5 #include "tree_build.c"
6 #include "tree_query.c"
7 #include "tree_free.c"
8
9 void mexFunction(int nlhs, mxArray *plhs[], int nrhs, const mxArray
10 *prhs[])
11 {
12     tree_t *tree;
13     int n, i;
14     int *point_idx, *root_idx;
15     range_t *range;
16     uchar *data;
17
18     if (nlhs != 1)
19 
```

```

18     mexErrMsgTxt("...");

20     if (nrhs < 5)
21         mexErrMsgTxt("...");
22     else if (nrhs > 5)
23         mexErrMsgTxt("...");

24     data = (uchar*) mxGetPr(prhs[0]);
25
26     tree = (tree_t*) malloc(sizeof(tree_t));
27     tree->first_free = mxGetM(prhs[0]) - sizeof(int);
28     tree->total_size = tree->first_free;
29     root_idx = (int*) data;
30     tree->root_index = *root_idx;
31     tree->data = data + sizeof(int);

32     n = mxGetN(prhs[0]);
33     if (n != 1)
34         mexErrMsgTxt("...");

35     range = range_query(tree, *mxGetPr(prhs[1]), *mxGetPr(prhs[2]),
36                          *mxGetPr(prhs[3]), *mxGetPr(prhs[4]));

37     plhs[0] = mxCreateNumericMatrix(range->n, 1, mxUINT32_CLASS, mxREAL);
38     point_idx = (int*) mxGetPr(plhs[0]);
39
40     for (i = 0; i < range->n; ++i)
41         point_idx[i] = range->point_idx[i] + 1;

42     free_range(range);
43     free(tree);
44 }

```

Listing 21: rangeQuery.c

```

1 #ifndef TREE_H
2 #define TREE_H
3
4 #include "tree_types.h"
5
6 /* build a 2D range tree using the given points */
7 tree_t* build_tree(point_t *points, int n);
8
9 /* query a range tree */
10 range_t* range_query(tree_t *tree, double x_min, double x_max, double
11                      y_min, double y_max);
12
13 /* free memory of a tree */
14 void free_tree(tree_t *tree);

```

```

16 /* free memory of a range */
17 void free_range(range_t *range);
18 #endif

```

Listing 22: tree.h

```

1 #ifndef TREE_BUILD_H
2 #define TREE_BUILD_H

4 #include "tree.h"

6 /* recursively build a subtree */
7 int build_subtree(tree_t *tree, double *x_vals, const int nx, point_t
8 *points, int *point_idx, const int np);
9
10 /* double comparison for qsort */
11 int compare_double(const void *a, const void *b);

12 /* index array sorting functions, sort point index array by point y
13   coordinates */
14 void index_sort_y(const point_t *points, int *point_idx, const int n);
15 void index_quicksort_y(const point_t *points, int *point_idx, int l, int
16 r);
17 int index_partition_y(const point_t *points, int *point_idx, int l, int r);
18
19 #endif

```

Listing 23: tree_build.h

```

1
2 #include <assert.h>
3 #include <stdio.h>
4 #include <stdlib.h>
5 #include <string.h>

7 #include "tree_build.h"

9 tree_t* build_tree(point_t *points, int n)
{
10     int nx, i, j, *point_idx;
11     double *x_vals;
12     tree_t *tree;

13     /* get x coordinate values of all points */
14     x_vals = (double*) malloc(n * sizeof(double));
15     for (i = 0; i < n; ++i)
16         x_vals[i] = points[i].x;
17
18     /* sort x values */
19

```

```

21     qsort(x_vals, n, sizeof(double), compare_double);

23     /* count number of unique x values */
24     nx = 1;
25     for (i = 1; i < n; ++i)
26         if (x_vals[i] != x_vals[i - 1])
27             ++nx;

29     /* remove duplicates */
30     j = 0;
31     for (i = 0; i < nx; ++i)
32     {
33         x_vals[i] = x_vals[j];
34         while (x_vals[i] == x_vals[j])
35             ++j;
36     }

37     /* create an index array */
38     point_idx = (int*) malloc(n * sizeof(int));
39     for (i = 0; i < n; ++i)
40         point_idx[i] = i;

43     /* sort index array by y coordinates of associated points */
44     index_sort_y(points, point_idx, n);

45     /* init tree */
46     tree = (tree_t*) malloc(sizeof(tree_t));
47     tree->total_size = n * sizeof(point_t);
48     tree->data = (uchar*) malloc(tree->total_size);

51     /* copy point coordinates to tree data */
52     memcpy(tree->data, points, n * sizeof(point_t));

53     /* set first free byte and root index of the tree */
54     tree->first_free = n * sizeof(point_t);
55     tree->root_index = tree->first_free;

57     /* recursively build tree */
58     build_subtree(tree, x_vals, nx, points, point_idx, n);

61     /* free temporaries */
62     free(x_vals);
63     return tree;
64 }

65

67 int build_subtree(tree_t *tree, double *x_vals, const int nx, point_t
68 *points, int *point_idx, const int np)
69 {
    int i, j, k, nx_left, np_left, node_size, right_idx;

```

```

    node_t *node;
71   int *node_point_idx, *point_idx_left, *point_idx_right, node_idx;
    uchar *new_data;

73   assert(nx > 0);
75   assert(np > 0);

77   /* allocate memory in the tree data structure */
    node_size = sizeof(node_t) + np * sizeof(int);
79   while (tree->first_free + node_size > tree->total_size)
{
81     tree->total_size <= 1;
82     new_data = (uchar*) malloc(tree->total_size * sizeof(uchar));
83     for (i = 0; i < tree->first_free; ++i)
84       new_data[i] = tree->data[i];
85     free(tree->data);
86     tree->data = new_data;
87   }
88   node_idx = tree->first_free;
89   node = (node_t*) &tree->data[node_idx];
90   tree->first_free += node_size;

91   /* set number of stored points */
92   node->np = np;
93   node_point_idx = (int*) (node + 1);

95   /* copy point indices to node */
96   memcpy(node_point_idx, point_idx, np * sizeof(int));

99   /* create child node if there is only one x value left, otherwise
100    create interior node */
101  if (nx == 1)
{
102    node->right_idx = -1;
103    node->x_val = x_vals[0];
104  }
105  else
{
106    /* get median of x values */
107    nx_left = nx >> 1;
108    node->x_val = x_vals[nx_left - 1];

109    /* count points belonging to the left child */
110    np_left = 0;
111    for (i = 0; i < np; ++i)
{
112      if (points[point_idx[i]].x <= node->x_val)
113        ++np_left;
114    }
115}
116}

```

```

119     /* allocate memory for children's index arrays */
120     point_idx_left = (int*) malloc(np_left * sizeof(int));
121     point_idx_right = (int*) malloc((np - np_left) * sizeof(int));
122
123     /* fill index arrays */
124     j = 0;
125     k = 0;
126     for (i = 0; i < np; ++i)
127     {
128         if (points[point_idx[i]].x <= node->x_val)
129             point_idx_left[j++] = point_idx[i];
130         else
131             point_idx_right[k++] = point_idx[i];
132     }
133
134     /* free current node's temporary index array */
135     free(point_idx);
136
137     /* build left subtree */
138     build_subtree(tree, x_vals, nx_left, points, point_idx_left,
139                   np_left);
140
141     /* build right subtree and get its root node index */
142     right_idx = build_subtree(tree, x_vals + nx_left, nx - nx_left,
143                               points, point_idx_right, np - np_left);
144     /* update node pointer (could have changed during build_subtree,
145      because of data allocation) */
146     node = (node_t*) &tree->data[node_idx];
147     /* update node's right child index */
148     node->right_idx = right_idx;
149 }
150
151 int compare_double(const void *a, const void *b)
152 {
153     double ad, bd;
154     ad = *((double*) a);
155     bd = *((double*) b);
156     return (ad < bd) ? -1 : (ad > bd) ? 1 : 0;
157 }
158
159 void index_sort_y(const point_t *points, int *point_idx, const int n)
160 {
161     index_quicksort_y(points, point_idx, 0, n - 1);
162 }
163
164 void index_quicksort_y(const point_t *points, int *point_idx, int l, int r)

```

```

{
167    int p;

169    /* quicksort point indices by point y coordinates, don't touch point
       array itself */
170    while (l < r)
171    {
172        p = index_partition_y(points, point_idx, l, r);
173        if (r - p > p - l)
174        {
175            index_quicksort_y(points, point_idx, l, p - 1);
176            l = p + 1;
177        }
178        else
179        {
180            index_quicksort_y(points, point_idx, p + 1, r);
181            r = p - 1;
182        }
183    }
184}
185
int index_partition_y(const point_t *points, int *point_idx, int l, int r)
186{
187    int i, j, tmp;
188    double pivot;

189    /* rightmost element is pivot */
190    i = l;
191    j = r - 1;
192    pivot = points[point_idx[r]].y;
193
194    /* quicksort partition */
195    do
196    {
197        while (points[point_idx[i]].y <= pivot && i < r)
198            ++i;
199
200        while (points[point_idx[j]].y >= pivot && j > l)
201            --j;
202
203        if (i < j)
204        {
205            tmp = point_idx[i];
206            point_idx[i] = point_idx[j];
207            point_idx[j] = tmp;
208        }
209    } while (i < j);

210    if (points[point_idx[i]].y > pivot)
211    {

```

```

215         tmp = point_idx[i];
216         point_idx[i] = point_idx[r];
217         point_idx[r] = tmp;
218     }
219
220     return i;
221 }
```

Listing 24: tree_build.c

```

1 #include <stdlib.h>
3
5 void free_tree(tree_t *tree)
7 {
8     free(tree->data);
9 }

11 void free_range(range_t *range)
12 {
13     free(range->point_idx);
14 }
```

Listing 25: tree_free.c

```

#ifndef TREE_QUERY_H
#define TREE_QUERY_H

#include "tree_types.h"

/* appends a point-index to a range, increases range capacity if needed */
void range_append(range_t *range, int idx);

/* finds the split node of a given query */
int find_split_node(tree_t *tree, int node_idx, range_t *range);

/* query the points of a node by a given range by y-coordinate */
void range_query_y(tree_t *tree, int node_idx, range_t *range);

#endif
```

Listing 26: tree_query.h

```

1 #include <assert.h>
3 #include <stdio.h>
# include <stdlib.h>
5
```

```

#include "tree_query.h"
7
#define LEFT_CHILD_IDX(node_idx, node) (node_idx) + sizeof(node_t) +
    (node)->np * sizeof(int)
9 #define RIGHT_CHILD_IDX(node_idx, node) (node)->right_idx
#define NODE_FROM_IDX(tree, node_idx) (node_t*) &(tree)->data[node_idx];
11
12 range_t* range_query(tree_t *tree, double x_min, double x_max, double
    y_min, double y_max)
13 {
14     int split_node_idx, node_idx;
15     node_t *split_node, *node;
16     range_t *range;
17
18     /* init range */
19     range = (range_t*) malloc(sizeof(range_t));
20     range->min.x = x_min;
21     range->max.x = x_max;
22     range->min.y = y_min;
23     range->max.y = y_max;
24     range->n = 0;
25     range->total_size = 16;
26     range->point_idx = (int*) malloc(range->total_size * sizeof(int));
27
28     /* find split node */
29     split_node_idx = find_split_node(tree, tree->root_index, range);
30     split_node = NODE_FROM_IDX(tree, split_node_idx);
31
32     /* if split node is a child */
33     if (split_node->right_idx == -1)
34     {
35         range_query_y(tree, split_node_idx, range);
36         return range;
37     }
38
39     /* follow left path of the split node */
40     node_idx = LEFT_CHILD_IDX(split_node_idx, split_node);
41     node = NODE_FROM_IDX(tree, node_idx);
42     while (node->right_idx != -1)
43     {
44         if (range->min.x <= node->x_val)
45         {
46             range_query_y(tree, RIGHT_CHILD_IDX(node_idx, node), range);
47             node_idx = LEFT_CHILD_IDX(node_idx, node);
48         }
49         else
50             node_idx = RIGHT_CHILD_IDX(node_idx, node);
51         node = NODE_FROM_IDX(tree, node_idx);
52     }
53     range_query_y(tree, node_idx, range);

```

```

55     /* follow right path of the split node */
56     node_idx = split_node->right_idx;
57     node = NODE_FROM_IDX(tree, node_idx);
58     while (node->right_idx != -1)
59     {
60         if (range->max.x > node->x_val)
61         {
62             range_query_y(tree, LEFT_CHILD_IDX(node_idx, node), range);
63             node_idx = RIGHT_CHILD_IDX(node_idx, node);
64         }
65         else
66             node_idx = LEFT_CHILD_IDX(node_idx, node);
67         node = NODE_FROM_IDX(tree, node_idx);
68     }
69     range_query_y(tree, node_idx, range);

70     return range;
71 }
72
73 void range_append(range_t *range, int idx)
74 {
75     int *new_point_idx;
76     int new_size, i;

77     /* just append if there is enough place, otherwise double capacity and
78      * append */
79     if (range->n < range->total_size)
80         range->point_idx[range->n++] = idx;
81     else
82     {
83         new_size = range->total_size << 1;
84         new_point_idx = (int*) malloc(new_size * sizeof(int));
85         for (i = 0; i < range->n; ++i)
86             new_point_idx[i] = range->point_idx[i];
87         new_point_idx[range->n++] = idx;
88         free(range->point_idx);
89         range->point_idx = new_point_idx;
90         range->total_size = new_size;
91     }
92 }

93 }

94 int find_split_node(tree_t *tree, int node_idx, range_t *range)
95 {
96     node_t *node;

97     node = (node_t*) &tree->data[node_idx];
98     /* check if this node is the split node */
99     if (range->min.x <= node->x_val && range->max.x > node->x_val)
100        return node_idx;

```

```

103
105     /* ...or if it is a child (and therefor the split node) */
106     if (node->right_idx == -1)
107         return node_idx;
108
109     /* otherwise search the split node at the left or right of the current
110      node */
111     if (range->max.x <= node->x_val)
112         return find_split_node(tree, LEFT_CHILD_IDX(node_idx, node),
113                               range);
114     else
115         return find_split_node(tree, RIGHT_CHILD_IDX(node_idx, node),
116                               range);
117 }
118
119 void range_query_y(tree_t *tree, int node_idx, range_t *range)
120 {
121     point_t *points;
122     double y;
123     int i, j, k, m, start, end;
124     int *point_idx;
125     node_t *node;
126
127     node = (node_t*) &tree->data[node_idx];
128     points = (point_t*) tree->data;
129     point_idx = (int*) (node + 1);
130
131     /* return if all points are outside the range */
132     if (points[point_idx[0]].y > range->max.y || points[point_idx[node->np
133 - 1]].y < range->min.y)
134         return;
135
136     /* binary search for lower end of the range */
137     y = range->min.y;
138     j = 0;
139     k = node->np - 1;
140     while (j != k)
141     {
142         m = (j + k) / 2;
143         if (points[point_idx[m]].y >= y)
144             k = m;
145         else
146             j = m + 1;
147     }
148     start = j;
149
150     /* binary search for higher end of the range */
151     y = range->max.y;
152     j = 0;
153     k = node->np - 1;

```

```

149     while (j != k)
150     {
151         m = (j + k + 1) / 2;
152         if (points[point_idx[m]].y > y)
153             k = m - 1;
154         else
155             j = m;
156     }
157     end = j;

158     /* append found points to the range */
159     for (i = start; i <= end; ++i)
160         if (points[point_idx[i]].x <= range->max.x)
161             range_append(range, point_idx[i]);
162 }


```

Listing 27: tree_query.c

```

#ifndef TREE_TYPES_H
#define TREE_TYPES_H

typedef unsigned char uchar;

/* 2D point */
typedef struct
{
    double x;
    double y;
} point_t;

/* tree */
typedef struct
{
    /* byte data array with points and nodes */
    uchar *data;

    /* index of first unused byte */
    int first_free;

    /* total number of allocated bytes */
    int total_size;

    /* index of the root node in the data array*/
    int root_index;
} tree_t;

/* node */
typedef struct
{


```

```

32     /* index of the right child node (left child follows directly after
33      current) */
34     int right_idx;
35
36     /* number of associated points */
37     int np;
38
39     /* associated x-coordinate value */
40     double x_val;
41 } node_t;
42
43 /* range */
44 typedef struct
45 {
46     /* point index list */
47     int *point_idx;
48
49     /* number of saved indices */
50     int n;
51
52     /* total number of allocated indices */
53     int total_size;
54
55     /* minimum range point */
56     point_t min;
57
58     /* maximum range point */
59     point_t max;
60 } range_t;
61
62 #endif

```

Listing 28: tree_types.h

9.1.3 *crew command code*

```

1 function data = addAgentRepulsiveForce(data)
%ADDAGENTREPULSIVEFORCE Summary of this function goes here
3 % Detailed explanation goes here
4
5 % Obstruction effects in case of physical interaction
6
7 % get maximum agent distance for which we calculate force
8 r_max = data.r_influence;
9 tree = 0;
10
11 for fi = 1:data.floor_count
12     pos = [arrayfun(@(a) a.p(1), data.floor(fi).agents);
13             arrayfun(@(a) a.p(2), data.floor(fi).agents)];

```

```

15    % update range tree of lower floor
16    tree_lower = tree;
17
18    agents_on_floor = length(data.floor(fi).agents);
19
20    % init range tree of current floor
21    if agents_on_floor > 0
22        tree = createRangeTree(pos);
23    end
24
25    for ai = 1:agents_on_floor
26        pi = data.floor(fi).agents(ai).p;
27        vi = data.floor(fi).agents(ai).v;
28        ri = data.floor(fi).agents(ai).r;
29
30        % use range tree to get the indices of all agents near agent ai
31        idx = rangeQuery(tree, pi(1) - r_max, pi(1) + r_max, ...
32                          pi(2) - r_max, pi(2) + r_max)';
33
34        % loop over agents near agent ai
35        for aj = idx
36
37            % if force has not been calculated yet...
38            if aj > ai
39                pj = data.floor(fi).agents(aj).p;
40                vj = data.floor(fi).agents(aj).v;
41                rj = data.floor(fi).agents(aj).r;
42
43                % vector pointing from j to i
44                nij = (pi - pj) * data.meter_per_pixel;
45
46                % distance of agents
47                d = norm(nij);
48
49                % normalized vector pointing from j to i
50                nij = nij / d;
51                % tangential direction
52                tij = [-nij(2), nij(1)];
53
54                % sum of radii
55                rij = (ri + rj);
56
57                % repulsive interaction forces
58                if d < rij
59                    T1 = data.k*(rij - d);
60                    T2 = data.kappa*(rij - d)*dot((vj - vi),tij)*tij;
61                else
62                    T1 = 0;
63                    T2 = 0;

```

```

        end
65      F = (data.A * exp((rij - d)/data.B) + T1)*nij + T2;
67
69      data.floor(fi).agents(ai).f = ...
70          data.floor(fi).agents(ai).f + F;
71      data.floor(fi).agents(aj).f = ...
72          data.floor(fi).agents(aj).f - F;
    end
73 end

75 % include agents on stairs!
76 if fi > 1
77     % use range tree to get the indices of all agents near agent ai
78     if ~isempty(data.floor(fi-1).agents)
79         idx = rangeQuery(tree_lower, pi(1) - r_max, ...
80                           pi(1) + r_max, pi(2) - r_max, pi(2) + r_max)';
81
82         % if there are any agents...
83         if ~isempty(idx)
84             for aj = idx
85                 pj = data.floor(fi-1).agents(aj).p;
86                 if data.floor(fi-1).img_stairs_up(round(pj(1)),
87                     round(pj(2)))
88
89                     vj = data.floor(fi-1).agents(aj).v;
90                     rj = data.floor(fi-1).agents(aj).r;
91
92                     % vector pointing from j to i
93                     nij = (pi - pj) * data.meter_per_pixel;
94
95                     % distance of agents
96                     d = norm(nij);
97
98                     % normalized vector pointing from j to i
99                     nij = nij / d;
100                    % tangential direction
101                    tij = [-nij(2), nij(1)];
102
103                    % sum of radii
104                    rij = (ri + rj);
105
106                    % repulsive interaction forces
107                    if d < rij
108                        T1 = data.k*(rij - d);
109                        T2 = data.kappa*(rij - d)*dot((vj -
110                            vi),tij)*tij;
111                    else
112                        T1 = 0;
113                        T2 = 0;

```

```

113           end
114           F = (data.A * exp((rij - d)/data.B) + T1)*nij
115           + T2;
116
117           data.floor(fi).agents(ai).f = ...
118               data.floor(fi).agents(ai).f + F;
119           data.floor(fi-1).agents(aj).f = ...
120               data.floor(fi-1).agents(aj).f - F;
121       end
122   end
123 end
124
125 end

```

Listing 29: addAgentRepulsiveForce.m

```

1 function data = addDesiredForce(data)
%ADDDESIREDFORCE add 'desired' force contribution (towards nearest exit or
3 %staircase)

5 for fi = 1:data.floor_count

7     for ai=1:length(data.floor(fi).agents)

9         % get agent's data
10        p = data.floor(fi).agents(ai).p;
11        m = data.floor(fi).agents(ai).m;
12        v0 = data.floor(fi).agents(ai).v0;
13        v = data.floor(fi).agents(ai).v;

15
16        % get direction towards nearest exit
17        ex = lerp2(data.floor(fi).img_dir_x, p(1), p(2));
18        ey = lerp2(data.floor(fi).img_dir_y, p(1), p(2));
19        e = [ex ey];

21        % get force
22        Fi = m * (v0*e - v)/data.tau;
23
24        % add force
25        data.floor(fi).agents(ai).f = data.floor(fi).agents(ai).f + Fi;
26    end
27 end

```

Listing 30: addDesiredForce.m

```
function data = addWallForce(data)
```

```

2 %ADDWALLFORCE adds wall's force contribution to each agent
4 for fi = 1:data.floor_count
6
8     for ai=1:length(data.floor(fi).agents)
10        % get agents data
12        p = data.floor(fi).agents(ai).p;
14        ri = data.floor(fi).agents(ai).r;
16        vi = data.floor(fi).agents(ai).v;
18
20        % get direction from nearest wall to agent
22        nx = lerp2(data.floor(fi).img_wall_dist_grad_x, p(1), p(2));
24        ny = lerp2(data.floor(fi).img_wall_dist_grad_y, p(1), p(2));
26
28        % get distance to nearest wall
30        diW = lerp2(data.floor(fi).img_wall_dist, p(1), p(2));
32
34        % get perpendicular and tangential unit vectors
36        niW = [ nx ny];
            tiW = [-ny nx];
38
40        % calculate force
42        if diW < ri
44            T1 = data.k * (ri - diW);
46            T2 = data.kappa * (ri - diW) * dot(vi, tiW) * tiW;
48        else
50            T1 = 0;
52            T2 = 0;
54        end
56        Fi = (data.A * exp((ri-diW)/data.B) + T1)*niW - T2;
58
60        % add force to agent's current force
62        data.floor(fi).agents(ai).f = data.floor(fi).agents(ai).f + Fi;
64    end
66
68 end

```

Listing 31: addWallForce.m

```

function data = applyForcesAndMove(data)
2 %APPLYFORCESANDMOVE apply current forces to agents and move them using
%the timestep and current velocity
4
n_velocity_clamps = 0;
6
% loop over all floors higher than exit floor
8 for fi = data.floor_exit:data.floor_count
10
    % init logical arrays to indicate agents that change the floor or exit
    % the simulation

```

```

12      floorchange = false(length(data.floor(fi).agents),1);
13      exited = false(length(data.floor(fi).agents),1);
14
15      % loop over all agents
16      for ai=1:length(data.floor(fi).agents)
17          % add current force contributions to velocity
18          v = data.floor(fi).agents(ai).v + data.dt * ...
19              data.floor(fi).agents(ai).f / data.floor(fi).agents(ai).m;
20
21          % clamp velocity
22          if norm(v) > data.v_max
23              v = v / norm(v) * data.v_max;
24              n_velocity_clamps = n_velocity_clamps + 1;
25          end
26
27          % get agent's new position
28          newp = data.floor(fi).agents(ai).p + ...
29              v * data.dt / data.meter_per_pixel;
30
31          % if the new position is inside a wall, remove perpendicular
32          % component of the agent's velocity
33          if lerp2(data.floor(fi).img_wall_dist, newp(1), newp(2)) < ...
34              data.floor(fi).agents(ai).r
35
36              % get agent's position
37              p = data.floor(fi).agents(ai).p;
38
39              % get wall distance gradient (which is off course perpendicular
40              % to the nearest wall)
41              nx = lerp2(data.floor(fi).img_wall_dist_grad_x, p(1), p(2));
42              ny = lerp2(data.floor(fi).img_wall_dist_grad_y, p(1), p(2));
43              n = [nx ny];
44
45              % project out perpendicular component of velocity vector
46              v = v - dot(n,v)/dot(n,n)*n;
47
48              % get agent's new position
49              newp = data.floor(fi).agents(ai).p + ...
50                  v * data.dt / data.meter_per_pixel;
51          end
52
53          % check if agents position is ok
54          % repositioning after 50 times clogging
55          % deleting if agent has a NaN position
56          if ~isnan(newp)
57              if data.floor(fi).img_wall(round(newp(1)), round(newp(2)))
58                  newp = data.floor(fi).agents(ai).p;
59                  v = [0 0];
60                  data.floor(fi).agents(ai).clogged =
61                      data.floor(fi).agents(ai).clogged + 1;

```

```

    fprintf('WARNING: clogging agent %i on floor %i (%i).
    Position
    (%f,%f).\n',ai,fi,data.floor(fi).agents(ai).clogged,newp(1),newp(2))
62  if data.floor(fi).agents(ai).clogged >= 40
       nx = rand(1)*2 - 1;
64      ny = rand(1)*2 - 1;
66      n = [nx ny];
68      v = n*data.v_max/2;
69      fprintf('WARNING: agent %i on floor %i velocity set
70          random to get out of wall. Position
71          (%f,%f).\n',ai,fi,newp(1),newp(2))

72      % get agent's new position
73      newp = data.floor(fi).agents(ai).p + ...
74          v * data.dt / data.meter_per_pixel;
75      if isnan(newp)
76          % get rid of disturbing agent
77          fprintf('WARNING: position of an agent is NaN!
78              Deleted this agent.\n')
79          exited(ai) = 1;
80          data.agents_exited = data.agents_exited +1;
81          data.output.deleted_agents=data.output.deleted_agents+1;
82          newp = [1 1];
83      end
84  end
85
86 else
87     % get rid of disturbing agent
88     fprintf('WARNING: position of an agent is NaN! Deleted this
89         agent.\n')
90     exited(ai) = 1;
91     data.agents_exited = data.agents_exited +1;
92     data.output.deleted_agents=data.output.deleted_agents+1;
93     newp = [1 1];
94 end

95
96     % update agent's velocity and position
97     data.floor(fi).agents(ai).v = v;
98     data.floor(fi).agents(ai).p = newp;

99
100    % reset forces for next timestep
101    data.floor(fi).agents(ai).f = [0 0];

102
103    % check if agent reached a staircase down and indicate floor change
104    if data.floor(fi).img_stairs_down(round(newp(1)), round(newp(2)))
       floorchange(ai) = 1;
105  end

106
107    % check if agent reached an exit

```

```

106     if data.floor(fi).img_exit(round(newp(1)), round(newp(2)))
107         exited(ai) = 1;
108         data.agents_exited = data.agents_exited +1;
109
110     %fprintf('agent exited from upper loop\n');
111
112     %save current exit nr
113     data.current_exit = data.exit_nr(round(newp(1)),
114                                     round(newp(2)));
115
116     %update exit_left
117     data.exit_left(1,data.current_exit) =
118         data.exit_left(1,data.exit_nr(round(newp(1)),
119                         round(newp(2)))) - 1;
120
121     %close exit if there is no more free space
122     if data.exit_left(1,data.current_exit) < 1
123
124         %change current exit to wall
125         data.floor(data.floor_exit).img_wall =
126             data.floor(data.floor_exit).img_wall == 1 ...
127                 | (data.exit_nr == (data.current_exit));
128         data.floor(data.floor_exit).img_exit =
129             data.floor(data.floor_exit).img_exit == 1 ...
130                 & (data.exit_nr ~= (data.current_exit));
131
132     %redo initEscapeRoutes and initWallForces with new exit
133         and wall parameters
134     data = initEscapeRoutes(data);
135     data = initWallForces(data);
136
137     %fprintf('new routes from upper loop\n');
138
139     end
140
141     end
142
143     % add appropriate agents to next lower floor
144     if fi > data.floor_exit
145         data.floor(fi-1).agents = [data.floor(fi-1).agents
146             data.floor(fi).agents(floorchange)];
147     end
148
149     % delete these and exited agents
150     data.floor(fi).agents = data.floor(fi).agents(~(floorchange|exited));
151
152 end

```

```

148
150
152 % loop over all floors lower than exit floor
152 for fi = 1:data.floor_exit
154
154 % init logical arrays to indicate agents that change the floor or exit
154 % the simulation
156 floorchange = false(length(data.floor(fi).agents),1);
156 exited = false(length(data.floor(fi).agents),1);
158
158 % loop over all agents
160 for ai=1:length(data.floor(fi).agents)
160
162 % add current force contributions to velocity
162 v = data.floor(fi).agents(ai).v + data.dt * ...
162 data.floor(fi).agents(ai).f / data.floor(fi).agents(ai).m;
164
164 % clamp velocity
166 if norm(v) > data.v_max
166 v = v / norm(v) * data.v_max;
168 n_velocity_clamps = n_velocity_clamps + 1;
168 end
170
170 % get agent's new position
172 newp = data.floor(fi).agents(ai).p + ...
172 v * data.dt / data.meter_per_pixel;
174
174 % if the new position is inside a wall, remove perpendicular
176 % component of the agent's velocity
176 if lerp2(data.floor(fi).img_wall_dist, newp(1), newp(2)) < ...
178 data.floor(fi).agents(ai).r
180
180 % get agent's position
182 p = data.floor(fi).agents(ai).p;
184
184 % get wall distance gradient (which is of course perpendicular
184 % to the nearest wall)
186 nx = lerp2(data.floor(fi).img_wall_dist_grad_x, p(1), p(2));
186 ny = lerp2(data.floor(fi).img_wall_dist_grad_y, p(1), p(2));
188 n = [nx ny];
188
190 % project out perpendicular component of velocity vector
190 v = v - dot(n,v)/dot(n,n)*n;
192
192 % get agent's new position
194 newp = data.floor(fi).agents(ai).p + ...
194 v * data.dt / data.meter_per_pixel;
196 end

```

```

198     % check if agents position is ok
199     % repositioning after 50 times clogging
200     % deleting if agent has a NaN position
201     if ~isnan(newp)
202         if data.floor(fi).img_wall(round(newp(1)), round(newp(2)))
203             newp = data.floor(fi).agents(ai).p;
204             v = [0 0];
205             data.floor(fi).agents(ai).clogged =
206                 data.floor(fi).agents(ai).clogged + 1;
207             fprintf('WARNING: clogging agent %i on floor %i (%i).
208                         Position
209                         (%f,%f).\n',ai,fi,data.floor(fi).agents(ai).clogged,newp(1),newp(2))
210             if data.floor(fi).agents(ai).clogged >= 40
211                 nx = rand(1)*2 - 1;
212                 ny = rand(1)*2 - 1;
213                 n = [nx ny];
214                 v = n*data.v_max/2;
215                 fprintf('WARNING: agent %i on floor %i velocity set
216                         random to get out of wall. Position
217                         (%f,%f).\n',ai,fi,newp(1),newp(2))
218
219             % get agent's new position
220             newp = data.floor(fi).agents(ai).p + ...
221                 v * data.dt / data.meter_per_pixel;
222             if isnan(newp)
223                 % get rid of disturbing agent
224                 fprintf('WARNING: position of an agent is NaN!
225                         Deleted this agent.\n')
226                 exited(ai) = 1;
227                 data.agents_exited = data.agents_exited +1;
228                 data.output.deleted_agents=data.output.deleted_agents+1;
229                 newp = [1 1];
230             end
231         end
232     else
233         % get rid of disturbing agent
234         fprintf('WARNING: position of an agent is NaN! Deleted this
235                         agent.\n')
236         exited(ai) = 1;
237         data.agents_exited = data.agents_exited +1;
238         data.output.deleted_agents=data.output.deleted_agents+1;
239         newp = [1 1];
240     end
241
242     % update agent's velocity and position
243     data.floor(fi).agents(ai).v = v;
244     data.floor(fi).agents(ai).p = newp;
245
246     % reset forces for next timestep

```

```

242     data.floor(fi).agents(ai).f = [0 0];
244
245     % check if agent reached a staircase up and indicate floor change
246     if data.floor(fi).img_stairs_up(round(newp(1)), round(newp(2)))
247         floorchange(ai) = 1;
248     end
249
250     % check if agent reached an exit
251     if data.floor(fi).img_exit(round(newp(1)), round(newp(2)))
252         exited(ai) = 1;
253         data.agents_exited = data.agents_exited +1;
254
255     %
256         fprintf('agent exited from lower loop\n');
257
258         %save current exit nr
259         data.current_exit = data.exit_nr(round(newp(1)),
260                                         round(newp(2)));
261
262         %update exit_left
263         data.exit_left(1,data.current_exit) =
264             data.exit_left(1,data.exit_nr(round(newp(1)),
265                                         round(newp(2)))) - 1;
266
267             %close exit if there is no more free space
268             if data.exit_left(1,data.current_exit) < 1
269
270                 %change current exit to wall
271                 data.floor(data.floor_exit).img_wall =
272                     data.floor(data.floor_exit).img_wall == 1 ...
273                         | (data.exit_nr == (data.current_exit));
274                 data.floor(data.floor_exit).img_exit =
275                     data.floor(data.floor_exit).img_exit == 1 ...
276                         & (data.exit_nr ~= (data.current_exit));
277
278                 %redo initEscapeRoutes and initWallForces with new exit
279                 % and wall parameters
280                 data = initEscapeRoutes(data);
281                 data = initWallForces(data);
282
283             %
284                 fprintf('new routes from lower loop\n');
285
286             end
287
288         end
289     end
290
291     % add appropriate agents to next lower floor
292     if fi < data.floor_exit
293         data.floor(fi+1).agents = [data.floor(fi+1).agents ...
294                                     data.floor(fi).agents(floorchange)];

```

```

    end
286
% delete these and exited agents
288 data.floor(fi).agents = data.floor(fi).agents(~(floorchange|exited));
end
290
if data.switch_done==0 && data.step ~=1 &&
291     data.open_on_x_agents_on_boat>sum(data.output.agents_per_floor(:,data.step-1))
292     data.floor(data.floor_exit).img_exit =
293         data.floor(data.floor_exit).img_exit_second;
294     data.floor(data.floor_exit).img_wall =
295         data.floor(data.floor_exit).img_wall_second;
296 data = initEscapeRoutes(data);
297 data = initWallForces(data);
298 data.switch_done=1;
299 fprintf('ALL BOATS ARE OPEN NOW FOR EVACUATION! Opened on time
300 %i\n',data.step*data.dt)
301
302 % if n_velocity_clamps > 0
303 %     fprintf(['WARNING: clamped velocity of %d agents, ...
304 %             \'possible simulation instability.\n'], n_velocity_clamps);
305 % end

```

Listing 32: applyForcesAndMove.m

```

1 function val = checkForIntersection(data, floor_idx, agent_idx)
% check an agent for an intersection with another agent or a wall
3 % the check is kept as simple as possible
%
5 % arguments:
%   data           global data structure
7 %   floor_idx      which floor to check
%   agent_idx      which agent on that floor
9 %   agent_new_pos  vector: [x,y], desired agent position to check
%
11 % return:
%   0             for no intersection
13 %   1             has an intersection with wall
%   2             with another agent
15
16 val = 0;
17
18 p = data.floor(floor_idx).agents(agent_idx).p;
19 r = data.floor(floor_idx).agents(agent_idx).r;
20
21 % check for agent intersection
22 for i=1:length(data.floor(floor_idx).agents)
23     if i~=agent_idx

```

```

    if norm(data.floor(floor_idx).agents(i).p-p)*data.meter_per_pixel
        ...
        <= r + data.floor(floor_idx).agents(i).r
        val=2;
        return;
    end
end
end

```

```

33 % check for wall intersection
if lerp2(data.floor(floor_idx).img_wall_dist, p(1), p(2)) < r
    val = 1;
end

```

Listing 33: checkForIntersection.m

```

1 mex 'fastSweeping.c'
mex 'getNormalizedGradient.c'
3 mex 'lerp2.c'
mex 'createRangeTree.c'
5 mex 'rangeQuery.c'

```

Listing 34: compileC.m

```

1 function data = initAgents(data)

3 % place agents randomly in desired spots, without overlapping
5

7 function radius = getAgentRadius()
    %radius of an agent in meters
9     radius = data.r_min + (data.r_max-data.r_min)*rand();
end

11
data.agents_exited = 0; %how many agents have reached the exit
13 data.total_agent_count = 0;

15 floors_with_agents = 0;
agent_count = data.agents_per_floor;
17 for i=1:data.floor_count
    data.floor(i).agents = [];
    [y,x] = find(data.floor(i).img_spawn);

    21 if ~isempty(x)
        floors_with_agents = floors_with_agents + 1;
    23 for j=1:agent_count
        cur_agent = length(data.floor(i).agents) + 1;
    25

```

```

27         % init agent
28     data.floor(i).agents(cur_agent).r = getAgentRadius();
29     data.floor(i).agents(cur_agent).v = [0, 0];
30     data.floor(i).agents(cur_agent).f = [0, 0];
31     data.floor(i).agents(cur_agent).m = data.m;
32     data.floor(i).agents(cur_agent).v0 = data.v0;
33     data.floor(i).agents(cur_agent).clogged = 0; %to check if
34         agent is hanging in the wall
35
36     tries = 10;
37     while tries > 0
38         % randomly pick a spot and check if it's free
39         idx = randi(length(x));
40         data.floor(i).agents(cur_agent).p = [y(idx), x(idx)];
41         if checkForIntersection(data, i, cur_agent) == 0
42             tries = -1; % leave the loop
43         end
44         tries = tries - 1;
45     end
46     if tries > -1
47         %remove the last agent
48         data.floor(i).agents = data.floor(i).agents(1:end-1);
49     end
50
51     data.total_agent_count = data.total_agent_count +
52         length(data.floor(i).agents);
53
54     if length(data.floor(i).agents) ~= agent_count
55         fprintf(['WARNING: could only place %d agents on floor %d , ...
56                 instead of the desired %d.\n'], ...
57                 length(data.floor(i).agents), i, agent_count);
58     end
59 end
60 if floors_with_agents==0
61     error('no spots to place agents!');
62 end
63

```

Listing 35: initAgents.m

```

function data = initEscapeRoutes(data)
%INITESCAPEROUTES Summary of this function goes here
% Detailed explanation goes here
for i=1:data.floor_count
    boundary_data = zeros(size(data.floor(i).img_wall));
    boundary_data(data.floor(i).img_wall) = 1;

```

```

10 if i<data.floor_exit
    boundary_data(data.floor(i).img_stairs_up) = -1;
12
13 elseif i>data.floor_exit
    boundary_data(data.floor(i).img_stairs_down) = -1;
14
15 else
    boundary_data(data.floor(i).img_exit) = -1;
16
17 end
18
19 exit_dist = fastSweeping(boundary_data) * data.meter_per_pixel;
20 [data.floor(i).img_dir_x, data.floor(i).img_dir_y] = ...
21     getNormalizedGradient(boundary_data, -exit_dist);
22
23 end

```

Listing 36: initEscapeRoutes.m

```

function data = initialize(config)
% initialize the internal data from the config data
%
4 % arguments:
% config      data structure from loadConfig()
6 %
% return:
8 % data       data structure: all internal data used for the main loop
%
10 %           all internal data is stored in pixels NOT in meters

12
13 data = config;
14
15 %for convenience
16 data.pixel_per_meter = 1/data.meter_per_pixel;

18 fprintf('Init escape routes...\n');
19 data = initEscapeRoutes(data);
20 fprintf('Init wall forces...\n');
21 data = initWallForces(data);
22 fprintf('Init agents...\n');
23 data = initAgents(data);
24
25 % maximum influence of agents on each other
26
27 data.r_influence = data.pixel_per_meter * ...
28     fzero(@(r) data.A * exp((2*data.r_max-r)/data.B) - 1e-4, data.r_max);

30 fprintf('Init plots...\n');
31 %init the plots
32 %exit plot

```

```

    data.figure_exit=figure;
34 hold on;
axis([0 data.duration 0 data.total_agent_count]);
36 title(sprintf('agents that reached the exit (total agents: %i)', data.total_agent_count));

38 % floors plot
    data.figure_floors=figure;
40 % figure('units','normalized','outerposition',[0 0 1 1])
    data.figure_floors_subplots_w = data.floor_count;
42 data.figure_floors_subplots_h = 4;
    for i=1:config.floor_count
        data.floor(i).agents_on_floor_plot =
            subplot(data.figure_floors_subplots_h,
                    data.figure_floors_subplots_w, 3*data.floor_count - i+1 +
                    data.figure_floors_subplots_w);
        if i == config.floor_exit - 1
46            data.floor(i).building_plot =
                subplot(data.figure_floors_subplots_h,
                        data.figure_floors_subplots_w,
                        [(2*config.floor_count+1):3*config.floor_count]);
        elseif i == config.floor_exit
48            data.floor(i).building_plot =
                subplot(data.figure_floors_subplots_h,
                        data.figure_floors_subplots_w,
                        [(config.floor_count+1):2*config.floor_count]);
        elseif i == config.floor_exit + 1
50            data.floor(i).building_plot =
                subplot(data.figure_floors_subplots_h,
                        data.figure_floors_subplots_w, [1:config.floor_count]);
        end
52    end

54 % init output matrizes
    data.output = struct;
56 data.output.config = config;
    data.output.agents_per_floor =
        ones(data.floor_count,data.duration/data.dt).*(-1);
58 data.output.exit_left = zeros(data.exit_count,data.duration/data.dt);

60 % prepare output file name
    data.output_file_name = ['output_' data.frame_basename];
62 % prepare video file name
64 data.video_file_name = ['video_' data.frame_basename '.avi'];

66 % set deleted_agents to zero
    data.output.deleted_agents = 0;

```

Listing 37: initialize.m

```

1 function data = initWallForces(data)
2 %INITWALLFORCES init wall distance maps and gradient maps for each floor
3
4 for i=1:data.floor_count
5
6     % init boundary data for fast sweeping method
7     boundary_data = zeros(size(data.floor(i).img_wall));
8     boundary_data(data.floor(i).img_wall) = -1;
9
10    % get wall distance
11    wall_dist = fastSweeping(boundary_data) * data.meter_per_pixel;
12    data.floor(i).img_wall_dist = wall_dist;
13
14    % get normalized wall distance gradient
15    [data.floor(i).img_wall_dist_grad_x, ...
16     data.floor(i).img_wall_dist_grad_y] = ...
17     getNormalizedGradient(boundary_data, wall_dist-data.meter_per_pixel);
18 end

```

Listing 38: initWallForces.m

```

1 function config = loadConfig(config_file)
2 % load the configuration file
3 %
4 % arguments:
5 % config_file      string, which configuration file to load
6 %
7
8 % get the path from the config file -> to read the images
9 config_path = fileparts(config_file);
10 if strcmp(config_path, '') == 1
11     config_path = '.';
12 end
13
14 fid = fopen(config_file);
15 input = textscan(fid, '%s=%s');
16 fclose(fid);
17
18 keynames = input{1};
19 values = input{2};
20
21 %convert numerical values from string to double
22 v = str2double(values);
23 idx = ~isnan(v);
24 values(idx) = num2cell(v(idx));
25
26 config = cell2struct(values, keynames);
27
28
29

```

```

% read the images
31 for i=1:config.floor_count

33     %building structure
34     file = config.(sprintf('floor_%d_build', i));
35     file_name = [config_path '/' file];
36     img_build = imread(file_name);

37     % decode images
38     config.floor(i).img_wall = (img_build(:, :, 1) == 0 ...
39                                 & img_build(:, :, 2) == 0 ...
40                                 & img_build(:, :, 3) == 0);

43     config.floor(i).img_spawn = (img_build(:, :, 1) == 255 ...
44                                 & img_build(:, :, 2) == 0 ...
45                                 & img_build(:, :, 3) == 255);

47 %second possibility:
48 %pixel is exit if 1-->0, 3-->0, and if 2 is between 255 and 230 or if no
49 %red or blue

51     config.floor(i).img_exit = (img_build(:, :, 1) == 0 ...
52                                 & img_build(:, :, 2) ~= 0 ...
53                                 & img_build(:, :, 3) == 0);

55     config.floor(i).img_stairs_up = (img_build(:, :, 1) == 255 ...
56                                     & img_build(:, :, 2) == 0 ...
57                                     & img_build(:, :, 3) == 0);

59     config.floor(i).img_stairs_down = (img_build(:, :, 1) == 0 ...
60                                     & img_build(:, :, 2) == 0 ...
61                                     & img_build(:, :, 3) == 255);

63

65     if i == config.floor_exit

67         %make the exit_nr matrix where the number of exit is indicated in
68         %each
69         %pixel

71         %make a zeroes matrix as big as img_exit
72         config.exit_nr=zeros(size(config.floor(config.floor_exit).img_exit));

73         %make a zeros vector as long as floor_exit
74         config.exit_left = zeros(1,config.exit_count);

75         %loop over all exits
76         for e=1:config.exit_count

```

```

79     %build the exit_nr matrix
80     config.exit_nr = config.exit_nr + e*( img_build(:, :, 1) == 0
81         & img_build(:, :, 2) == (256-e) & img_build(:, :, 3) == 0 )
82 ;
83
84     %build the exit_left matrix
85     config.exit_left(1,e) = config.(sprintf('exit_%d_nr', e));
86
87
88     end
89
90
91     %init the plot image here, because this won't change
92     config.floor(i).img_plot = 5*config.floor(i).img_wall ...
93         + 4*config.floor(i).img_stairs_up ...
94         + 3*config.floor(i).img_stairs_down ...
95         + 2*config.floor(i).img_exit ...
96         + 1*config.floor(i).img_spawn;
97     config.color_map = [1 1 1; 0.9 0.9 0.9; 0 1 0; 0.4 0.4 1; 1 0.4 0.4; 0
98         0 0];
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115

```

Listing 39: loadConfig.m

```

function plotAgentsPerFloor(data, floor_idx)
2 %plot time vs agents on floor

```

```

4 h = subplot(data.floor(floor_idx).agents_on_floor_plot);
6 set(h, 'position',[0.05+(data.floor_count -
    floor_idx)/(data.figure_floors_subplots_w+0.2), ...
    0.05, 1/(data.figure_floors_subplots_w*1.2), 0.3-0.05]);
8
10 if floor_idx~=data.floor_count
11     set(h,'ytick',[ ]) %hide y-axis label
12 end
13
14 axis([0 data.time+data.dt 0 data.agents_per_floor*2]);
15
16 %axis([0 data.duration 0 data.agents_per_floor*2]);
17
18 hold on;
19 plot(data.time, length(data.floor(floor_idx).agents), 'b-');
20 hold off;
21
22 title(sprintf('%i', floor_idx));

```

Listing 40: plotAgentsPerFloor.m

```

function plotExitedAgents(data)
%plot time vs exited agents

4 hold on;
5 plot(data.time, data.agents_exited, 'r-');
6 hold off;

```

Listing 41: plotExitedAgents.m

```

function plotFloor(data, floor_idx)
2
3 if floor_idx == data.floor_exit-1 || floor_idx == data.floor_exit ||
4     floor_idx == data.floor_exit+1
5     h=subplot(data.floor(floor_idx).building_plot);
6
7 set(h,
8     'position',[0,0.35+0.65/3*(floor_idx-data.floor_exit+1),1,0.65/3-0.005]);
9
10 hold off;
11 % the building image
12 imagesc(data.floor(floor_idx).img_plot);
13 hold on;
14
15 %plot options
16 colormap(data.color_map);
17 axis equal;
18 axis manual; %do not change axis on window resize

```

```

18 set(h, 'Visible', 'off')
% title(sprintf('floor %i', floor_idx))
20
% plot agents
22 if ~isempty(data.floor(floor_idx).agents)
    ang = [linspace(0,2*pi, 10) nan]';
24    rmul = [cos(ang) sin(ang)] * data.pixel_per_meter;
    draw = cell2mat(arrayfun(@(a) repmat(a.p,length(ang),1) + a.r*rmul, ...
26        data.floor(floor_idx).agents, 'UniformOutput', false)');
    line(draw(:,2), draw(:,1), 'Color', 'r');
28 end
30 hold off;
end
32 end

```

Listing 42: plotFloor.m

```

function simulate(config_file)
% run this to start the simulation

% start recording the matlab output window for debugging reasons
diary log
if nargin==0
    config_file='../data/config1.conf';
end
fprintf('Load config file...\n');
config = loadConfig(config_file);

data = initialize(config);

data.step = 1;
data.time = 0;
fprintf('Start simulation...\n');

% tic until simulation end
simstart = tic;
%make video while simulation
if data.save_frames==1
    vidObj=VideoWriter(data.video_file_name);
    open(vidObj);
end
while (data.time < data.duration)
    % tic until timestep end
    tstart=tic;

```

```

32     data = addDesiredForce(data);
33     data = addWallForce(data);
34     data = addAgentRepulsiveForce(data);
35     data = applyForcesAndMove(data);

36
37     % dump agents_per_floor to output
38     for floor=1:data.floor_count
39         data.output.agents_per_floor(floor,data.step) =
40             length(data.floor(floor).agents);
41     end

42     % dump exit_left to output
43     data.output.exit_left(:,data.step) = data.exit_left';
44
45     if mod(data.step,data.save_step) == 0
46
47         % do the plotting
48         set(0,'CurrentFigure',data.figure_floors);
49         for floor=1:data.floor_count
50             plotAgentsPerFloor(data, floor);
51             plotFloor(data, floor);
52         end
53
54         if data.save_frames==1
55             %
56             % print('-depsc2',sprintf('frames/%s_%04i.eps', ...
57             % data.frame_basename,data.step), data.figure_floors);
58
59             %
60             % make video while simulate
61             currFrame=getframe(data.figure_floors);
62             writeVideo(vidObj,currFrame);
63
64             set(0,'CurrentFigure',data.figure_exit);
65             plotExitedAgents(data);
66
67             if data.agents_exited == data.total_agent_count
68                 fprintf('All agents are now saved (or are they?). Time: %.2f
69                     sec\n', data.time);
70                 fprintf('Total Agents: %i\n', data.total_agent_count);
71
72                 print('-depsc2',sprintf('frames/exited_agents_%s.eps', ...
73                     data.frame_basename), data.figure_floors);
74                 break;
75             end
76
77             % toc of timestep
78             data.telapsed = toc(tstart);
79             % toc of whole simulation
80             data.output.simulation_time = toc(simstart);

```

```

80
82     % save output
83     output = data.output;
84     save(data.output_file_name, 'output')
85     fprintf('Frame %i done (took %.3fs; %.3fs out of %.3gs
86             simulated).\n', data.step, data.telapsed, data.time,
87             data.duration);

88     end

89     % update step
90     data.step = data.step+1;

91     % update time
92     if (data.time + data.dt > data.duration)
93         data.dt = data.duration - data.time;
94         data.time = data.duration;
95     else
96         data.time = data.time + data.dt;
97     end
98
99 end

100 %make video while simulation
101 close(vidObj);

102 % toc of whole simulation
103 data.output.simulation_time = toc(simstart);
104
105 % save complete simulation
106 output = data.output;
107 save('output','output')
108 fprintf('Simulation done in %i seconds and saved data to output file.\n',
109         data.output.simulation_time);

110 % save diary
111 diary

```

Listing 43: simulate.m