Agent Based Modelling for crowd movement in Het Concertgebouw: a case study

Alexander Uitendaal, Milou Fuhri Snethlage, Maarten Both, Eline Rietdijk, Marcus van Bergen
Computational Science
University of Amsterdam

Abstract—**In this paper, a grid-based Agent-Based Model (ABM) is constructed for simulating the crowd flow in Het Concertgebouw. The crowd simulation spans from the entrance period up until the start of the concert. The constructed model is used to investigate whether changing the location of the entrance helps reduce the uncomfortable densities of visitors in bottleneck areas in the building, before the start of the concert. Statistical tests indicate that changing the direction of the entrance is an effective strategy to achieve lower densities in these areas.**

Index Terms—**Crowd simulation, Concertgebouw, Agent based modelling**

Code Base on GitHub [1]

I. Introduction

MODELLING CROWD DYNAMICS is a tool that is widely used by architects in the design of modern-day buildings. Classically, this type of modelling was done through the use of Network models, which only captured human movement without treating the human as a responsive entity [2]. Nowadays, a more advanced modelling method used for these kinds of simulations is an Agent-Based Model (ABM). The popularity of ABMs is rooted in its ability to capture dynamics of crowd movement on both the micro- and macro scale [4]. There are many examples of how ABMs are used for the simulation of an evacuation event [8] [9]. In this case, the agents have a clear objective: getting themselves to safety in the fastest way possible. They try to achieve this by making observations, locating the exit, and then moving towards their goal. However, ABMs can also be used for the simulation of crowd movements; while trying to optimise the flow or analyse some other properties of interest.

Het Concertgebouw is one of the most famous concert halls in the entire world. Located at the museum square in Amsterdam, it is where the best orchestras in the world have been performing classical concerts since being established in 1883. The venue accommodates roughly 2000 people. Its interior design is characteristic, enchanting and part of the Dutch cultural heritage. However, at the same time this interior design is the cause of problems that arise with respect to crowd handling. The main hall is surrounded by small corridors, and the cloakroom is located in the middle of the hallway that leads to the main entrance. This combination results in various bottlenecks in which visitor overflow and congestion is observed. Customer feedback questionnaires have pointed out that this negatively influences the experience of the visitors. Therefore, understanding the crowd flow has become of great importance for Het Concertgebouw. The management team of the venue is considering changing the location of one of the entrances to decrease the observed density of people.

The analysis in this paper is twofold. First, an ABM will be constructed to simulate the crowd flow in Het Concertgebouw. The focus will be on recreating observed dynamics, and trying understanding the factors that contribute the most to these dynamics. Secondly, this model will be used to conduct experiments. The main question is whether opening the new entrance will lower visitor density in bottleneck areas. The structure of the paper will proceed as follows: A theoretical background on crowd simulation models and relevant literature will be provided; the model will be explained according to the revised ODD format proposed by Grimm (2010) [1]. Furthermore, results are presented, as well as the conclusion of the research. Eventually, shortcomings of the analysis, and possible future research directions, are discussed.

II. Theoretical Framework

A. Thematic overview

As mentioned in the introduction, agent-based modelling has been widely applied to crowd simulation and crowd movement. In the first stages of this research field, a wide

[1] https://github.com/marcusvb/abm-orchestra

variety of modelling frameworks for capturing relevant crowd dynamics were used [4]. Early models of crowd movement were often based on fluid dynamics. The focus on aggregate factors in these models resulted in shortcomings with respect to capturing microscopic dynamics. One important alternative modelling framework came from Helbing [3], who incorporated social forces into ABMs to capture a more diverse set of dynamics such as self-organisation, crowd-avoidance and even injuries. A different approach was presented by A. Kirchner and A. Schadschneider [5], who implemented a Cellular Automaton in which the behaviour of agents was only determined by local information.

In other research, pedestrian dynamics were simulated with a grid-based model, where each agent uses its position on the grid and its surroundings to determine which action to take [5]. This model served as a basis for the popular grid-based ABM framework in crowd simulation. This framework starts with the idea that agents are positioned on a grid. Conveniently, the grid environment serves both as a mechanism that tracks movement, as well as a platform that stores agent-specific data. This data often refers to information about exits, paths or goals that agents try to achieve.

There are two primary purposes for research on crowd movement. It has the goal to research behaviour of the agents themselves or it analyses the specific environment. In some of the literature, the analysis revolves around simulations made with a specific, predefined framework. Other analyses revolve around defining the most appropriate performance metrics for certain types of research questions. Furthermore, the literature focuses on the practical use of crowd modelling research, such as evacuation modelling. These types of research are often presented as a business application or a case study. The research performed in this paper concerns the third category.

B. Relevant literature

This research uses a grid-based environment to model the crowd flow in Het Concertgebouw. Note that there is a wide variety in the types of grid-based models used in agent-based modelling. However, strong similarities can be found in their aggregate design. For the definition of model design, we refer to the revised ODD framework for reporting on ABMs [1].

A few important mechanisms that determine agent behaviour are discrete-choice theory, game theory or behaviour based on probability theory [7]. In our research, agent behaviour is goal directed. Agents determine their goals through probability distributions. The research by Wei [13] and Torres [10] are examples that show grid-based environment models where agents behaviour is goal-directed. In their research, agents pursue individual objectives, and there is no group formation.

It turns out that how agents behave is strongly dependent on the scope of the research [7]. In our research, we attempt to reproduce the observed dynamics of a specific venue; we also experiment within this environment. Hence, papers that propose models for comparable goals are used as inspiration for the choice of our modelling framework. Many of the literature that focuses on one specific venue, focuses on crowd simulation in the context of evacuation. In some papers, venue specific research is combined with grid-based models and discrete choice theory which tries to capture heterogeneity between agents. Other research uses grid based models in combination with agent-specific path planning [12] [11]. In this following Section, a concise overview of our model will be provided.

III. Model Overview

A. Purpose

The first aim is to create a realistic framework for the behaviour of agents walking around the hall in Het Concertgebouw. A model is designed to replicate the actual dynamics at Het Concertgebouw. The simulation spans from the first agent entering the environment, until the start of the concert. The problem in Het Concertgebouw is that visitor jams originate in the area between the main entrance and the main cloakroom. It is expected that relocating the second entrance results in a more even distribution of visitors over the entrance hall, and thus the visitor jams in the target area will reduce. When a realistic model is achieved, this study tries to investigate if the relocation of one of the entrances has a positive influence on the number of jams in the area between the head entrance and the main cloakroom (see the arrows in Figure 5).

B. Entities, state variables and scales

1) Agents: The agents in our ABM are the people visiting Het Concertgebouw to enjoy the concert that night. There are no different types of agents, the agents are homogeneous. The state variables that distinguish an agent from other agents, are defined with a certain probability at the arrival of an agent. These state variables are the following:

- The start location of an agent, which is the coordinate of a grid cell that is located around one of the two entrances.
- The first objective, which reflects the first location the agent will start moving to when it enters the simulation.
- The end objective frame, which reflects the frame number at which the agent will abandon its current objective and will start moving to its end objective and leave our simulation.
- The end objective, which is the position where the agent will eventually enter the concert hall from the entrance hall and leave our simulation.

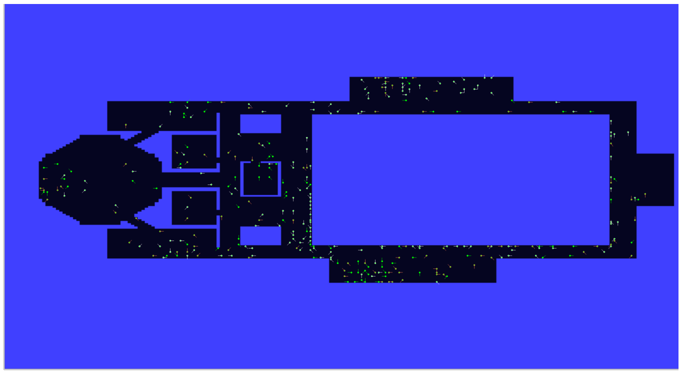


Fig. 1: A single frame of a simulation using our model. Agents are coloured either white, red or green based on their movement mechanism.

The state variables for the agents are shown in Table I.

If an agent enters the simulation in the first three-quarters of the simulation, the end goal frame is sampled from a skew-normal distribution with $location = 0.1$, $scale = 1$ and skew parameter $\alpha = 15$, scaled by 4. That is because the chance that an agent enters the concert hall is the largest in the last quarter. Agents that enter the simulation in the last quarter of the simulation sample their end goal frame from a normal distribution, with mean $m = \frac{2000-\alpha}{2}$ and variance $v = \frac{2000-\alpha}{10}$, where α is the frame number at which the agent entered the simulation.

C. Spatial units

The spatial units in this model are grid cells. The state variables of the cells are the location and whether a cell is available for agent positioning. A position is available if it is not represented by an obstacle or occupied by another agent. These state variables are static since these walls can not move. The only dynamic state variable for the spatial units is the presence or absence of an agent on each grid cell. This state variable is changed every frame, along with the movement of the agents. The state variables resembles the actual floor plan of Het Concertgebouw.

1) Environment: The environment is a grid of 200 by 200 cells, with the layout of the floor plan of Het Concertgebouw; the environment is static. Every possible agent objective is represented by a gradient map, which resembles the 200 by 200 floor plan grid of the environment. Every grid cell in the gradient map either represents an obstacle, a goal location or a gradient value that represents the distance of the grid cell to a goal location. One objective can have different goal locations (see Section IV-D). In that case, the gradient value. The gradient value represents the distance to the goal location from the cell. The scale of the model correlates to reality. The doors at Het Concertgebouw open at 19:35 and the concert begins at 20:15, so the real-time of the simulation is 40 minutes. The total simulation consists of 2000 frames, so each frame scales down to 1.2 seconds. We assume an average walking speed of about 0.35 m/s, and each grid space represents 0.41 meter of real floor space in Het Concertgebouw.

2) State variables: In Table II, an overview of the state variables is displayed. It primarily contains the probabilities of agents receiving a certain objective. However, it also shows other parameter values, including the probability that an agent enters the simulation at each time frame. This probability is changed every quarter (500 time frames) based on the basic principles of this model.

D. Process overview and Scheduling

The time of this model is discrete, with the frame number as time unit. Each frame, different processes take place. First, new agents initialise with a certain probability. All agents present in the system are saved in the agent manager. Then, all agents that are in the agent manager will perform their move function, in the order that they entered into the agent manager. In the move function, an agent will move to the next grid cell or will not move. If an agent reaches its current objective, depending on the reached objective, this agent is removed or obtains a new goal. For an overview of the complete process or our model, see Algorithm 1. A detailed description of the step function of an agent is shown in the flowchart in Figure 2.

The objective probabilities are designed in such a way that most of the agents reach their end objective. Thus, these agents are removed from the system before the end of the simulation.

Algorithm 1 Scheduling for the model

```
Result: Agent schedual
initialization;
 agent_manager = [];

while current_frame != end_frame do
    if newagent then
        agent = create_agent();
         agent_manager.append(agent);
    end
    for agent in agent_manager do
        step();
         if current_frame >end_goal_frame then
         |  agent.goal_location = final_location
        end
        if location == agent.goal_loaction then
            if agent.goal_location == final_location then
             |  agent_manager.delete(agent)
            else
             |  agent.goal_location = get_new_goal()
            end
        end
    end
end
```

IV. Design Concepts

A. Basic principles

The probabilities for the start location, the start objective, the end objective and the mid objective(s) of the agents are based on real measurements recorded in Het Concertgebouw

TABLE I: State variables for the agents

variable	definition	type	options / scale
Start objective	The first objective of an agent	Gradient Map	Main cloakroom or stairs cloakroom
End objective	The final objective of an agent before it is removed from the simulation	Gradient Map	Concert hall entrance 1-7
End goal frame	The frame number[1] at which the agent will abandon its current objective and receive its end objective	int	[α , 2000][2]

[1] As compared to the total frame number of the simulation, which ranges from 0 to 2000.
[2] Here, α is the frame number at which the agent enters the simulation

TABLE II: State variables of the model

variable	definition	objective number	value
D	Design Concertgebouw (floorplan, location of different rooms ect.)		
$start_1$[1]	Start objective probability for the main cloakrooom	1	0.95
$start_2$	Start objective probability for one of the four stairs cloakrooms	2	0.05
β_1[2]	Mid objective probability for the mens toilet	3	0.075
β_2	Mid objective probability for one of the womens toilets	4	0.075
β_3	Mid objective probability for bar 1	5	0.4
β_4	Mid objective probability for bar 2	6	0.15
β_5	Mid objective probability for bar 3	7	0.2
β_6	Mid objective probability for bar 4	8	0.1
β_7	Mid objective probability for walking around	-	0.1
end_1[3]	End objective probability for stairs entrance 1	2A	0.035
end_2	End objective probability for stairs entrance 2	2B	0.035
end_3	End objective probability for stairs entrance 3	2C	0.035
end_4	End objective probability for stairs entrance 4	2D	0.035
end_5	End objective probability for concert hall entrance 1	9A	0.335
end_6	End objective probability for concert hall entrance 2	9B	0.066
end_7	End objective probability for concert hall entrance 3	9C	0.066
end_8	End objective probability for concert hall entrance 4	9D	0.066
end_9	End objective probability for concert hall entrance 5	9E	0.066
end_{10}	End objective probability for concert hall entrance 6	9F	0.066
end_{11}	End objective probability for concert hall entrance 7	9G	0.335
$enter_1$[4]	The probability at each frame that an agent enters the simulation at the main entrance	-	[0.208, 0.166, 0.166, 0.126]
$enter_2$	The probability at each frame that an agent enters the simulation at the small entrance	-	[0.104, 0.083, 0.083, 0.063]
agent_weight	The fraction with which the gradient value is increased when it is occupied by an agent in the altered gradient map	-	0.1
cloakroom_waiting	The number of frames that an agent waits at the main cloakroom before the objective is finished	-	10
random_steps	The range of number of random steps that an agent takes upon reaching one of the bars[5]	-	[5, 15]
bar_waiting	the number of frames that an agent waits at its current location when the bar is reached and the random steps are taken	-	150

[1] The start objective probabilities sum up to 1
[2] The mid objective probabilities sum up to 1
[3] The end objective probabilities sum up to 1
[4] The enter probabilities are changed every quarter, therefore 4 probabilities are shown in the table.
[5] Objective number 5 - 9 in Figure 3

during the walk-in of 40 minutes before a concert. We measured the arrival rates of visitors at the entrance, the rate of visits to six different places in the entrance hall and the exit rates of visitors from the entrance hall into the concert hall, where they would find their seats.

The time of measurement was divided into four sets of ten minutes, representing the four quarters that constitute the total time that is the target of our simulation. In each of the quarters, every rate was measured for four minutes. This means the measurements were performed once every quarter. The arrival rates of visitors in the entrance hall were measured at the two entrances. The visitation rates were measured for the following locations: men toilets, south bar, north bar, main cloakroom area and one of the stairwell coat racks. Lastly, the entrance rates of visitors from the entrance hall into the actual concert hall (where the visitors find their seat) were measured at four different doorways. A more detailed explanation of all the measurements that were made can be found in appendix A.

B. Emergence

Given the location of the entrances, a high density around the south hall up until the cloakroom is expected. Another phenomena expected in the simulation is a high density of people around the areas that are used as agent goals in the

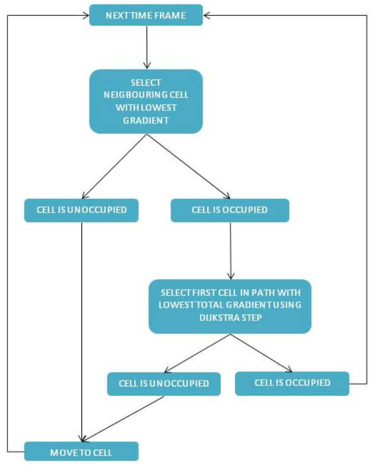


Fig. 2: Flowchart of the step function that is called at each time frame for each agent.

simulation. No congestion is expected in the areas that do not reflect agent goals, such as the corridors around the main hall.

C. Adaptation

Every frame, an agent determines to which neighbouring cell they move. This choice depends on the current objective. Thus the location of the agent's goal. Furthermore, it depends on the environment and if there are obstacles positioned on the route of an agent and their goal. The objective of an agent is assigned with a certain probability, as described in more detail in the next section on objectives.

D. Objectives

All agents have multiple objectives during their total time in the simulation. As described in III-B1, each agent has a start objective and an end objective frame. After finishing their start objective and before reaching the end objective frame, the agent will obtain different mid objectives. All possible objectives are shown in Figure 3, where the red and yellow blocks in the figure correspond to the following objectives:

- **Start objectives**
  - The main cloakroom (1).
  - One of the four stairs cloakrooms (2).
- **Mid objectives**
  - The men's toilet (3)
  - One of the two women's toilets (4)
  - One of the two main bars (5)
  - Bar 1 - 3 (6, 7, 8)
  - Walking around
- **End objectives**
  - Staircase 1 - 4 (2)
  - Hall entrance 1 - 7 (9)

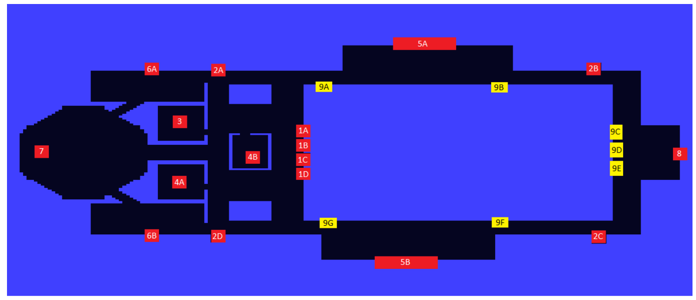


Fig. 3: All possible objectives for the agents. The yellow blocks represent the entrances into the concert hall. For the red blocks, numbers 1A-D represent the locations of the main cloakroom. Numbers 2A-D represent the entrances of the stairs cloakrooms. Number 3 is the men's toilet and number 4A and 4B are both toilets for women. 5A and 5B represent the two main bars, and number 6 - 8 represent four smaller bars. All locations that have the same number are part of the same objective.

The objective of walking around is different from the other objectives. To finish this objective, an agent needs to move to the four staircases subsequently, such that the agent walks around the entire hall. The first staircase is chosen randomly, and from there each other staircase is visited clockwise, to create the dynamics of walking around. Furthermore, upon reaching the goal location, for some objectives, another action is required before the objective is completed:

- The main cloakroom: when the location of the main cloakroom is reached, the agent waits for a specific number of frames (parameter: `cloakroom_waiting`).
- The toilets: when the location of the men's or women's toilet is reached, the agent waits for a specific number of frames (parameter: `toilet_waiting`)
- The bars: when the location of one of the bars is reached, the agent takes a random number of random steps (parameter: `random_steps`) and subsequently waits for a number of frames (parameter: `bar_waiting`).

For the parameter values, see Table II.

In Figure 3, it can be seen that some objectives, represented as individual numbers, have multiple goal locations. These are represented by a letter. For example, objective number 5, the main bar, is a combination of two locations. In that case, the agent finishes the objective if they reach one of the goal locations. In the Figure 3, all locations that have the same number are part of the same objective. If an agent has the start objective to go to one of the four stairs-cloakrooms, in the corners of the environment, we assume that the agent goes upstairs. Therefore, the agent will be removed from the simulation upon reaching the goal location. The upper floor of Het Concertgebouw is not part of our simulation, since this part of the building is without influence to our research question. If an agent has as start objective to go to the main cloakroom, the agent will receive a new objective upon reaching that goal location. After finishing this objective, the agent will keep receiving new objectives until the end goal frame is reached. Then, the agent will receive its end objective and start moving towards it. When an agent reaches its end objective, it will be removed from the simulation. This corresponds with the entrance of the concert hall where the visitors will find their seat. Our simulation does not take into account the seating process in the main hall.

E. Sensing

The information an agent has about the environment consists of the gradient map linked to their current objective and the collision map that records for each grid cell, whether an agent already occupies it. Each move is first based on the gradient map. The agent uses the gradient value of each grid cell around them with a range of one cell and chooses the grid cell with the lowest gradient value, since that is closest to the goal location of the objective. Then, the agent uses the collision map to see whether another agent already occupies the grid cell, If it is not, the agent moves to the grid cell. If the collision map shows that the desired step cannot be taken, the agent uses another method to pick its next location, which will be referred to as the Dijkstra step.

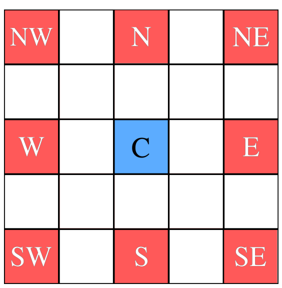


Fig. 4: Modified Moore neighbourhood which is used for the Dijkstra step. Each red grid represents the outermost point which is taken into consideration by the weighted path algorithm. C represents the agent at its current grid position.

In the Dijkstra step, an altered gradient map is used where the gradient values of every cell are increased with 0.1 (parameter: `agent_weight`, see Table II) of its original value if another agent occupies it. With the altered gradient map, the agent uses the gradient values of all grid cell around a specified range; in this case two. We use a modified Moore neighbourhood, where a selection of the outermost points is considered. Then, the Weighted Dijkstra algorithm is used to calculate the total path weight/cost to each outermost point. The value of each grid determines the costs of the paths from the modified gradient map. The agent will choose the first grid cell of the cheapest two grid cell path. The agent moves to the chosen cell if it is unoccupied, otherwise it will not move in the current step.

F. Interactions

Agents can never move to a grid cell if another agent already occupies it. As described before, if an agent encounters another agent on its path, it will calculate another path or wait. Other than that, the agents have no interaction with each other.

G. Stochasticity

In order to enforce agent behaviours to occur with a certain frequency, stochasticity is used to determine the following agent decisions: time of entrance, entrance location, start objective, mid objectives, end objective and the time at which the agent will start moving to its end objective. Probabilities for these decisions were based on the basic principles of our model and can be found in Table II.

H. Observations

During this study, we observed the real system of Het Concertgebouw. These observations were used to set our state variables in Table II; more details on how and where this was done can be found in Appendix A. Two types of observations have been made in order to validate our model. First, information was gathered on the number of agents passing trough a corridor (the flow of visitors) in the hall in specific time ranges. The number of visitors that walked through a corridor in this area was counted for every 10 minutes of the 40 minute walk-in period.

Secondly, the number of agents in a specific area (the density of visitors) was counted at multiple time frames; this was done by taking pictures of the crowd. The position where the data was collected can be found in the lower area of Figure 3. In this area, the 'Zuid' bar is located. The density was counted at specific points in time during the walk-in of visitors.

Finally, we also face validated our model. Each simulation's data yields a heatmap of the crowd-densities. This heatmap counts the number of agents that were located on each grid spaces to portray an overview of crowding in Het Concertgebouw. During face validation, we analyse if the most crowded spots during a simulation correspond with the most crowded areas during a real night in Het Concertgebouw. Since we had an expert to our disposal, his judgement calls could be viewed as observations as well.

V. Details

A. Initialisation

The initial state of the model is an empty grid of the floorplan of Het Concertgebouw, as described in Section III-C1. The system starts at frame number 0, and upon initialisation, no agents are present in the system yet.

B. Input Data

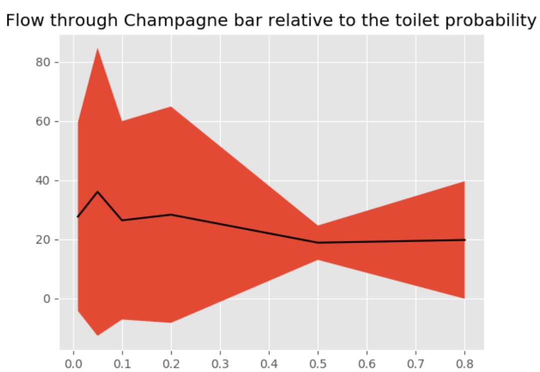
To represent time-varying processes, a set of environmental parameters change each quarter of the running time: the probabilities for the agent decision, as described in Section IV-G, are altered based on the measurements that were made in Het Concertgebouw. Also, the cloakroom location, is changed each quarter in order to make the simulation better resembling the real situation. In the real situation, the cloakroom is changed approximately every quarter. The first cloakroom location is 1A in Figure 3, followed by 1B, 1C and 1D in that order.

VI. Experiment

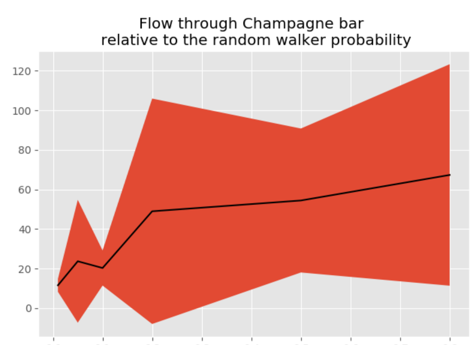
The ABM as described in the Sections III, IV, and V had to be verified before it was possible to do experiments with it. First, we performed a sensitivity analysis to see which parameters were the most important and what their influence on the outcomes was. Secondly, the model had to be configured in such a way that we could perform experiments that answered our second research question.

A. Sensitivity Analysis

1) One factor at a time (OFAT): We performed an OFAT sensitivity analysis for all the outputs of our model. The complete set of figures can be found in Appendix B. Here, we provide the two plots that are most interesting in Figures 5a and 5b. The variance in the champagne area is the least stable compared to the other outputs. For the toilet probability, we see a remarkable dip in the variance around 0.5 in Figure 5a. In the lower domain (from 0 to 0 .2) of the random walker probability in Figure 5b, we see that the flow through the Champagne bar increases more than it does in the higher domain (from 0.2 to 0.8).



(a) OFAT for the crowd flow through the Champagne bar on the right side of the Figure 3 while increasing the probability of the agents going to the toilet.



(b) OFAT for the crowd flow through the Champagne bar on the right side of the Figure 3 while increasing the probability of the agents walking around randomly.

2) Global (Sobol) analysis: Due to the complexity of our simulations, and the large number of parameters it contains, it was not possible to perform sensitivity analysis for all the parameter settings. Therefore, the sensitivity analysis was narrowed down to three parameters that were most important for our research: toilet probability, the random walker probability (which means the probability an agent would start walking circles around the concert hall), and the agent weight. We chose these parameters because the probabilities of going to any bar or any toilet are negatively correlated.

Using Sobol analysis for all these parameters was not possible, since the input parameters are not independent. However, the random walker probability is not correlated to the toilet probability, so these two were fit for Sobol analysis. Finally, the sensitivity of the agent weight was researched in the interval of 0 to 0.3 because we noted that if this parameter was set any higher, the agents would repel each other which would yield unrealistic jams such that the entire system would freeze. The Figures can be found in Appendix B. From these Figures we can conclude that the agent weight has the least influence on the variance in the outcome of the simulation, while the toilet probability has the highest contribution to the total variance of the output. This is logical because the agent weight was already limited to an interval where potential realistic outcomes were found based on visual judgement of the simulation.

Furthermore, the difference between the sensitivity regarding the two outputs, 'Zuid count' and 'Garderobe' (or cloakroom) density can be explained. This is because a higher random walker probability does directly lead to fewer people in the cloakroom area. For the flow through the 'Zuid bar' there is less of an influence, since the route the random walkers take runs through the 'Zuid bar' as well. A conclusion that can be drawn from the analysis is: each probability that the agent picks for a specific goal is a highly sensitive parameter; while the interactions between agents are less sensitive.

B. Validation

To validate our model, we measured two of the outputs from the simulation (the flow through the 'Zuid bar' and the density in the 'Zuid bar' area at a specific time frame) at Het Concertgebouw. Doing so allows us to compare data from the real system with the output from our model.

C. Face validation

The real system at Het Concertgebouw is stochastic just as our model is. The system's outcomes are influenced by random behaviour of the visitors. This made our validation measurements quite unreliable; the measurement took place during one single concert. Therefore we based the configuration of our model on the opinion of an expert, this process is called face validation. A human expert who has been working at Het Concertgebouw for more than three years made a judgement call on how realistic the simulation appears. Even though this may seem like a nonscientific method, face validation does result in the plausibility of our model [6].

VII. Results

A. Validation

As indicated in the Sections IV-H and VI-B, the outputs of our model were compared with real measurements. However, using these measurements to set out input parameters resulted in an invalid and unrealistic model. Two examples of invalid dynamics are jams in the corners [2] of the hall and a complete jam at the cloakroom [3]. Instead, we ended up fitting our model with parameters which satisfied the face validation of the expert working at Het Concertgebouw[4].

B. 'Noord' versus 'Zuid' entrance performance

In Figure 5, the heatmaps for the two different scenario's are depicted. These heatmaps are yeilded by running the model. Upper heatmap is the current entrance situation. The lower heatmap makes use of the new entrance location. In the upper heatmap, the area with problematic crowding is the hall on the south side. It has a high heat signature. Comparing the lower heatmap with the upper heatmap, we notice that density in areas that contain a bar, are spread more evenly. This suggests that the new entrance does affect crowd density in bottle-necked areas.

Furthermore, it appears that when using the north entrance, the density of the cloakroom area is lower. To confirm this, multiple simulations were run. From every run the values of the 10 highest density points on the grid are averaged. This information is used to compare the two different situations. In Figure 6, this is displayed in a boxplot. From the boxplot, we can see that the mean of the model with the new entrance is lower than the current situation. This too suggests that it would be beneficial to use the north entrance. Moreover, it seems that the difference between the two highest densities is statistically significant. To confirm significance, a t-test was performed. The p-value of this test is low enough (values in caption Figure 6), that we can reject the null-hypothesis and confirm that the means significantly differ from each other with a significance level of 1%.

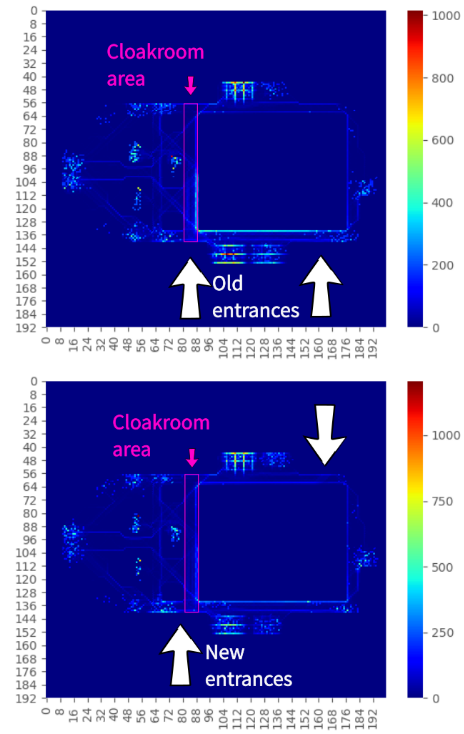


Fig. 5: This Figure contains two examples of the heatmap that is rendered after each simulation is finished. At each step in the simulation, the value of each grid space in the heatmap is updated by adding a value of one to only those grid spaces that contain an agent. This way, we can use the final heatmap to see which positions have been visited the most frequently during the simulation. The cloakroom area is indicated within the pink square.

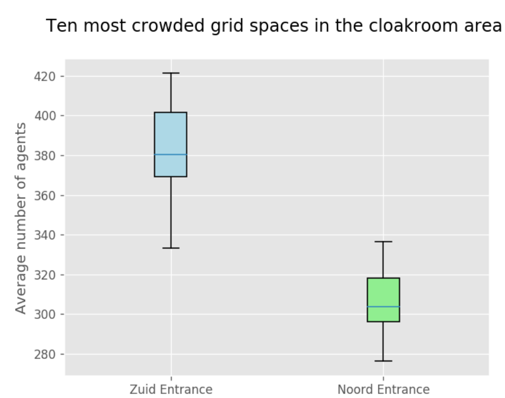


Fig. 6: This boxplot suggests that the use of the Noord entrance results in a less crowded flow of people in the cloakroom area. Each box is made up of an average of the ten grid spaces that were visited the most in the long hall of the cloakroom area (see Figure 5). There is a significant improvement in the level of crowdedness. A t-test was performed on the two data sets, this gives a t statistic of 13.64815 and the p-value $= 8.69798 \cdot 10^{-18}$

VIII. Conclusion and Discussion

In this research, a model was made for crowd simulation in Het Concertgebouw. We were able to deliver a valid model which yielded interesting insights into the crowd movement in Het Concertgebouw.

To recall, the aim of this research was to answer multiple questions: can we create a model which replicates observed dynamics in Het Concertgebouw? Can we use said model to understand what factors contribute the most to these dynamics? Finally our main research question was: does opening the North entrance lower visitor density in bottlenecked areas?

Important steps in creating a model which replicates observed dynamics in Het Concertgebouw were validation and sensitivity analysis. The sensitivity analysis of our model provided insights into the dynamics of the crowd movement in Het Concertgebouw. The variance in the flow through the area of the 'Zuid' bar is not affected much by changing the random walker probability. This is because all the agents have to pass through this area if they want to hang their coats at the cloakroom. The purpose of this observation is to understand

[2]https://youtu.be/HTfG4hHILic
[3]https://youtu.be/EWgem9_qXLo
[4]https://youtu.be/pwq_kpS9ins

crowd dynamics in cases where agents might be more or less familiarly with the environment.

On the other hand, an area where the variance in the density is more sensitive to the random walker probability is the cloakroom area. This is because the route the random walker agents take does not run through the cloakroom area. If more agents are walking randomly, this means that more agents are drawn away from the cloakroom as well.

We attempted to validate our model using data recorded from a concert at Het Concertgebouw. Unfortunately using this data resulted in invalid and unrealistic model outputs. Instead, we validated our model using facial validation. With the validated model an experiment was performed to find out whether opening a new entrance could lower crowdedness in the cloakroom area. As the result in Figure 6 indicates, we found that this was the case. These results are statistically significant. Our recommendation to Het Concertgebouw is thus to change the location of one of the entrances to the other side of the building.

The model we present can be used to provide similar analyses for other venues as well; it is specifically fit for crowds of people that have different goals within the same environment. For future research it would be interesting to see if the model provides valid results for other venues.

Also, further research can be done using this model on crowd dynamics of Het Concertgebouw. It could be interesting to investigate other possibilities which could help improve the crowd flow. For example, the positioning of the bars could be optimised (possibly through the use of a genetic algorithm). Another research opportunity would be to integrate signing into the model. Signing around the halls could possibly yield positive results for the crowd flow.

However, this model is not without its shortcomings. First, our model assumes agents arrive and operate individually. This is a strong assumption because most people visit Het Concertgebouw in groups. How the output of the model changes without this assumption might be interesting for future research. Since concerts are usually a social event, it would be logical to extend the agents to include a social network structure too. Secondly, the agents in our model are fixed on one objective at a time. This is not entirely realistic, because there could be many more scenarios included for the behaviour of the agents. In reality people might change their objective halfway and thus change directions. This is something our model does not account for. An even simpler scenario our model fails to capture is that agents might not know where the bars are located. Our model's environment is entirely accessible, but this might not always be the case.

Furthermore, some visitors of Het Concertgebouw have never been at the location before. We attempted to account for this by making a certain portion of the agents walk around the entire hall (random walkers). The agents that do this, walk in one direction, which is certainly not the case in the real system. This was done because if the agents walked in opposite directions, there would be many more collisions. This would lead to more agents using the Dijkstra step, which is computationally expensive and therefore the simulation would surpass our computational budget.

Finally, when comparing our model to other models we observe one main shortcoming. Due to the computational complexity of our model we had to scale down the number of agents simulated in the experiments. Other well known crowd flow models might be more computationally efficient. This leads us to believe that using one of these more efficient models might have allowed us to simulate Het Concertgebouw at full capacity.

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APPENDICES

A. Measurements at Het Concertgebouw

We took measurements to determine the probabilities that the agents would choose a specific location as their goal. These measurements were used to determine the probability distributions in the Table II. The number of visitors that we counted can be seen in Figure 7.

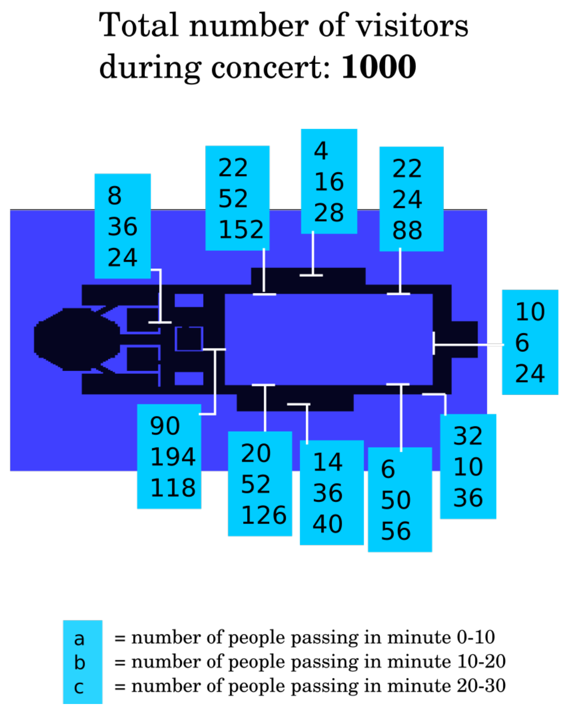


Fig. 7: Number of visitors passing a certain point, which comes across with a specific goal in Figure 3.

Next, to validate our model, we performed similar measurements at different locations and checked if they would come across with the values that we drew from our simulations. Unfortunately this was not the case, as is described in Section VII-A.

B. *Sensitivity analysis*

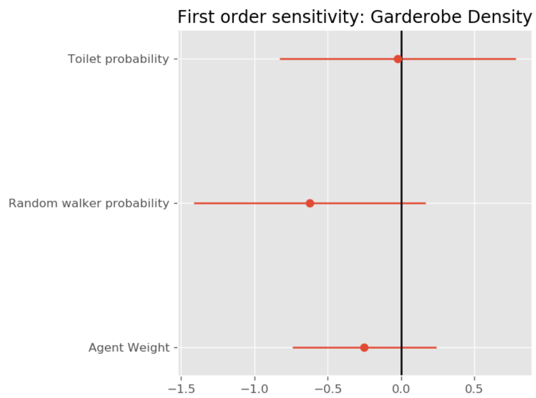
For the sensitivity analysis, both the one Factor at a time method (OFAT) and Sobol global analysis were performed. We chose three input parameters: toilet probability, random walker probability and the agent weight. The reasons why these parameters were chosen can be found in Section VI-A2. The OFAT analysis suggests that the agent weight parameter is an unimportant parameter in our model. This means that the observed dynamics are barely influenced by how much the agents get out of each other's way. The toilet and random walker probability appear to be negatively correlated with the density in the Noord and the Zuid bar.

(a) The influence of the toilet probability on the different outputs

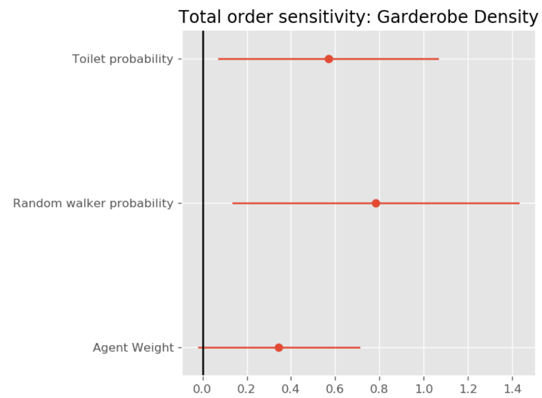
(b) The influence of the random walker probability on the different outputs

(c) The influence of the agent weight on the different outputs

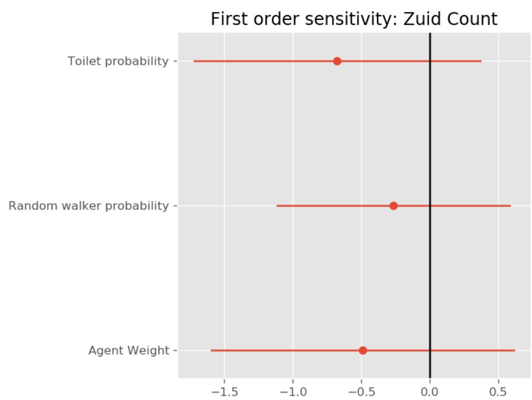
For the same three parameters, global sensitivity was also performed. For the output, we only took the flow count through the Zuid bar and the crowd density in a small portion of the cloakroom area at a specific frame in the simulation. The input parameters are the probability that an agent has the goal to go to the toilet, the probability that an agent starts walking randomly in rounds and the weight that other agents have in each others gradient map. From the first-order Sobol analysis, not much information can be withheld. All the inputs have a sensitivity index of zero, in Figure 8d and 8f it looks like they have negative values, but the actual index is zero. This means that the variance of these inputs has no influence on the variance in the output of the model. The total order sensitivity analysis does contain some interesting information which is described in Section VI-A2 and the conclusion.



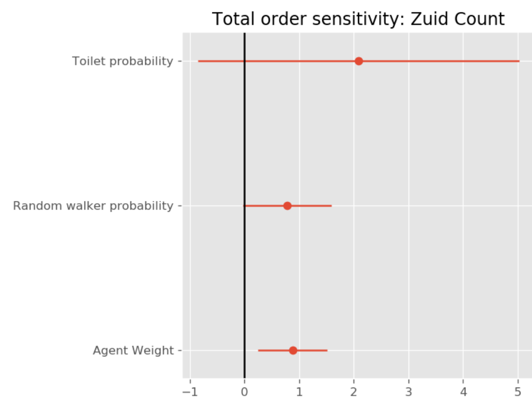
(d) First-order sensitivity of density in Cloakroom area



(e) Total order sensitivity of density in Cloakroom area



(f) First order sensitivity of flow of people through the Zuid bar



(g) Total order sensitivity of flow of people through the Zuid bar