Evacuation of the TU Delft library

An agent-based modeling study

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Research performed in the context of the Master course SEN1211 of the TU Delft

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1. Introduction

Being prepared for disasters can not only save money but also lives, as stressed by Zambello (2013) from The International Federation of Red Cross and Red Crescent Societies. He mentioned the importance of drills and simulations to train staff and assess the overall response to a disaster. But how can one prepare for disasters best with the least possible disturbance to everyday practices possible?

This study aims to apply agent-based modeling as a means to simulate an evacuation event without disrupting the real system. The academic library of the Technical University of Delft will be used as the area of study. This study intends to determine the total evacuation time in case of an emergency situation and test the effects of multiple strategies and population configurations on this temporal element. This will be done by constructing a model of the environment of the library and the entities inside it. We, therefore, target to answer the following two questions in this research:

1. *What is the difference in total evacuation time if all agents exit via the main entrance versus all agents exit via the nearest exit?*

2. *What is the relation between which exits are used and the evacuation time?*

3. *How does gender influence total evacuation time?*

This study will start with the conceptualization of the elements relating to the physical library and the entities acting inside it. Secondly, the conceptual model will be translated to a programmatic model which enables us to simulate the effects of the evacuation. Consequently, model verification and validation will be done. Lastly, an extensive analysis of model results will be performed to end this research with a clear conclusion and implementations for the disaster preparation for the library of the TU Delft.

2. Literature study

This section discusses elements found in literature that are used to construct the programmatic model. While not all elements are based on literature, but also reasoning of the authors themselves, some crucial elements are:

When a fire alarm goes off, one would think that people would leave the building as fast as possible. In fact, this is not the case. Research has shown that people tend to ignore fire alarms due to the following reasons (Proulx, 2000):

- People fail to recognize the sound of an alarm
- People lose confidence in the system due to for example testing of the alarm
- People don't hear the alarm

Other research has shown that the dimension of the family is very important in evacuations regarding students (Vásquez et al., 2018). Children even move slower than adults in evacuations (Larusdottir & Dederichs, 2011). Females walk slower than males during an evacuation when the visibility is bad (Shen et al., 2014).

In the city of Delft, the city where the library is located, there is a larger number of male students than female students (CBS, n.d.). Based on CBS (n.d.), we estimate that about 63% of the agents in the simulation are male and 37% female.

Research has found that social influence is an important factor during an evacuation (Nilsson & Johansson, 2009). Social influence also decreases with increasing distance between evacuants (Nilsson & Johansson, 2009).

Another study has found that visitors in a building react much faster to an alarm when alerted by staff members, in comparison with just hearing the alarm (Galea et al., 2010). Furthermore, this study found that the response time of visitors was found to be dependent on what kind of task they were executing.

3. Conceptual model

This section covers the first step of this study, which consists of the conceptualization of the system of interest. The conceptualization was based on the literature found in chapter 2, and the initial problem formulation in chapter 1.

The TU Delft library was conceptualized as a one-floor system, where agents do certain tasks or exit the building. See figure 1. In the model, there are 2 types of agents, visitors, and staff members. Visitors can either search for a book, study, or ask a staff member a question at the desk. Staff members can work in the office or desk or can perform library duties while moving. Once the alarm will go off, agents will start evacuating.

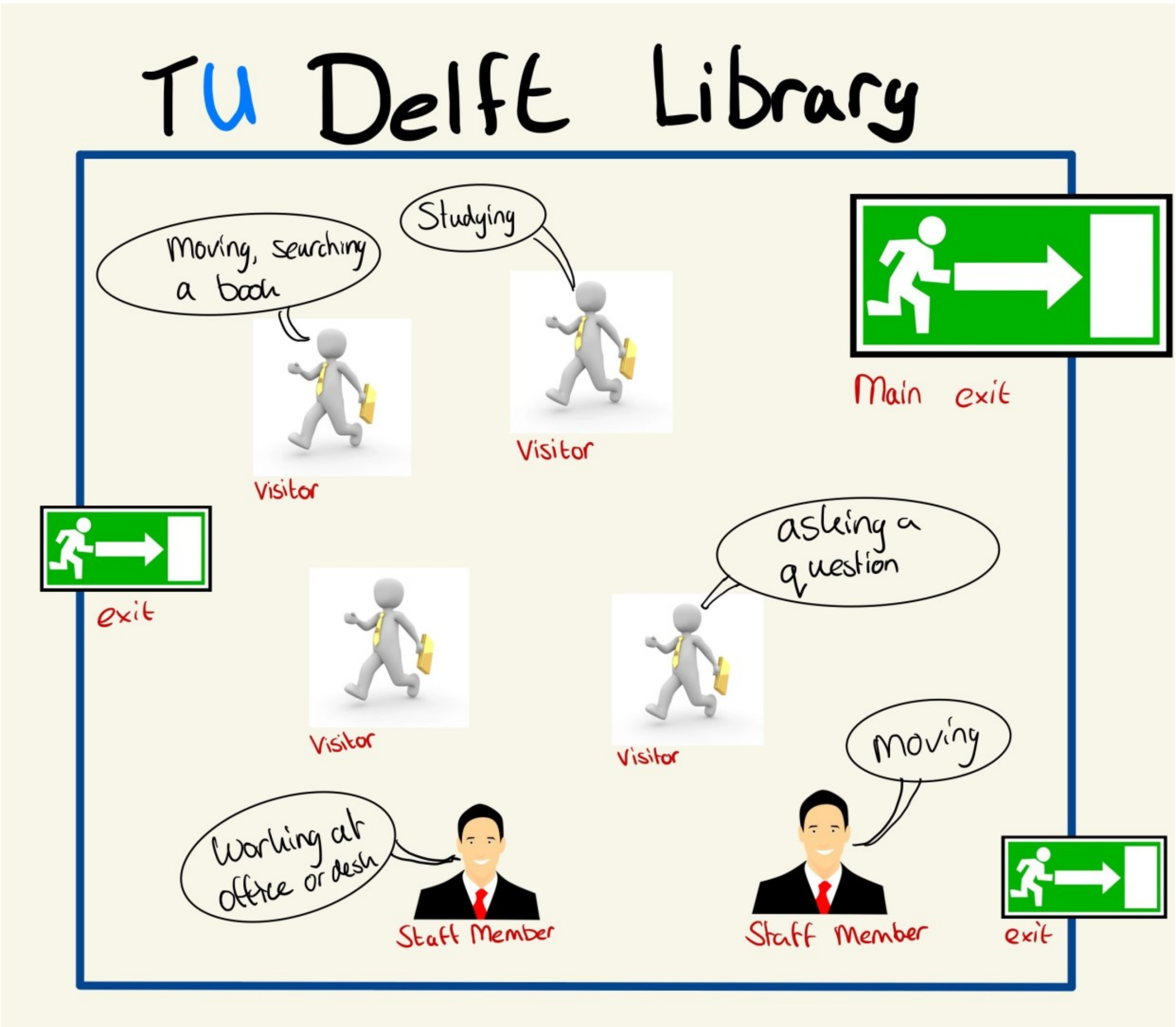

Figure 1, Conceptual model. (n.d.-a; *Free Image on Pixabay - Avatar, People, Person, Business*, n.d., n.d.-b)

4. Implementation

This section covers the implementation of the conceptual model into a programmatic agent-based model in the software package Netlogo. The full constructed model can be found in the attached “model/final.nlogo” file, whereas all the needed additional .nsl files are attached inside the “model/import folder”. First pre- and post-alarm behavior in the model will be described. Afterward, a list of assumptions in the model is provided.

4.1 Pre-alarm behavior

When the alarm is off, visitors and staff perform tasks. Visitors can walk around, study, or ask a question at an information desk. Staff members can walk around or perform a stationary duty, like operating a desk. Children with parents will follow their parents around. Children without parents can walk around freely, but won’t study or ask questions. When the alarm is switched on and off again, all turtles will assume it was a false alarm and behave the same way as if the alarm was never turned on.

4.2 Pathfinding and evacuation

As a resource for this project, we were provided pathfinding algorithms for turtles to locate the nearest exit during an evacuation, using the shortest path algorithm. However, since the shortest path has to be calculated for every turtle, model performance was severely worsened. We, therefore, developed our own pathfinding algorithm for this project, the “closeness-to-exit” algorithm. This algorithm uses patches to determine evacuation routes for all turtles, instead of calculating individual paths per turtle. Because this algorithm only has to run twice during setup, the model performance during the run greatly improves. This enables the model to simulate significantly higher agent amounts than before, at least up to 5000, while running smoothly.

4.2.1 The “closeness-to-exit” algorithm

The algorithm functions as follows:
During setup, all red patches (exits) are given a “closeness-to-exit” (CTE) value of 0. Then patches with a CTE of 0 are asked to give walkable (no walls) neighboring patches without an assigned value a CTE of $CTE_{self} + 1$. After this patches with CTE 1 are asked to do the same etc. This repeats until all walkable patches are covered. Figure 2 shows how the algorithm spreads through the library.

Figure 2, closeness-to-exit algorithm visualized

Visitors will evacuate by continually moving to the patch with the lowest CTE-value in a radius of 2, eventually reaching an exit. Using a lower search radius, e.g. 1, reduced the functionality of the algorithm greatly because turtles weren't able to find patches around them with lower closeness to exit values sometimes. Visitors could theoretically move through walls if they stand next to a wall and a walkable patch on the other side comes into the radius 2. To prevent this two measures were taken:

- All white patches adjacent to a wall have an increased CTE-value of +1. This discourages turtles from walking close to walls in the first place.
- Walls have been thickened close to doors and exit routes, preventing walkable patches on the other side from coming in the radius 2.

One of the experiments that this model is meant to carry out is varying the exit where most visitors head towards by default. The same CTE algorithm is used for this, but with an additional variable per patch: "Closeness-to-preferred-exit" (CTPE). There are three exit locations in the library: The main door, the lower-left exit, and the upper right exit. In the model, the preferred exit can be varied with a chooser button. Figure 3 shows the CTPE being determined with the lower-left door selected as a preferred exit.

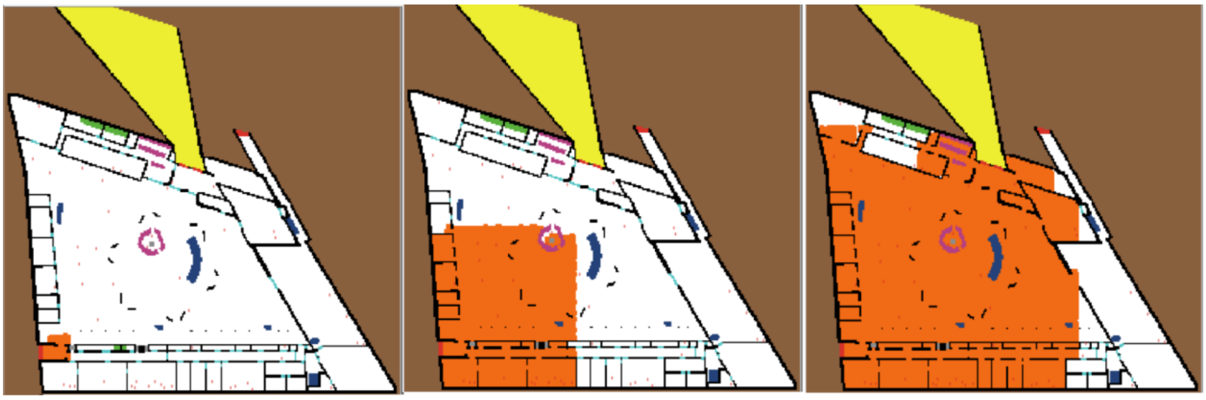

Figure 3, closeness-to-preferred-exit algorithm visualized (lower left door)

It is important to note that when a preferred exit door is chosen for all turtles to head towards, the distance that turtles will have to run to evacuate is often higher than when running towards the closest exit. This can be reflected in the maximum values for CTE and CTPE. The highest CTE/CTPE shows the maximal distance between a patch and the designated exit. Next to the value, the time it takes to run this distance by the slowest turtle (female child) is shown.

- CTE_{max} (closest exit preferred) 160 patches, 3 min 42 sec
- $CTPE_{max}$ (main exit preferred) 209 patches, 4 min 50 sec
- $CTPE_{max}$ (lower left exit preferred) 240 patches, 5 min 33 sec
- $CTPE_{max}$ (upper right exit preferred) 268 patches, 6 min 12 sec

As seen all max CTPE are higher than the max CTE. The CTPE of 268 means that theoretically, to reach the upper right exit, a turtle will maximally have to travel 268 patches (402m). This takes the slowest turtle 6 minutes and 12 seconds. Note that this evacuation time assumes no congestion, which is often not the case.

4.2.2 Evacuation behavior

When the alarm turns on visitors, excluding children with parents, are assigned a response time before they start evacuating. The response time is determined by the task the visitor is doing at the tick that the alarm turns on. When the timer runs out, the visitor starts evacuating.
As long as this timer is not yet done, the visitor will continue what they were doing as if there was no alarm. However, they do look around at other visitors to see if others evacuate. When in their alerting range (parameter “alerting-range”) the majority of visitors are evacuating, there is a 10% chance per tick they will also start evacuating.

Staff-members (and visitors with fire training) will instantly start moving to the closest exit. Every time a visitor that is not yet evacuating enters their alerting range (parameter “alerting-range”), a staff-member will stop and tell the visitor to evacuate. They will also tell any visitor in their alerting range where the closest exit is. This comes in handy when staff-members come across visitors blindly heading towards the preferred exit, for example.

Children with parents always follow their parent-turtle, regardless of the alarm. Because of this, they will only evacuate when their parent-turtle does so.

When evacuating, congestion can occur when there are too many visitors on the same patch. When the maximum capacity (parameter: “max-turtles-per-patch”) of a patch is reached, visitors who want to move there can’t and thus are stopped. Narrow paths like doors could cause visitors to pile up and stop moving until there is room to do so.

4.3 Overview of all assumptions

Table 1 contains all assumptions that are made to translate the conceptual model of the library into a Netlogo model that can be used for analysis. A large fraction of these assumptions is based on literature findings, as presented in section 2. Other assumptions are based on assumptions or argumentation. In the constructed model, all living people are represented by turtles in this model. Physical elements, like building structures, are modeled with patches.

Table 1, model assumptions

Model section	Assumption
Staff member spawn location	50% (variable parameter) of staff members are placed randomly on orange patches (desk locations, see figure 4). The remaining staff members are placed randomly on white patches throughout the library. After this, all orange spaces are colored white to show that orange patches represent the same flooring as white patches.
Visitor spawn location	Visitors are placed randomly on white patches throughout the library during the setup.
Response time	Visitors have a response time which determines the time it takes to finish a task or respond to the alarm going off. We assume an average of 60

seconds for this (parameter “Average-response-time”). This results in a time that is based on the following rules:

- The response time of a studying visitor equals 1.5 times the “average-response-time”
- The response time of a visitor asking a question equals half the “average-response-time”
- The response time of a visitor that is walking equals the “average-response-time”
- The response time of children without parents equals the “average-response-time”
- Children with parents only evacuate once their parent turtle’s response timer reaches 0
- Visitors have a 10% chance per tick of reducing their remaining response time to 0, if the majority of visitors around them (radius: “alerting-range”) have a remaining response time of 0

Walking speed	All agents have a walking speed, where men walk faster than women and adults faster than children. If too close to each other, some can not walk, hence decreasing the overall speed. The variable “max-turtles-per-patch” determines how many turtles fit on one patch during an evacuation. We assume a number of 1 turtle per patch. Since a patch represents 1,5 by 1,5 meters, the number is assumed to be 1 person because running at high speed requires a lot of room. Since turtles do not run during a non-evacuation situation, this maximum only holds during evacuation. Staff members do not count towards this total. Speeds are as follows: ● Speeds (men): 0.7 patches/tick walking, 1 patch/tick running ● Speeds (women): 0.6 patches/tick walking, 0.9 patches/tick running ● Children walk and run 20% slower for both genders ● Parents of children reduce their walking and running speed to that of their child
Library population	By default, there are 450 total people in the library. Of this population, 63% is assumed male, and 37% is assumed, female. The population consists of two main classes, library staff members and visitors. There are always 50 staff members, while the number of visitors can range from zero to 4950 visitors. The visitor class consists of two subclasses, adults and children. Some adults are parents of children. The percentage of the population that is underage is adjustable and is assumed at 5%, following the assumption that there will not be a lot of children in a university library.
Physical library	A premade scaled map is used based on the characteristics of the library. This map is translated to patches in Netlogo, where one patch represents 1.5m^2. Some code is added to translate these colors to the right Netlogo colors with ranges for color-coding. For this model, we used the provided layout of the TU library. The original layout was edited slightly for better model functionality. The final

	layout is illustrated in figure 4. Some additions were made to the originally provided map: ● Several walls (black) have been thickened. This was done to prevent turtles from walking through walls when evacuating. ● Offices and desk spaces have partly been colored orange. These spaces are indicators of places where staff members can perform stationary duties. A percentage (parameter) spawns on these orange patches and performs stationary duties until the alarm goes on. These orange patches are colored white after the setup is complete.
Tasks	It is assumed that visitors and staff-members have certain tasks. We used the following rules for this: ● Staff-members either have a stationary duty (like operating a helpdesk) in which they don't move or a non-stationary duty in which they move throughout the building. We assumed a percentage of 50% for this. ● Two vertical lines can separate the library in thirds. It is assumed that visitors can only study on patches in the left and right third. ● When on a patch that can be studied on, visitors have a 5% chance every tick that they will start studying. Studying lasts 100 ticks ● When a desk patch is within a radius of 2 of a visitor, visitors have a 15% chance every tick that they will stand still and ask a question. Asking a question lasts 20 ticks
Staff member alert range	It is assumed that staff members can warn visitors within a certain range. Since one patch in this model represents 1,5 square meters we assume a standard “alerting-radius” of 6 patches.
Types of agents	It assumed that there are two types of agents in the model, visitors, and staff members. Children are modeled as visitors.
Alarm	An audible alarm will go off in the entire building after 30 seconds (30 ticks). All agents inside the library will evacuate (minding the response time). Evacuating turtles follow “closeness-to-exit” or “closeness-to-preferred-exit” values on each patch. Each tick turtles move towards the patch with the lowest “closeness-to-exit” in a radius of 2
Temporal element	The model has a unit of time of seconds, where each tick represents one second.
Congestion	During an evacuation, a maximum number of turtles is able to run on a patch. Staff members do not count towards this total, as they are assumed to get out of the way to let visitors evacuate.

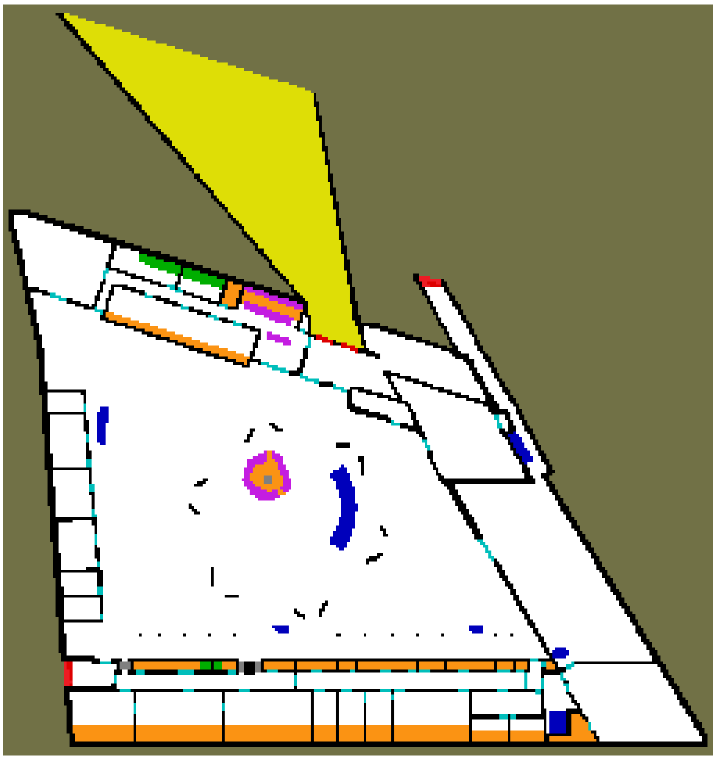

Figure 4, modified map of the TU Delft library

4.4 Model layout

The constructed Netlogo model contains an overview of the modeled system that represents the library. A set of performance indicators is used to measure model results depending on user input parameter settings. This section relevant user-visible elements of the model to give an illustration of the constructed model. For the complete model, the attached code can be consulted.

All basic model functionalities are laid out in table 2. Note that both the verbose and debug functionality are visible to the user, but will likely not be needed.

Table 2, basic model functionality

Function	Description	Range
setup	(Re)Sets the model to the default settings	-
go (once)	Runs the model for one tick (second)	-
go (forever)	Runs the model forever or until the library is empty	-
verbose	Can be useful to track what the model is doing	on/off

debug	Can be useful for solving bugs	on/off
alarm?	Manually activates the alarm	on/off

Table 3 illustrates all parameters that can be influenced by the user. The included ranges give an overview of all possible values that can be set. Mind however that this does not mean that all values within this range are plausible. For plausible values and assumptions that are used in this research, table 1 can be consulted.

Table 3, model parameters

Parameter	Description	Range	Unit
agents-at-start	Total numbers of people at the start	50-5000	Persons
percentage-female	Percentage of people female	0-100%	-
percentage-children	Percentage of people children	0-100%	-
percentage-stationary-staff	Percentage of staff that will remain stationary during a non-evacuation situation	0-100%	-
alerting-range	Range in which staff members can alert visitors during an evacuation	0-10	Patches (1,5 m^2)
average-response-time	Average time it takes for people to start evacuating	0-120	Ticks (seconds)
max-turtles-per-patch	Maximum number of turtles allowed on patch during an evacuation	1-8	Persons/patch
percentage-visitors-go-to-preferred-exit	Percentage of visitors that will initially go to the selected preferred exit	0-100%	-
Preferred-exit-door	Enables the model to pick a specific exit that people will take	“upper-right”, “upper-left”, “main”	-

Table 4 contains all performance indicators of the model. These are used to measure model outcomes and analyze them. More on this analysis can be found in section 6.

Table 4, model performance indicators (KPI's)

KPI	Description	Type
people over time	Plots total people, staff-members and visitors that are in the building with three separate lines over time	Plot
people-in-building	Gives the total number of people in the building	Monitor
evacuation duration	Gives the time in seconds that are elapsed since the alarm became active	Monitor
event duration	Gives the total time the model is running in seconds	Monitor
percentage visitors currently not evacuating	Gives the percentage of people that are not evacuating which changes over time	Monitor

5. Verification & Validation

The model as constructed in this research should be useful for the user, meaning that an evacuation situation in the library is modeled correctly. As Wilensky and Rand (2015) state, the accuracy of the model can be determined by three modeling processes: validation, verification, and replication. This section covers both the verification and validation steps that are performed on the constructed model.

5.1 Verification

During the verification, it is checked whether the model code performs as it was intended during writing. We have performed two kinds of tests in order to verify the constructed model. Firstly, we test our model by normal visual verification. With this we mean that we visually inspected the model under normal circumstances and looked for strange or incorrect behavior. Secondly, we performed a similar visual check for the model under extreme conditions. Lastly, a sensitivity analysis is performed, where the effects of changes in input variables are tested on model outcomes. This way, we determined the overall sensitivity of the model and which factors have the most influence on it.

5.1.1 Normal visual verification

Table 5 shows the model elements that are visually checked in order to perform this normal visual verification. The model is run under parameter settings considered normal, as illustrated in table 1.

Table 5, visual verification

Behavior to be monitored	expected behavior	occurs as expected?
Movement of turtles	Turtles do not walk through walls	yes. Exception: during evacuation with extreme visitor count (>5000) with low max-turtles per patch, Visitors (<10) could clip through walls.
Exiting of turtles	Turtles die when exiting the building, regardless of whether the alarm is on or off	yes
Movement of children with parents	Children with parents always follow their parents, even when they are performing a task	yes
Stationary and moving staff	Some staff stay stationary in designated areas, while others freely roam	yes
Alarm switch on	When the alarm turns on, eventually all turtles exit the building	yes
Alarm switch off	Behavior of all turtles switches back to “pre-alarm”-behavior, even if the alarm was turned on and off before	yes
Pathfinding	Turtles head to the designated exit following the shortest path to the exit	yes
Staff-members aiding visitors	Staff-members standstill while visitors are in alerting range during an evacuation.	yes
Visitors watching other visitors’ reactions to the alarm	Visitors can reduce their remaining response time to 0 if many others are in alerting range with a response time of 0	yes
Congestion	Narrow exiting routes cause congestion. This is amplified by the max-turtles-per-patch parameter	yes

5.1.2 Extreme conditions

This section covers model results under extreme circumstances. Table 6 shows the parameter changes that are used to create circumstances that are considered extreme.

Table 6, extreme conditions setup

Parameter	Range
Number of visitors	N = 0 or 5000 turtles
Fraction of children	0% or 100% of visitors
Response time	0 sec or 120 sec
Maximum turtles per patch	1 or 8 turtles/patch
Alerting radius	0 or 10 patches
Visitors going to preferred exit (not closest)	0% or 100% of visitors

One issue the model faces when under extreme conditions is agents clipping through walls when evacuating. Clipping happens with an extreme visitor count (5000), a very low maximum turtles per patch (1), and 100% of turtles exiting to a side exit (lower-left).
The result is a large congested clump of turtles, as seen in figure 5. In some areas of the library, the wall is only one patch thick. When pressed against a wall due to congestion, sometimes a patch on the other side of the wall comes into the search radius 2 of the evacuation algorithm, causing turtles to jump through the wall. Measures were already taken to prevent clipping near doors. These prevent almost all clipping issues at N = 450 turtles. However, under extreme conditions congestion clumps can become so large that clipping can still occur in surrounding walls. Clipping could be further prevented by thickening all walls in the library, but this has not fully been done. This limits the validity of the current model at very high turtle counts.

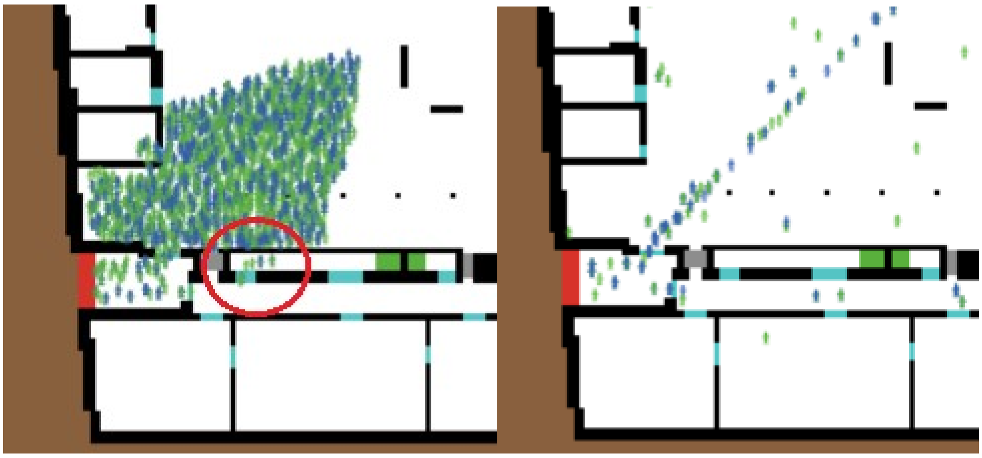

figure 5, congestion-caused clipping at N=5000; effect not present at N=450

Under different extreme conditions, the model also shows interesting behavior: high alerting radius and a high percentage of visitors going to preferred exit (lower-left). When the alerting radius is very high, almost all turtles are quickly in range of a staff member during evacuation. This results in almost all turtles heading to the nearest exit, effectively nullifying the parameter “percentage-visitors-go-to-preferred-exit”. This effect holds true for both high and low turtle counts. It is however not very realistic to assume a high alerting radius (15m), because panic and noise caused by the fire alarm could impair the ability of staff members to communicate with visitors.

5.1.3 Sensitivity analysis

In order to perform the last verification step, the model is tested on sensitivity. This is done by varying model parameters by plus ten and minus ten percent. The following parameters were varied for this:

Table 7, sensitivity analysis setup

Parameter	Range (-10%, normal, +10%)
Percentage female (gender)	33,3 - 37 - 40,7
Percentage children (age)	4,5 -5 - 5,5
Percentage visitors go to preferred exit	86,4 - 96 - not relevant (>100%)
Alerting range	5,4 - 6 - 6,6

The combinations as illustrated in table 7 are each run 20 times. Table 7 gives an overview of the results of this sensitivity analysis. It is however important to note that the results deviate significantly each run, the standard deviations in evacuation time were high. Due to computational and size limitations, more repetitions per combination were not achievable at this point.

Table 8, sensitivity analysis results

Parameter	Change parameter	Change evacuation time
Percentage female	+10%	-2,7%
Percentage female	-10%	-7,2%
Percentage children	+10%	+1,5
Percentage children	-10%	-0,1%
Percentage visitors go to preferred exit	-10%	-0,4%
Alerting range	+10%	-2,9%
Alerting range	-10%	-3%

As shown in table 8, relations between parameters and outputs are not always straightforward. A higher alerting range would arguably lead to an expected faster evacuation. While this was indeed the case, a lower alerting range also leads to a faster evacuation. This could be due to a limited amount of repetitions done, with a very large deviations between results. However, the results indicate that the model seems sensitive to gender and alerting range, and less sensitive to age and familiarity.

5.2 Validation

Validation examines whether the constructed model behaves in a way that is suitable for providing insight into the behavior of the physical system. The constructed model simulates an evacuation of the TU Library. The building layout used is accurate enough to simulate the pathways and exit locations in the physical system. Turtles exit the building during an evacuation realistically. Visual inspection concludes that the way turtles exit the building matches our perception of how the TU library would evacuate. Do note that since there was no actual visual/numeric data provided of an actual evacuation event in the TU library, it is difficult to fully validate that the behavior is accurate. The behavior of visitors has therefore been based on studied literature, as well as guidelines provided by the assignment.

The model outputs values that monitor evacuation duration. These outputs are influenced by the input parameters that model users can vary. This way the effect of parameters on evacuation behavior can be studied. This means that the model is able to execute the intended use case of the model. From these findings, the model is concluded to be valid for research purposes.

The model seemed to have reasonable evacuation times. The evacuation time found was about 6 minutes in the base scenario. In a study of an evacuation of several apartments, the evacuation time was found to be about nine minutes (Proulx, 1995). Although our case is a library, the reported evacuation times are in the same order of magnitude.

6. Analysis

This section covers the analysis part of this research. The set of performed experiments are discussed first, after which the results from these experiments are translated to meaningful insight with the use of Python.

6.1 Experimental setup

Three experiments will be conducted. To see what the main difference in evacuation time is when all agents exit via the main exit or the nearest exit, experiment 1 was conducted. See table 9. To see what the difference was in evacuation time when a different exit was preferred, experiment 2 was conducted. Experiment 3 was conducted to see what the influence of the percentage gender and percentage of children is. The experimental setup of experiments 2 and 3 can be seen in table 10 and table 11 respectively.

Table 9, experiment 1 (1100 runs, 100 repetitions)

Parameter	Values
Percentage female	37
Percentage stationary staff	50
Alarm	True
Percentage children	5
Max turtles per patch	1
average response time	60
agents at start	450
percentage visitors go to preferred door	0 up to 100, step 10
preferred exit door	main
alerting range	6

Table 10, experiment 2 (600 runs, 50 repetitions)

Parameter	Values
Percentage female	37
Percentage stationary staff	50
Alarm	True
Percentage children	5
Max turtles per patch	1 up to 4, step 1
average response time	60
agents at start	450
percentage visitors go to preferred door	96
preferred door	main, lower left, upper right
alerting range	6

Table 11, experiment 3 (1800 runs, 50 repetitions)

Parameter	Values
Percentage female	0 up to 100, step 20
Percentage stationary staff	50
Alarm	True
Percentage children	0 up to 100, step 20
Max turtles per patch	1
average response time	60
agents at start	450
percentage visitors go to preferred door	96
preferred door	main
alerting range	6

6.2 Analysis

The generated results from the three experiments are analyzed using Python scripts. This section covers the results from these analyses. The used scripts can be found attached to this report in the folder named “model/analysis”.

6.2.1 Effect of using the main door or nearest door on evacuation time

In experiment 1, the average evacuation times per percentage of visitors going to the main door ranged from 344 seconds to 370 seconds (+7.5%). In experiment 1, in a standard scenario, ceteris paribus, the difference in evacuation time was about 26 seconds. This difference was found when evaluating a scenario in which all visitors know the closest exit and a scenario where all visitors know only the main entrance. Figure 6 illustrates the found values for the evacuation time when the percentage of visitors that go to the main door ranges from 0 to 100.

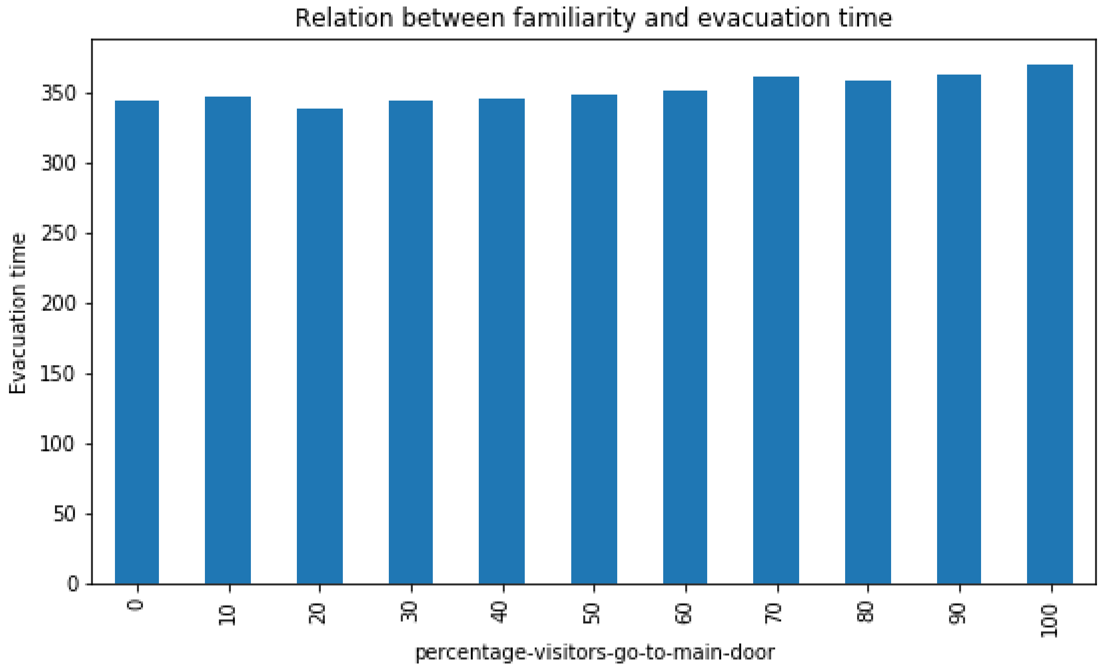

Figure 6, Percentage visitors going to main door and evacuation time.

6.2.2 Influence of available exit doors

There is a clear relationship between the preferred exit door and the evacuation time. As seen in figure 7 there were clear differences, even when the maximum amount of agents per patch was varied. The main door yielded the lowest evacuation time, followed by the lower left door and the upper right door.

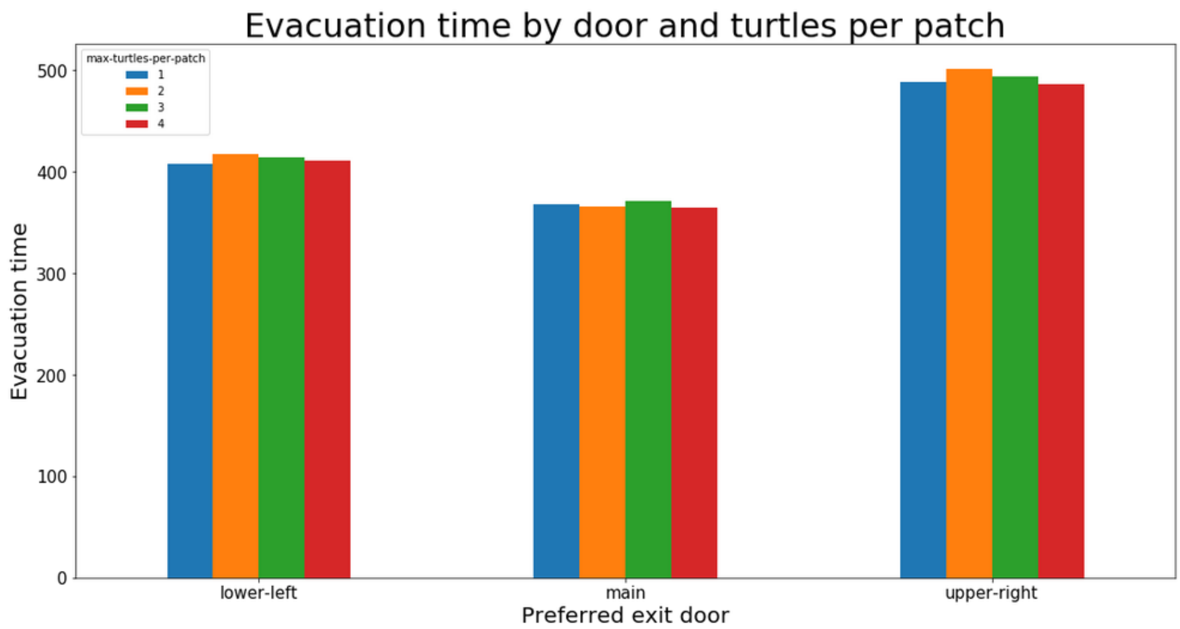

Figure 7, evacuation time by door and turtles per patch

Paragraph 4.1.1 mentioned the maximal time, without congestion, that it could take a visitor to reach any of the preferred exits. These theoretical times can be compared to the maximum time it has taken for turtles to reach the exits during the experiment:

Table 12, comparison of theoretical maximum evacuation time and experimental results

Preferred exit	Theoretical time	Experimental time	Δ_{time}
main exit	4 min 50 sec	6 min 7 sec	+ 1 min 17 sec
lower left	5 min 33 sec	6 min 52 sec	+ 1 min 19 sec
upper right	6 min 12 sec	8 min 12 sec	+ 2 min

As seen in table 12, all experimental times are higher than the theoretical times. Two main factors contribute to this: congestion and response time. These factors were not taken into account when calculating the theoretical time. The theoretical time is merely the time it takes to run from the furthest removed patch to an exit.
While response time was kept constant during all runs, congestion is an emergent model property that manifests itself in different ways based on the layout near the doors. This could explain why the upper right door has the highest added time delta. To reach the upper right door, turtles have to navigate through a long narrow hallway and several narrow doors. This makes the upper right door less accessible to large crowds and thus causes extra congestion. The main and lower left exits are more easily accessible and thus have less congestion and a lower added delta.

6.2.3 Influence of gender and children on evacuation time

In experiment 3, the percentage of children and females was varied. Regression analysis yielded a beta of 0.24 for percentage female and 0.13 for percentage children. Thus, it could be concluded that a variation in the number of females yields the biggest difference in evacuation times. More females generally lead to a higher evacuation time.

For each combination of parameters, the average evacuation duration was calculated. This was plotted in figure 8. In this plot, one can see that a higher percentage of females always leads to higher evacuation times. This is not true when one looks at the effects of the number of children. This relation is rather complex, as seen in figure 8.

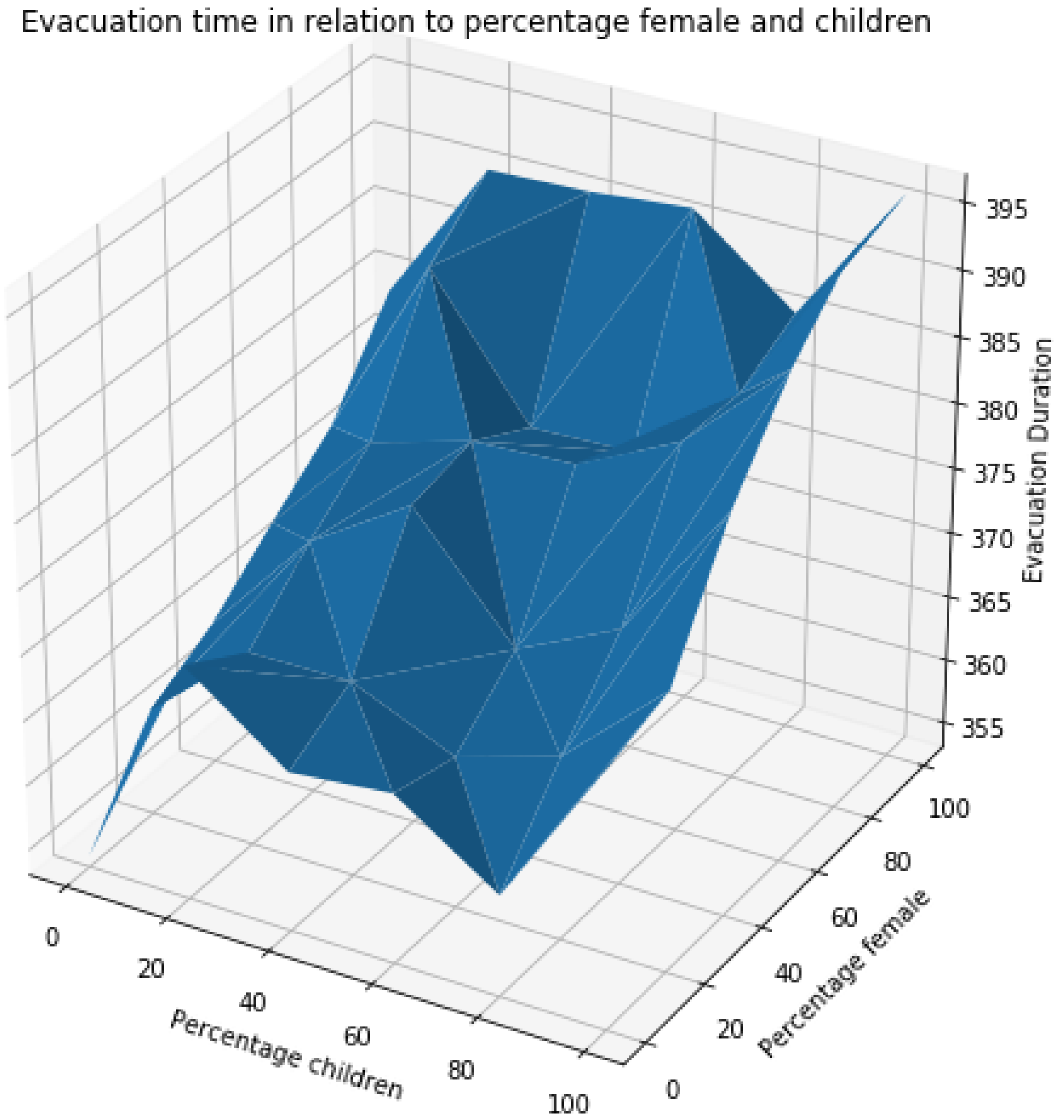

Figure 8, Relation between percentage children, female and evacuation duration.

7. Conclusion

Now that all experiments have been performed, the research questions can be answered.

1. What is the difference in total evacuation time if all agents exit via the main entrance versus all agents exit via the nearest exit?

When all agents are initially given the instruction to head to the main door during evacuation, instead of the nearest exit, evacuation time rises by 7.5%. From this difference, we can conclude that familiarity plays a significant role in determining evacuation duration.
It is important to note that in the experiments, everyone was given an initial instruction to head to the main door. However, staff-members could have altered this heading by alerting visitors where the nearest exit is. In short, even though everyone initially heads to the main door, visitors who encountered staff-members would still have exited through the nearest exit.

2. What is the relation between which exits are used and the evacuation time?

Experimentation revealed a clear relation between which door was used primarily and the total evacuation time. The main door of the library yielded in the lowest evacuation times (6 min 7 sec), followed by the lower left (6 min 52 sec) and the upper right door (8 min 12 sec).

3. How does gender influence total evacuation time?

In our model, a higher percentage of females yielded higher evacuation times. Such a clear relation was not found with the number of children and the total evacuation time. The relation between the number of children and females was found to be rather complex.

The model has a few limitations. First, the model is only applicable to the TU library and only to the ground floor. Evacuations on multiple floor levels have not been researched. Furthermore, this model simulates a fire event, but no actual fire has been implemented in the model. Wounded or incapacitated visitors have therefore not been implemented.

From examining evacuations of the TU library, insight was gained into how to improve evacuation speed. One recommendation for the TU Delft is to add an emergency exit in the lower right corner of the building, as seen in figure 9. This corner is furthest removed from any exit. Adding an exit here reduces the maximum distance from any patch to the closest exit in the building by 58.5 meters. With this exit added, the furthest patch removed from an exit becomes a patch in an office, not adjacent to an exterior wall. Even though we hypothesize that this addition would reduce evacuation time, it is unclear what the precise effect of adding this exit would be on evacuation duration. This could be the topic of further research.

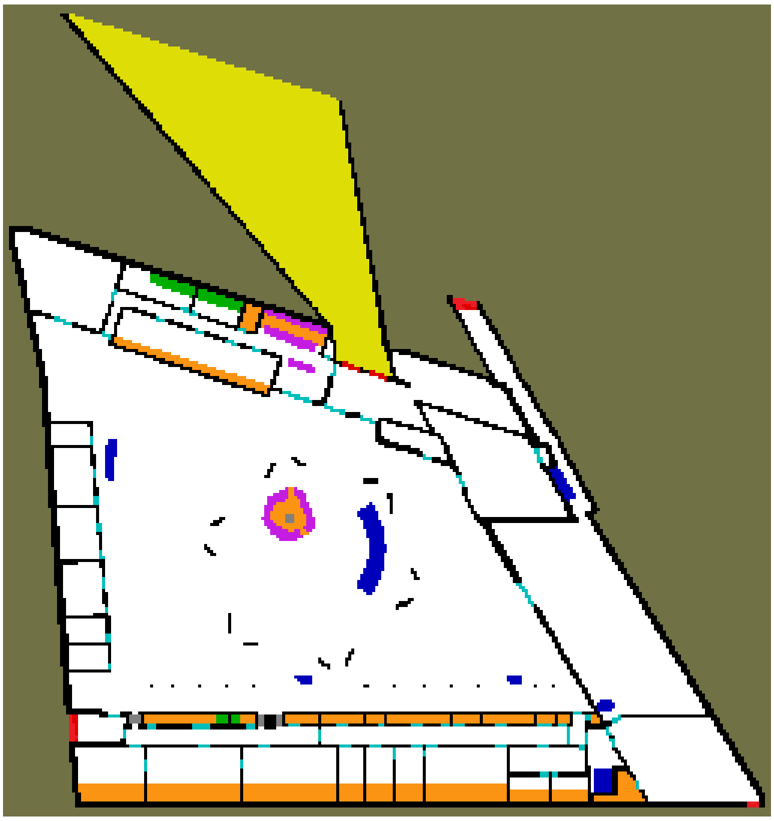

Figure 9, library with a door added in the lower right corner

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