MASTER

Human behaviour simulation
an application in the architectural design process

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HUMAN BEHAVIOUR SIMULATION
AN APPLICATION IN THE ARCHITECTURAL DESIGN PROCESS

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Human behaviour simulation
An application in the architectural design process

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Human behaviour simulation: an application in the architectural design process, is the result of my graduation project conducted in the Architecture and Design Systems design studio. This report is the result of almost a year of dedicated research and hard work. I feel this research could not have existed without the help of several people that I therefore wish to thank.

First of all I would like to thank Prof. dr. ir. Bauke de Vries for his supportive comments during the different interim colloquia and the opportunity to graduate in a studio focussing on both Architecture and Design Systems.

Secondly, I would like to thank ir. Maarten Willems and ir. ing. Aant van der Zee for their weekly tutoring sessions. These sessions never failed to provide new inspiration as well as a critical reflection upon my existing ideas, for which I am very grateful.

Furthermore I would like to thank my family for providing the supportive environment in which I was able to complete this research.

Finally I would like to thank my fellow students for their wide variety of reactions upon my project. These reactions ranged from questions as: "How did you track all the people entering the station?" to: “Shouldn't you be working on your project, instead of playing games?” when they saw me working with the model.
ABSTRACT

The Architecture and Design Systems graduation studio focuses on how new technological inventions can be applied in the architectural design process. In this studio, this research was started by investigating a new innovation in the building industry, agent based simulation. During this investigation a framework was developed to evaluate and relate several studies form various fields of research. These studies represent the state of the art of agent based simulation models.

In addition to this theoretical research, a multi agent simulation model was developed to test the practical implementation of several aspects of human behaviour found during the literature study. The model developed during this research is able to simulate human behaviour in the context of a train station. Important aspects of behaviour included in the model are: different kinds of sensory perception, a realistic procedure for route planning based on an individual agenda and personal preferences, psychological based routines for wayfinding and collision avoidance, and various routines to evaluate a design.

After the model was completed its potential for application in an architectural design process was investigated by using the model as an integral part of a design process for a new train station in the city of Eindhoven. This design process consisted of three stages and was started by using the model to evaluate several different possible station layouts. After determining the most optimal layout, this layout was selected and further developed during the second phase.
of the design process. The second phase consisted of redefining the building requirements to better fit the needs of a station in Eindhoven and further optimizing the morphology of the station. During this phase the model proved its ability to support a design process by making the movement of the station’s visitors insightful. By actively involving this movement in the design process it became possible to improve upon the generic solution of a straight hallway. Ultimately, the second phase resulted in a decrease of the overall density experienced throughout the station of 8%, solely achieved by shaping the morphology of the station. Finally in the last phase, the floorplan that was developed during the previous phases was transformed into a spatial design. A vital aspect of this spatial design is the notion that different parts of the station all have a specific relation with the occurring movement of their users and should therefore have different levels of expressing this movement. This notion is clearly reflected in the design of different parts of the station that all received their specific treatment. During this stage the model proved to be of great use by providing quantitative data about the passenger flows, which was used as an the main initiator for the geometry of the station.

The eventual design shows various examples of how the results obtained from an agent based model could be incorporated in an architectural design process. During this research it has become clear how agent based models are able to exceed the common sense in predicting the future use of a station. The results obtained during this research show the potential of agent based models in improving a design process by making different complex aspects of human behaviour insightful. This allows a designer to actively involve phenomena such as passenger flows in the design process and create a closer collaboration between form and function. Although the potential benefits of agent based models might differ for different building typologies this research proves the need for an application of agent based models in the design process of public transport facilities.
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**Bibliography**
This research is the result of my graduation project conducted in the Architecture and Design Systems graduation studio. This studio, which was started in September 2014 under the supervision of Prof. dr. ir. B. de Vries, ir. ing. A. van der Zee, and ir. M.H.P.M. Willems, aims to explore how new technological inventions can be applied in the architectural design process.

A new invention that has made its entrance into the building industry is the application of various types of simulation software in the design process. But although throughout the last decades it has become common courtesy to embrace simulation software as an important part of the architectural design process the way the movement of the building’s inhabitants influences their experience and how the shape of the building influences this movement is often excluded from these simulation packages. Incorporating human movement and experience in simulation software could therefore further improve the use of these packages by linking the stimuli of an environment to its perceiver.

Although the anticipated future use of a building will always be an approximation, a system that is able to support decisions concerning this future use by making it more insightful, can be a very useful tool for any designer. Such a tool could enable designers to make better informed and more rationally substantiated decisions. At the moment there are some models that are able to simulate human movement but the results obtained from these models are insufficient for a full scale implementation in architectural design. Improving upon previously
developed models by either creating a model that is able to simulate more realistic behaviour or creating a model better suited for an application in a design process can be an imported step towards integrating human behaviour simulation in the architectural discipline.

A research field concerned with the creation of models that are able to simulate different kinds of complex behaviour, for which human behaviour unmistakably qualifies, is the research field of agent based simulations. A definition of agent based simulations and their potential for the simulation of human behaviour is given by Endriss[1]:

"Multiagent systems are systems composed of several autonomous agents, e.g., computer programs or robots, that interact with each other in a variety of ways, including coordination, cooperation, and competition. There are clear parallels to the ways in which individual people interact with each other as members of our society. It therefore is not surprising that formalisms and methods developed in the social and economic sciences, originally intended for the purposes of modelling and analysing humans and human society, have found rich applications also in the field of autonomous agents and multiagent systems."[1]

Because of their potential for the simulation of human behaviour it was decided to use a multi agent modelling approach to develop the model that has been applied during this research. The need to actively involve the behaviour and movement of a building's users in the design process becomes clear from a quote by the famous architect Rem Koolhaas:

"As more and more architecture is finally unmasked as the mere organization of flow—shopping centers, airports—it is evident that circulation is what makes or breaks public architecture...."[2]

This quote not only states the importance of movement but automatically shows the potential for software that is able to accurately predict this movement. A model able to simulate and visualize the future movement in a building could therefore be applied in different stages of a design process. The results of the model could potentially be used to improve a design
and make better informed design decisions. The quote also stresses that this movement is especially important in public architecture. This research therefore aims to develop a model capable of simulating various aspects of human behaviour as well as to design a new train station for the city of Eindhoven in close collaboration with this model. This would provide the ultimate test for the potential of the application of multi agent systems in the architectural discipline. To guide the process of this research, the following research question was formulated:

**How can simulations of the human experience of architecture improve an architectural design process for a new train station in the city of Eindhoven?**

To substantiate this research question several sub questions have been formulated, to be answered during the process of this research:

*How can different aspects of human behaviour be simulated in a multi agent simulation environment?*

*Can a model that is able to simulate human behaviour exceed the human ability to predict this behaviour?*

*How does making a model that is able to predict the future behaviour of a building’s visitors influence an architectural design process?*

*What implications does using a model that is able to predict the future behaviour of a building’s visitors entail on an architectural design?*

*To what extent should a model be validated in order to be of use in an architectural design process?*
Research methodology:

The first step towards answering the research questions was conducting a literature study focussing on the simulation of human behaviour in a multi agent simulation environment. During this study a framework was developed to relate and evaluate different researches from various disciplines. The ultimate goal of this review was to take the most relevant parts of these investigations and prepare them for an application in the model used in the latter phases of this research.

The second step consisted of the implementation of the findings from the previously mentioned literature study in the Netlogo simulation environment. After the model was completed, its practical application was tested by an application in the design process of a train station. The design process was started by conducting research into the needs of a train station, the requirements for the city of Eindhoven, and the influence of movement on architectural design. This part of the research formed the foundation of the next stage of the design process concerned with the application of the model which eventually resulted in the design of the station.
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LITERATURE REVIEW

Work in the area of simulating human behaviour in the build environment is mainly conducted in the fields of urban design and psychology. In architecture, the research is mostly limited to analyses of existing buildings or focused on evacuation protocols in emergency situations, although there are a few models suited for application during the design phase. To incorporate a broad range of different aspects of human behaviour a review of different researches from various fields has been conducted. A brief summary of researches that contributed a method to simulate human behaviour included in the model is presented in this chapter.

Architecture

A research in the simulation of human behaviour from the architectural field is the work of Narahara[3], who recognizes the need for the use of visualisation tools of human behaviour in architectural design and the potential of agent based models to overcome the absence of this functionality in contemporary architectural design software. Narahara[3] proposes a model consisting of agents that are able to evaluate the famous Barcelona pavilion by Mies van de Rohe.

Other research from the field of architecture is the work of Narain et al.[4] as they developed a system capable of supporting the design process of public buildings by modelling the dynamics of crowd simulations. Their model is similar to the commercial software package
called MassMotion[5]. Although the goal of these packages is similar to the objective of this research, it is important to note that there are some fundamental differences considering the approach used to achieve the behaviour of the ‘agents’ when compared to an agent based system such as proposed by Narahara[3].

The difference between the different modelling paradigms is mentioned in the work of Macal and North[4]. Based on their work, the model of Narain et al.[4] and the Massmotion[5] package can be described as a macroscopic modelling approaches, relying on differential equations to calculate the movement of the agents. Opposed to the macroscopic approach are microscopic models such as agent based modelling, that have a finer-grained representation of the system and a more explicit way of taking into account individual characteristics and behaviour of the agents. Macal and North[6] state that:

"[When] weighing the pros and cons, agent-based modeling seems most promising when dealing with complex systems characterized by a large number of individually acting entities."[6]

Using an agent based model could therefore potentially improve upon models such as the Massmotion[5] package by creating more realistic behaviour.

A microscopic model that is able to support a design process by modelling passenger flows, is the NOMAD research project by Hoogendoorn[7]. The system is capable of predicting the most likely cause of action of agents, given their personal preferences, during the selection of activities for their personal agenda as well as during the execution of these activities. Another microscopic model, called SimPed, is presented in the work of Daamen[8]. Both of these researches have contributed several insights with regard to modelling agents moving through public transport facilities.

Finally, in the work of Tabak[9] a model has been developed that evaluates building performance based on the activities of the buildings members. Particularly interesting in this research is the agent’s ability to select multiple activities and assemble them in an agenda.
**Behavioural psychology**

Rymill[10] delivers by far the most sophisticated model for the simulation of human perception and movement. The aim of Rymill[10] was to improve behaviour simulation models by making use of several ideas from psychological research. The agents’ cognition exists of procedures for collision avoidance (based on observed practices), procedures for vision and attention simulation, and a direct relation between the emotions of the agents and their behaviour. Eventually Rymill[10] is able to conclude:

“This thesis demonstrates that the use of techniques based on psychology research leads to a qualitative and quantitative improvement in the simulation of human behaviour”[10]

**Emergency egress**

Another field in which different simulation techniques have made an entrance is that of the simulation of human behaviour in evacuation situations. One of the researches into this particular subject is conducted by Pan[11]. Although the goals of egress simulation models differ from the goals for this research project his work recreates several aspects of human behaviour that also hold under ‘normal’ circumstances. Some aspects mentioned by Pan[11] are therefore included in the model as they yield a clear and effective representation of human assets without becoming unnecessary complex.

**Urban planning**

Although the work of Dijkstra et al.[12] mainly focuses on behaviour in a urban context, several aspects of the model’s implementation in the Netlogo simulation environment are interesting. Such as: the arrival and departure of the agents from the model and storing the information considering the agent’s agenda in the memory of the agent.
Based on the research evaluated in the literature review a conceptual framework was developed to classify different aspects of human behaviour. The framework subdivides human behaviour into four categories. These categories are: the behaviour of the agents that is directly perceivable such as walking and moving, creating goals and subdividing them into achievable sub goals, a perception of the agents’ environment, and experiencing and interpreting stimuli.

The framework has proven to be a very useful tool to summarize and compare different models from various fields of research. Although the same subdivisions are not necessarily used by the authors of the different articles it is a division that can be used for most of the articles and functions as a starting point for a comparison of the different articles. A similar distinction is made by Teahan[13] who also uses four categories:

“There are also various aspects to behaviour, including the following: sensing and movement (sensory-motor co-ordination); recognition of the current situation (classification); decision-making (selection of an appropriate response); performance (execution of the response).”[13]

For the development of the model it is important to recreate different parts of behaviour that are a part of the different categories. The behavioural aspects included in the model will now be described in further detail.
Perception

One of the most basic requirements for an agent to possess some sort of intelligence is the ability to react to and interact with its environment. The agents are therefore equipped with procedures to receive various stimuli from their environment.

For the visual perception of the agents a routine has been developed based on the work of Pan[11]. Every agent is equipped with a field of vision of 15 meters and an angle of 180 degrees. This number of 180 degrees is a little higher than the human field of vision which approximates 180 degrees. This slightly wider angle produces a more realistic field of vision as the wider angle compensates for movement that occurs while moving. The agent’s perceptual field is able to recognise other agents or objects close to the perceiver. These other agents are then evaluated with a ray tracing algorithm that checks if the agents are occluded and should therefore be excluded from any further assumptions about the environment. The ray tracing algorithm can be thought of as drawing an imaginary line towards a target. If the line is interrupted somewhere between the perceiver and the target this means the target is occluded and will not be visible for the perceiver. This procedure is visible in Figure 3.

An important aspect of our experience of a train station is the extent to which the station feels crowded. Evaluating this aspect of experience introduces the need for a routine that is able to evaluate the agents near surroundings and the amount of other agents present in its close proximity.

The process of evaluating our environment is composed of a multitude of senses working harmoniously together. Visual perception, touch, smell and others all play their part in perceiving our environment. Instead of recreating all these different aspects, a procedure has been developed to evaluate the environment and count the amount of agents surrounding an agent in an eight meter radius. Although the agent becomes aware of these other agents and includes them in its evaluation of its surroundings, these agents are excluded from any

Fig 3, above: The ray tracing algorithm is able to reach the agent without any interruption.
Below: The ray tracing algorithm is interrupted and the agent is therefore occluded.
routines that influence the directly perceivable behaviour of the agent, such as movement and collision avoidance.

Finally, the agents are able to extract data about the amount of daylight present in the environment. This data can be included in the model by mapping the data from external daylight simulations to the floorplan used for the simulation.

**Goal selection**

A very important aspect of obtaining realistic behaviour is realistic goal selection and route planning. One of the most important benefits of enabling agents to choose realistic goals and routes is enabling the agents with the evaluation of various aspects concerned with the decision. This can be illustrated by an example where a shop is located far away from all of the train platforms. When the agents randomly select a shop to visit, this particular shop will get roughly as many visitors as any other shop (located closer to the train platforms). In reality, people will often reconsider their choice if they consider the walking distance being too big, especially when the time until the departure of their train is limited. If such a decision would be included in the agents’ cognition, this decline of visitors, due to the location of the store, can be predicted. This prediction could then be used as an argument to change a design. The process of determining which activities an agent wishes to undertake and the selection of an appropriate place for this activity all start with the assembly of an activity agenda.

**Agenda assembly:**

Although people visit train stations for a variety of reasons in general three types of visitors can be distinguished.

The first category exists of pedestrians who use the station merely as a passage from one side of the city to the other side. These people do not have the intention to use any of the
transportation facilities of the station but are potential customers for shops located in the station.

The second category exists of people who arrive at the station by any means of transport and leave by another. These are for instance people who arrive by train and leave by bus or arrive by car and leave by train.

The third category exists of people who use the station to change trains, arriving at one train platform and departing from another. All of these categories have different characteristics related to the use of the train station’s secondary facilities. Ideally, the exact quantity of use of these facilities should be obtained by analysing related projects in close collaboration with the client. Although this data could easily be incorporated in the model, harvesting this data is a time consuming process. For this project an estimation of the frequencies of store visits and average service time has been used as input for the model. These numbers, based on the numbers presented by Daamen[8], are visible in Figure 4. Based on this estimation the agent gets allocated an agenda containing the activities the agent has to perform. The order in which to perform the activities is randomly chosen and remains fixed during any further steps of the selection process. Finally, the end goal of the agent is added at the end of its agenda.

**Route selection**

The next step is finding a route that matches the agent’s agenda. For this step it is assumed that visitors of the station have an understanding of the layout of the station and are able to make informed decisions about their preferred route. In different researches, various approaches to find an optimal route while passing through various sub goals have been modelled. An important difference between the model developed for this thesis and the models described in literature, is the amount of variables evaluated in the route selection procedure. Other models often find either the shortest path between different activity locations or find a path along locations that have the highest utility based on the agent’s preferences. These modelling...
approaches exclude an important aspect of human route selection by ignoring the time factor in the decision process. The approaches therefore fail to answer an essential question present in the decision process: “If I go to that shop, will I be able to catch my train?”. This question bears a distinct notion of time and asks for a different approach of finding an optimal route. An approach that takes into account the arrival of the next train enables the agent to attend his favourite establishment at the other side of the station when this train will depart in half an hour or pick a shop nearby if the train is departing in five minutes.

The procedure that determines the optimal route starts by selecting all the locations appropriate for the execution of the activities present in the agent’s agenda. These locations can be included in the simulation environment by color-coding certain areas of the floorplan. The locations get a value between zero and ten, which represents the agent’s preference for certain establishments. At the moment people’s preferences for different shops are unknown and the model therefore uses random values for their preferences. In future research it would be possible to replace these values with a set of numbers related to the predicted visitor numbers of different shops. These locations are then arranged as the vertices of a decision graph. The graph is started with the current location of the agent as it enters the simulation. Subsequently, the different possible activity locations and the possible exits of the station are added to the graph. Last, an estimation of the travelling time between the various activity locations is added to the edges of the graph. This estimate is based on the distances between the different locations. These distances have been calculated during the setup procedure of the model by making use of the A* pathfinding algorithm, which will be further explained during the pathfinding section. The distances are then divided by the agent’s preferred walking speed.

Based on the values present in the decision graph it becomes possible to select a route along the agent’s preferred locations and calculate the agent’s estimation of its traveling time. This is done by making use of Dijkstra’s shortest optimal path algorithm. It is important to note that the implementation of Dijkstra’s algorithm only takes into account the values of the vertices.
of the decision graph. For the agents that do not have a train as their eventual goal this initial route is selected. For the agents that do have a train as their final destination the values assigned to the edges connecting the vertices are then added to obtain the overall travel time of this route. The agents then add a 20 percent buffer to this travel time to account for small delays and compare it to the time available until the arrival of the next train. If the travel time would exceed this available time and traversing this route would result in failing to reach the train in time, the agent’s decision graph is updated by excluding the destination of the last activity. Dijkstra’s algorithm is then used again to find the optimal path in the new decision graph. This process is repeated until the agent finds a path that allows it to reach the train in time. If such a route does not exist, because the next train will, for instance, leave the station 2 seconds after the agent has entered the station, the initial graph is re-used and the travel time is compared to the arrival time of the next train. An example of an illustrative route choice procedure is visible in Figure 5.

**Wayfinding towards goals**

After the selection of the locations the agent will select a route towards the first location present in its agenda. This process of route selection, which is concerned with a different level of scale as the previously mentioned route selection, is also known as wayfinding. To determine the most convenient route towards the goal the agents make use of the A* path finding algorithm. Rymill[10] proposes this algorithm developed by Hart, Nilsson and Raphael[15]. Using the A* pathfinding technique has the advantage that it will always find the shortest path and is capable of finding different paths on different runs. Rymill notes that:

> "These are both characteristics of human route-planning: people will not on the whole choose to walk further than they need to, but they will choose different ways of getting to the same place." [10]
In the work of Rymill[10], the agents are allocated to different (random) goals. This yields a problem as people who enter a train station often have the same goals. When the A* implementation of Rymill[10] is used to find a limited number of goals, the algorithm will too often produce the same paths, not fully resembling human movement. Different heuristics were tested to increase the variety of paths that the algorithm returns. Examples of these heuristics were: using different techniques to calculate the distance towards the goal of the algorithm, to calculated this distance implementations where tested that used the Manhattan distance, Diagonal distance and Euclidean distance, and using different techniques to solve ties between the values obtained while looking for sub paths by assigning random tie breakers and tie breakers based on the relative position of the sub goals. The differences between the different methods to calculate the distance towards the agent’s target are visible in Figure 6.

Eventually a heuristic function is chosen that uses the euclidean distance and assigns a small random tiebreaker to the different sub paths. Another aspect that is changed in comparison to the ‘standard’ implementation, is that the algorithm at first hand (when looking for the possible paths) excludes the possibility of walking diagonally which is often possible with A* implementations. After a path has been found, this orthogonal path, existing of only 90 degree angles, is converted into a path that allows multiple degrees of movement. The benefit of initially excluding for instance diagonal walking is that, under normal circumstances, walking diagonally is often the most ‘cost’ effective. Because of the nature of the A* algorithm this benefit will be utilized at the beginning of the route. Resulting in the algorithm finding the same path during multiple runs, this path is diagonally in the beginning and orthogonally at the end as is visible in the first image of Figure 7. Initially excluding walking diagonally and converting this path later on produces more varied paths that all have the same cost. Examples of these paths can be seen in the second, third and fourth image of Figure 7.

The conversion of the orthogonal paths into paths that allow multiple degrees of freedom is done by first subdividing the path into hippogonally placed sub goals. The hippogonal movement, between these sub goals, could be described as the movement of the knight in a chess game or as a combination of one orthogonal and one diagonal step. If it becomes
impossible to further subdivide the path into hippogonal sub goals the path is (if possible) further divided into diagonal sub goals. An example of such a conversion is visible in Figure 8. The benefit of these extra degrees of freedom is that they enable the agents to find even more direct paths towards their goal. The eventual path can then be traversed by the agents. In different pieces of literature data is present about how people walk towards their goal while following a path that they have preselected[3][6][10]. For instance, data is present on the average speed that people tend to use.

Movement towards goals while avoiding collisions

After the selection of an optimal path this path is stored in the memory of the agent. This path does not take into account any other agents present in the simulation. Following the initial path without responding to the direct environment would therefore result in the occurrence of collisions. The avoidance of collisions has been extensively studied in behavioural psychology and is described in the work of Wolff[16] and Collet and Marsh[17]. The results of these works have been the basis of the behavioural rules and guidelines implemented in the work of Rymill[10]. This extensive implementation of rules has resulted in the most sophisticated model present in the reviewed literature and forms the basis for the movement of the agents in the model.

The avoidance of a collision starts with the detection of the approaching collision. Collision detection is performed by all the agents on each step of the simulation before moving. This is done by evaluating all the other agents present in their visual fields and estimating their future positions. In the simulation, the future positions are retrieved by evaluating the other agents current position and speed. In reality, we would estimate a person’s future position based on the difference in their position over time. Although the two methods are somewhat different the outcome will be the same as both of these methods are able to provide the persons future positions. After the speed of the other agents has been received it becomes possible to predict the future positions of the other agents and compare them with the agent’s own
future positions. If the future positions are too close to each other this indicates an upcoming collision. The procedure does not anticipate any collision caused by sudden changes in direction or speed of the other agents, just as people cannot completely predict the behaviour of other people in reality.

If multiple collisions are predicted, the place of the most urgent collision will be chosen for the actual avoidance of the collision. To determine exactly how the collision should be avoided, Wolff[14] distinguishes three different types of collisions: towards collisions, glancing collisions and away collisions. These different types all have a distinct avoidance routine.

**Avoiding towards collisions**

Wolff[16] and Collet and Marsh[17] describe that people tend to avoid head-on or towards collisions with as little change to their initial route as possible. In general they will first try to change their direction by the smallest possible angle that will avoid the collision. In the model, this is simulated by testing if the collision can be avoided by changing the direction of the agent successively by 10, -10, 20, -20, 30, -30, 40, -40, 50, -50, 60 & -60 degrees, see Figure 9. The procedure used for this test is similar to the previously mentioned method for predicting collisions. It is important to note that the agent checks all of the other agents in its field of vision to make sure changing its direction will not result in another collision occurring before the initial collision. The procedure also ensures that the change in direction will not result in a collision with other elements such as, for instance, walls.

The second best thing to a change of direction seems to be a change of walking speed, so if changing its direction will not resolve the collision or will result in another collision the agent will try to alter its walking speed. First, by speeding up or slowing down by 10%, then by its negative counter value (-10%). If this will not avoid the collision the percentage is further increased up to a value of 50 %. In between the speed changes, checks are performed to see if the change resolves the collision without creating new, more urgent, collisions. In case

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Fig 9, above: A predicted towards collision and the angles evaluated to avoid this collision. Below: A predicted glancing collision and an alternation of speed to avoid this collision.
changing only its direction or its speed will not resolve a collision, the agent will try several combinations of changing both its speed and direction at the same time.

**Avoiding glancing collisions**

In order to avoid collisions that occur while people are walking side by side, called glancing collisions, people tend to apply a fairly similar avoidance routine as used to avoid towards collisions. The routine exist of trying different kinds of speed and direction changes to avoid a future collision, see Figure 10.

**Avoiding away collisions**

The procedure for avoiding away collisions, that occur while people are walking in the same direction with different speeds, starts with the choice to slow-down or overtake the person walking in front of the agent. If the agent decides to slow-down and keep walking behind its predecessor, the agent alters its walking speed until one of the agents changes its direction, as seen in Figure 10. However, if the agent decides that it wants to overtake, a more complicated overtaking procedure is started. This procedure starts with finding a path around the other agent. This path is found by checking if changing the direction of the agent by a certain degree will result in a point from where it would be safe to resume the initial heading of the agent. If such a path exists, the agent estimates if following this path will not result in any other collisions which would make overtaking impossible or more time consuming than slowing-down. If new collisions are detected, the agent tries to find yet another path. When no new collisions are predicted the agent will start to overtake, as can be seen in Figure 10. During the overtaking procedure the agent will increase its speed to 125% of its initial speed as people will often do when overtaking[8].

After a possible solution for the avoidance of a collision has been found, the agent will start to avoid the collision. When the collision has been avoided, which is checked on every step
that is performed, while the agent’s ‘collision avoidance attribute’ is activated by any of the avoidance procedures, the agent will return to its initial path. To mimic real human behaviour the first sub goal of the initial path is chosen that can be reached without changing the direction of the agent by more than 45 degrees. This results in a smooth motion resembling reality. If no sub goal can be found that meets this criteria, a new path to the initial goal is found by the A* algorithm.

Avoiding crowded areas

An addition to the avoidance of single agents is a procedure that runs before the agent checks for collisions. This procedure checks if there are areas directly in front of the agent that the agent considers crowded. If such an area is detected the agent runs a group collision avoidance procedure. This procedure uses the A* path finding algorithm to find a path around the crowded area. This procedure differs from the method used by Rymill[8] but seems to produce more realistic behaviour as the initial implementation based on his work, by better mimicking the human tendency to avoid crowded areas.

Evaluating the design

The first goal of the model is to visualise the passenger flows occurring in a future building to make them insightful for the designer. A second goal is the ability to produce data directly related to the experience of the agents. To evaluate this experience, the model makes use of several different indicators. The primary concern during the selection process of these indicators was their impact on the user’s experience of a train station. This entails that different indicators should be incorporated in the model for different building typologies. The selected criteria for the evaluation of a train station can be subdivided in two categories. The first category exists of criteria that have been directly observed by the agents. Such directly observable criteria will be referred to as agent measured performance indicators and are now discussed in further detail.
**Average crowd density**

The density of people surrounding the agent in an eight meter radius is measured during every second of the simulation. All people that are in another room than the agent are excluded from the total sum. After counting the people present in the same room, the number is divided by the amount of freely available floor space.

**Average flow speed**

The average flow speed is calculated by retrieving the walking speed of the agents in the observer’s surrounding. These values are subtracted from the agent’s preferred walking speed to get the relative speed of the agent’s surroundings. This relative speed is important as it dictates the speed that the agent will be able to walk as well as its experience.

**Level of service**

The above mentioned performance indicators were selected during the start of this project. Because of their familiarity between these indicators and the variables used for the level of service concept it was decided to adopt the level of service concept as a means of measurement to make the results of the model more generally applicable. The level of service concept was developed by Fruin[18] and is often used to measure comfort levels based on occurring densities and flow speeds in public transport facilities. The variables used to represent the level of service are visible in Figure 12. The level of service concept is used in the work of Daamen[8] and by the ‘Nederlandse spoorwegen’ (NS) to quantify their goals.

**Absolute distance travelled**

The absolute distance travelled is calculated every second of the simulation by adding the walking speeds of the last second. It is used as a performance indicator as people prefer to walk smaller distances.
The relative distance travelled

The relative distance travelled is calculated when an agent arrives at its destination by dividing the absolute distance travelled by the approximation of its walking distance made upon entering the station. The reason for the difference between these two values are detours forced upon the agent in order to avoid collisions.

Average utility of establishments the agent was able to visit

Because of the way the agents’ route selection procedure is made, the agent is able to evaluate to what extent it was able to reach his preferred establishments.

Floor based performance indicators

The second category exist of criteria directly mapped to the floorplan of the design, such as crowd density and average walking speed. The difference between these categories can be illustrated by the example of a bottleneck which retains the pedestrian flow for a short amount of time. Although such a bottleneck will have only a small influence on the agent’s overall experienced average density, it will be clearly unveiled when the average density of the floorplan around the bottleneck is evaluated. The second category indicators use the same methodology to calculate the average distance and flow speeds as before, although the procedures are now executed for the patches on the floorplan. The result of these floorplan based performance indicators are presented in images. Examples of these images can be found in Figure 13, showing the average density and average flow speed performance indicators respectively. To interpret the values shown in the images, scales are used to transform the color values into the level of service values. To ensure an optimal functioning of the station the scale has been limited to values of category A, as any lower predicted values could reflect negatively on the design.

Fig 13: The average density and flow speed occurring on a floorplan simulated for 2000 seconds.
The influence of light

The importance of lighting and daylight in particular becomes instantly clear as one enters a poorly lit room. Lighting is not only a crucial aspect of architectural design, a direct relationship between the amount of daylight and a user’s evaluation of public transport facilities exists. This becomes clear in a quote by Norman Foster, talking in an interview about his design of Stansted airport:

“When we reconsidered that [the conventional idea of a terminal] and put all the air handling at the bottom, underneath, so that you could open the top to natural light and sunlight, so for most of the time you did not need electric light. You suddenly had something that was joyful, that would uplift the spirit and suddenly becomes popular with the most important people, who are the paying customers.” [19]

An interesting aspect of the relationship between light and design is for instance the impact of the design’s ceiling’s heights on the amount of light that is able to enter a building. Incorporating this kind of data in the simulation environment allows the simulation to exceed its two dimensional nature and to more accurately represent our three dimensional experience.

An extra dimension that makes daylight an even more interesting addition to the model is the fact that lighting does not only influence our experience but even our observable behaviour. It is therefore decided to select the amount of daylight received by the agents along their path through the station, as an exemplary addition to the model. Other phenomena could also be included in the model in a similar fashion.

To model the impact of daylight on our behaviour, various sources from the field of behavioural psychology have been evaluated. Although there is an abundance of qualitative research stating the relation between daylight and human movement, elaborate quantitative data
remains absent. There is however one seminal work by Taylor and Socov[20] that is (to some extent) able to provide this data. This research presents an experiment which will now be briefly described. In the experiment, 111 people enter a room and are faced with a message projected onto a wall placed immediately in front of them. The message asks the subject to walk either to an exit to the left or right of the wall they are facing. By varying the illumination ratios of the rooms at the left and right of the wall and keeping track of the chosen exits, the researchers were able to formulate relations between illumination ratios and human wayfinding.

To implement the result from this research, the A* wayfinding algorithm was expanded to incorporate the amount of daylight that is present in the room. A standard implementation of the algorithm only takes into account the cost to travel to a given location and the distances from that location to the eventual destination. The implementation used in this research is also able to take the daylight values assigned to the floorplan into account. By doing so, the algorithm becomes tempted to pick a route that receives more daylight. To ensure the right balance between the different variables (it was assumed that people prefer shorter routes over better illuminated routes, not taking into account places that would be considered as extremely dark) the experiment of Taylor and Socov[20] was virtually recreated to calibrate the values used by the algorithm.

Eventually, the model is able to incorporate daylight levels from external simulation software and map them to the floorplan. These values can then be converted to values serving as input for the wayfinding algorithm. This results in the agents being attracted to zones that receive a lot of daylight and a small reconfiguration of the occurring passenger flows.

The overall intelligence of the agents is summarized in the map shown in Figure 14. In this map, the various procedures that make up the behaviour of the agents are related to each other and presented in relation to the framework developed during this research to classify different aspects of human behaviour. In the map a subdivision has been made between procedures that represent an action of the agent, which are shown in a white circle, and
procedures that serve as input and output for these actions, which are represented by a grey circle. The relationships between the procedures are represented by either an arrow or a diamond connecting both of the procedures. An arrow connection marks a "uses" relationship which is for instance present between the route choice procedure (located at the top left corner of the map) and the collection of data that consist of information about the train schedule. A diamond connection marks a "consists of" relationship and is for instance present between activities and visit food shop, as visit food shop is an example of an activity.

Fig 14: Map showing the cognition of the agents.
Although an in-depth analysis of the historical and cultural context of Eindhoven’s train station and city centre falls outside the scope of this project, the station’s direct surroundings, the so-called ‘spoorzone’, still remains crucial for the eventual design.

To get a clear and complete understanding of the context of the building location it was decided to study multiple researches that have already been conducted rather than perform new, separate analyses. Luckily the development of Eindhoven’s station area has been a topic of interest to the municipality of Eindhoven and ProRail for quite some time and extensive analyses have been conducted[21] [22] [23].

One study, by Crimson Architectural Historians[21], investigates the architectural concepts of the station and both its historical and urban context. In their report, Crimson Architectural Historians[21] make two important remarks concerning the station’s context that are important for the eventual design.

First of all, the study stresses the importance of the diagonal connection between the station and the recently transformed 18th September square, existing of the sight line from the old station to the ‘Lichttoren’ and the urban entrance of Eindhoven’s shopping area. They recommend to increase the transport facilities at the northern side of the railway tracks as it would allow the southern side of the station to orient its character towards a more qualitative

Fig 15: Southern entrance of the current station of Eindhoven.
stay. The second important remark is that the South entrance of the station in combination with its tower and the railway tracks forms a complex composition that needs its surrounding space to function, both visually and spatially as well as from a practical point of view.

This remark becomes even more evident as we evaluate the performance of the station and its masterplan on a daily basis. We can clearly see how the increasing passenger numbers have forced Eindhoven’s station area to evolve into a vibrant area of public transport. This evolution has added several new means of transport to the initial train station. These new means of transport and increasing passenger numbers have resulted in a fragmented layout of the masterplan. This fragmentation consists of different functions such as: bicycle storages, the bus station, taxi stands and commercial spaces. This has resulted in a masterplan that contains a multitude of intersecting passenger flows and ill defined spaces. These influences have greatly affected the carefully thought of ensemble and the overall feel of Eindhoven’s station square, transforming it into a quite negatively reviewed area.

**Future changes to the context**

As mentioned before, the development of Eindhoven’s station area has been receiving interest from the municipality of Eindhoven for quite some time. In addition to plans for the spoorzone, several other plans have been developed that influence the spoorzones direct surroundings, of which some are already under construction.

The first plan is for the redevelopment of the Lichthoven area[24], which is located at the South-East border of the spoorzone. The plan called “Lichthoven (The Student Hotel)”[24] describes the realisation of four office buildings, three residential buildings and a big student hotel facing the station square. The buildings will be evenly distributed into two rows. In between these rows will be a void, creating a connection between the station square and the Dommel river. This connection will have a park like character and can be an interesting addition to the green areas located around the station square.

Fig 16: Eindhoven’s spoorzone.
Another plan that influences the station on a bigger, more urban scale is the plan called: “To connect and reside”[25]. This rather ambitious plan aims at revising the spoorzone as part of a bigger urban intervention. The plan formulates several changes for the context of the station. The most important change for the functioning of the station area is a redirection of car traffic around the station by changing the Vestdijk into a one way street that only allows cars to travel North. Besides this, the bicycle lane will be expanded to make Eindhoven’s shopping centre easier accessible by bike.

The plan states several requirements regarding the program of the station’s masterplan. These requirements include a parking garage of 60,000 m².

The final research that is of a great importance for this project is a prognosis by the municipality of Eindhoven[23] of the amount of train passengers that the station will serve. This number, which was 60,000 passengers in 2010, is expected to increase to 86,000 train passengers in 2020. This increase will not only occur in the amount of train passengers but even more in the overall usage numbers of the station such as people using the bus station or passage of the station. This amount is expected to almost double from 77,500 to 147,000 passengers, not including any extra traffic caused by the addition of a parking garage. This increase would be devastating, not only for the current design of the station, but for the masterplan as a whole, as their maximum capacity is already exploited. A rigorous redesign of the masterplan is therefore of vital importance for the design of the new station.

Fig 17: Eindhoven’s station square.
The new masterplan focuses on forging all the different aspects of the program into an integral design. Besides combining different functions in one central building the masterplan aims at a restructuration of traffic flows and a restoration of the quality of stay of Eindhoven’s station square.

To restructure the traffic flow up and around the masterplan, a parking garage will be executed at the Northern side of the masterplan. This parking garage will provide space for all the cars arriving at the masterplan, an underground bicycle storage, and the taxi station. This parking garage will be directly connected to the Northern entrance hall of the station providing easy access to all of the station’s facilities. The parking garage will be accessible by car through its entrances located both underneath the Vestdijk tunnel and the entrance route to the Kennedy square.

By restructuring the passenger flows the Northern side of the station is transformed into the station’s main focal point of transportation. This relieves the Southern part of the station of its burden of serving many different means of transportation at the same time, allowing a restoration of the monumental feel of the station square and the restoration of the Southern entrance’s role as an entrance to the city of Eindhoven. Because of the monumental value of the old station entrance it is a vital part of the masterplan to preserve this part of the station. Unfortunately, the old entrance is not suited to continue its role as the main entrance of the station.

Fig 18: Masterplan for the context of the station.
It is therefore decided to give the building a new role as the station’s office facility. In order to better position the entrance of the station in line with the pedestrian routes from Eindhoven’s city centre, the new entrance hall should be located to the East of the old entrance. This repositioning also enforces the connection between the station square and the 18th of September square located in front of the Piazza.

**Design requirements**

The new building program focuses on creating a station that will serve the city of Eindhoven for the next decades. To ensure the future of the station, the program needs a big update of its office facilities, commercial facilities, and most importantly traffic space. The current office facilities of the station are important for the station’s role as the region office for the Southern part of the Netherlands. For the new office spaces of the station it is important to preserve and if possible enhance their connection with the daily functioning of the station to enhance the affinity of the station’s employees with their product of train travel.

The increase in commercial and travel facilities is directly linked to the predicted increase in passenger numbers as presented by the municipality of Eindhoven[23]. The predicted passenger flows are shown in Figure 19. This image shows the different passenger flows arriving and departing from the station. For the correct interpretation of this image it is important to note that the report by the municipality[23] does not make a distinction between the different train platforms. The numbers shown in Figure 19 are used for an initial estimation of the building program. This program is further optimized in collaboration with the model. The findings of this collaboration will be discussed in further detail in the chapter describing the design process of the station.

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*Fig 19: Predicted passenger flows for the station of Eindhoven in the year 2020 as presented by the municipality of Eindhoven[23].*
The workflow of the model start with the making of a conceptual floorplan in Autodesk AutoCAD. AutoCAD was chosen because it is the default drawing program for many designers, enabling them to create quick but precise drawings. On the floorplan, the designer marks the walls that construct the building and places of interest such as shops and entrances. After the floorplan has been finished the drawing can be saved in the .dwg format which can be converted into GIS shape files by the use of FME workbench.

These shape files, that contain information about the positioning of walls, the different shops, toilets and entrances, can be imported directly in Netlogo by making use of its GIS extension. The model imports these shape files on every setup at the beginning of every simulation cycle. During the setup procedure the model subdivides the information from the shape files into different clusters that contain the same information. These different clusters all get allocated an unique color value belonging to a range of color values reserved for the category of the activity to perform. Every entrance at the north side of the station for instance is marked with a different shade of red. This process ensures that every location can be distinguished and identified without the designer needing to use different colors for every individual location.

Currently the model is able to support the following categories: entrances on the North-East side of the station, entrances on the North-West side of the station, entrances on the South-East side of the station, entrances on the South-West side of the station, entrances from the train platforms.
parking garage, stairs leading to platform one, stairs leading to platform two, stairs leading to platform three, shops for food items, shops for non-food items, and toilets. If necessary, these categories can easily be extended to allow for a wider range of activities. These categories all receive a specific color-code. The entrances on the Northern side of the station get a shade of purple, the entrances of the Southern side of the station a shade of red, the entrances of the train platforms a shade of yellow, the shops for food items a shade of light green, the non-food shops a shade of darker green and the toilets a shade of blue as is visible in Figure 20.

The next step in the setup procedure is the initialisation of the network of distances between the different activity locations. This process is executed by running the same A* algorithm implementation as used by the agents to calculate their route. This network is used later on by the agents during their route selection procedure.

The last step of the setup procedure is the creation of the train schedule. As input for this schedule the user is asked to fill in the departure time of the trains from the station’s platforms, relative to the start of the simulation. This schedule serves as input for the agents’ estimation of the remaining time until the departure of their train.

After the setup procedure is finished the simulation can be started. Besides the input variables concerned with the agents’ cognition the model uses several secondary input parameters during the simulation.

The first important setting is based on the predicted traffic flows presented by the municipality of Eindhoven[23]. This report presents the average total passenger numbers in the year 2020. By subdividing the total passenger numbers by the station’s daily opening time, ratios are obtained that represent the average number of passengers arriving at the various entrances at every seconds. The model assumes that these arrivals follow a Poisson arrival process. For the simulations this arrival number is multiplied by four to get an approximation of the numbers during rush hour. In order to determine the goals of the passengers the same values as in Figure 19 have been used.
Because the simulation is started with an empty station the model makes use of an initialisation period of 100 seconds to fill the station. The amount of agents that enter the station during this period represent the people who had already entered the station before the start of rush hour. During the initialisation period of the simulation the floor based performance indicators remain inactive. The agents however do already start their evaluation of the station. This is clearly visible in the differing shape of the figures representing their data as can for instance be seen in Figure 21. As the data during the initialisation period is not representable for the future functioning of the station this first part of the figures is therefore disregarded during any further analysis.

A final setting that influences the results of the simulation is its simulation time. To ensure the validity of the results obtained from the simulation the simulation time has been set to 2000 seconds during the majority of the simulations. Every floorplan used in this report has been simulated for at least three times, the average values from the tree simulations are eventually presented in this report. After the simulation time has exceeded the simulation is stopped and the different results can be exported.

Fig 21: Chart showing the average flow speed during a simulation, the first part of the chart is not representative for the functioning of the station.
The first notion of movement as a fundamental aspect of architecture was made by Giedion[26] [27]. Ever since this publication, denying the importance of movement for our experience of architecture has become practically impossible. The importance of different types of motion becomes even more evident as we engage ourselves in a small ‘poetic experiment’ as described by Voorthuis[28]:

"Picture yourself now in a building, picture your eyes as they roam through the spaces turning to the light, touching upon the textures and colours as you move with your easy, elegant rhythmical walk; enjoy them changing as you change your position relative to a window for example, think of your ears and skin as it registers the movement of air molecules, your nose and tongue as they register the smells of place. Think of your own memories and associations, of the stories of the place. It is this perambulating dance of sensible registration as you move, that enjoyment of order, rhythm and harmony, forming, breaking up and reforming in movement that constitutes the true melody of Architecture."

If we adopt this vision on movement as an essential aspect of our experience, stating the importance of taking this movement into account becomes obvious. For this research it is therefore more interesting to determine to what extent motion should determine architecture rather than whether it is an important topic in architectural design. To answer this question a distinction can be made between two different design-philosophies, both acknowledging

Fig 22: Passenger movement in the station of Eindhoven.
the importance of movement through architecture. On the one hand there are architects that embrace the concept of this ‘flow’ and use it as a fundamental concept for the shape of their designs. A good example of such a design is the Mercedes Benz Museum in Stuttgart, which is visible in Figure 23. The shape of the museum clearly reflects the two downwards spiralling ramps that make up the tour through the museum.

A great protagonist of this way of thinking is the architect Greg Lynn. He explains how forces (that could be the result of movement) can define (a static) form[27]. To illustrate his vision, Lynn provides the example of a sail boat hull, which is specifically designed to perform differently under varying conditions such as sailing up or downwind. Although the hull does not change its shape, it is able to use the different forces, created by sailing in different directions, as its shape is determined by these forces during the design process. He further explains how a similar process could be used in architectural design:

“Instead of a neutral abstract space for design the context for design becomes an active abstract space that directs form within a current of forces that can be stored as information in the shape of the form. Rather than as a frame through which time and space pass, architecture can be modeled as a participant immersed within dynamical flows.”[27]

Another example of this philosophy is the Mobius house shown in Figure 23, designed by Ben van Berkel. It is a clear expression of the movement of people through their house. This design, based upon the daily routine of the members of the household and the movement provoked by the routine, shows movement as a direct derivative of function, implying form following not only function but movement as well.

Opposed to this view is a philosophy that also strongly acknowledges the importance of movement but grants it too big of a complexity for a direct expression into form. This philosophy is present in the work of Rem Koolhaas[29].
The opposing views can perhaps best be illustrated by a discussion between Ben van Berkel and Rem Koolhaas at the ‘anyhow’ conference held in Rotterdam.

“Commenting on his Moebius House, Van Berkel claims that it is the role of architects to provide flows with a convenient form. Koolhaas replies to this statement that flows can take any form and assume any trajectory and that the desired relation between flow and function remains a hopeless nonsense. He offers the example of Heathrow airport where the daily changes effecting the trajectories of flows make any attempt to design spaces according to flows look very absurd. Describing these spaces, he says:

“They are ugly spaces with no aesthetic except in terms of sheer complexity, in terms of times that you have to go up and down, the number of times that you have to turn corners, the number of times that you find astonishing obstacles, and your incredible ability to handle them without effort.”[30][29]

Both of the philosophies have extraordinary examples of perfect applications in architectural design and arguments based on valid points. This eventually leads to quite a ‘political’ conclusion, concerning the extent to which the shape of the building should be determined by the movement of its inhabitants. In my opinion this extent should be based not on a predefined notion but derived from the use of a building. This conclusion can be illustrated by the example of a library, which bears much less of a connection with movement than a train station and should therefore make less of a priority of expressing this movement. This conclusion will be elaborated further during the formulation of the project design concept.
Develop conceptual layouts → Evaluate → Select optimal layout → Improve floorplan → Evaluate → Select optimal floorplan → Transform into spatial design → Evaluate → Perform solar studies → Design
After analysis of different stations, it became clear how a station can often be subdivided into four different parts, all requiring their own specific treatment. There are the two entrance halls at either side of the railway track, the passage and the train platforms. The concept for the design derives from the notion that the extent to which the shape of a design should be determined by the motion of its users is directly linked to the purpose of the design. If the purpose of the design derives from this motion, as it is in the case of a station, the use of the station asks for a more direct expression of this moment then in a design less concerned with the movement of its users. This concept can be illustrated by subsequently evaluating the needs of the different parts of the design.

The Southern entrance of the station is the station’s connection to Eindhoven’s shopping area and in many ways the entrance to the city. The entrance therefore has to make a grand gesture towards the city and be clearly recognizable as the entrance of Eindhoven’s central station. This means that the direct expression of the occurring movement becomes of secondary importance.

The Northern side of the station has evolved into the busiest part of the station and, although the Southern part of the station is still clearly perceived as the station’s main entrance, the Northern side serves more visitors every day. This clearly shows that the design of this part of the station should have a more direct connection to the occurring movements.

Fig 24: Design process.
The passage is the part of the station that has the biggest connection to its movement as its sole purpose is enabling this movement. This part of the station therefore needs the results of the simulation as its main initiator of space. For the final design this entails that the application of the model will be mainly focused on the design of the station’s passage.

Finally, the train platforms in many ways function as the main asset that makes a train station recognizable, as for many visitors it is either the only, first or last thing they see of the station. This means that, in addition to the platforms primary goal of providing a comfortable waiting area for the people during their expectation of the trains arrival, they also have a strong representative function.

**Determining the train station’s spatial layout**

The design process started with applying the model to resolve different questions regarding the spatial layout of the train station. In the current design this layout exists of the Northern and Southern entrance halls that are connected by the passenger tunnel. These three elements are visible in Figure 25. A comparable layout of these elements can be found in a wide variety of executions, differing in size and the balance of space between the different building components. The impact of changes concerned with the size, placement and connection of these elements are difficult to predict but have a big influence on the functioning of the station. With the use of the model it becomes possible to quantify the effect of different variations of the station’s spatial layout. Important design decisions derived from testing such variations will now be discussed in further detail.

Fig 25: The Northern and Southern entrance halls and passenger tunnel of the current station.
An important factor in the station’s design is the balance of space between the entrance halls and the tunnel. This balance, that is greatly influenced by the location of the commercial areas of the station, determines a big part of the final design. A good example of a station with a big entrance hall, especially when compared to the size of its passage, is the station of Rotterdam by Benthem and Crouwel Architects, visible in Figure 26. To determine the impact of locating most of the commercial activities in both of the entrance halls rather than locating them along the side, the model was used to evaluate the conceptual floorplans. If we compare the two layouts used for this test, visible in Figure 27, we can easily see that all of the commercial activities of the first layout are located alongside both of the entrance halls. In the second layout on the other hand, they are all located alongside the passage.

The result of shifting the balance of space towards bigger entrance halls that are able to host a majority of the commercial activities, is a passage that has a higher average passenger density. This can be seen from both of the ‘heat maps’ in Figure 27, as well as from the chart showing the agents’ overall experienced density in Figure 28. A second downside of locating the commercial facilities at different sides of the station is that, on average, it forces people to walk bigger distances through the station. This can be explained by thinking of an agent that wants to visit a shop at the other side of the station, forcing the agent to traverse the entire length of the entrance hall twice.

Fig 26: Entrance hall of the central station of Rotterdam.
Fig 27: ‘Heat maps’ showing the results of simulations of 2000 seconds.
Fig 28: Charts showing the different results of the simulation, the red line describes the results of the layout with the bigger passage, the black line describes the results of the layout with the bigger entrance halls.
Another important aspect of the spatial layout of a train station is the connection between both of the station’s entrances. This connection can be made in various ways, the two most popular options are either a connection made by one big hallway, as seen in the central station of Arnhem designed by UNstudio, or by the use of two smaller hallways as is done in the new design for the central train station of Eindhoven proposed by Arcadis. Although the second option is used less often, there are several designs, like the new station of Rotterdam, that use one big passage divided by various elements such as benches and elevators. This eventually results in the passage being experienced as if comprised out of two separate hallways. A comparison of the two alternatives shows that two smaller hallways result in a density that is only slightly higher. Looking at the density map of this layout, visible in Figure 30 however, shows that the distribution of the density causes problems as one of the hallways will become much more crowded than the other. This is caused by a disbalance in travelling distance, as one of the hallway’s routes will always provide a shorter route to the most popular destinations. in order to avoid big differences in density between separate parts of the station it was chosen to focus on layouts with one big passage.

Fig 29: Passenger tunnels of the central stations of Rotterdam and Arnhem.
Fig 30: ‘Heat maps’ showing the results of simulations of 2000 seconds.
Fig 31: Charts showing the different results of the simulation, the black line describes the results of the layout with a single passage, the red line describes the results of the layout with two smaller passages.
The third comparison is especially interesting for a new station in Eindhoven as because of its urban context and the positioning of the railway tracks, there are a limited amount of possibilities for the connection between the passage and the train platform. In modern train stations, it is often decided to make use of stairs and escalators at both sides of the passage to connect the passage to the train platforms, as can be seen in the stations of Rotterdam and Arnhem. Because the biggest part of the platforms of Eindhoven’s station are located to the West of its entrances the current design only has stairs at one side of the tunnel. However, this greatly limits the capacity of the connection. In the design proposed by Arcadis this problem is seized to deviate from the standard layout, using one set of stairs at one side of the passage and other stairs in the middle of the passage, both with the same orientation of entering the platforms.

To determine the optimal solution three different layouts were tested with different variations concerning the placement of the stairs (marked with a brown color). The first layout, shown in Figure 32, shows how locating the stairs leading to the train platforms at the Western side of the passage forces people to walk at this side of the passage. This results in a crowded area that is clearly visible on the floorplan. The second layout has stairs at both sides of the passage resulting in the most evenly distributed crowd density. The third layout has stairs at both the western side of the passage as well as in the middle of the passage. From this layout we can observe how the stairs in the middle disrupt the passenger flows and create crowded areas throughout a big part of the passage. The comparison clearly shows that stairs at both sides of the passage are crucial for a smooth direction of the passenger flows. Although for the station of Eindhoven this means that the stairs located at the Eastern side of the passage serve a smaller part of the train platforms, the results from this test are convincing enough to prove their overall benefit.
Fig 32: ‘Heat maps’ showing the results of simulations of 2000 seconds.
After the basic principles of the design had unveiled themselves, the model was used to re-evaluate the spatial requirements formulated in the building program. This is an application of ‘behaviour simulation software’ as it is also already used in practice during the design of train stations. The model proved to be very useful in re-dimensioning the passage to a size with an optimal balance between passenger densities and building costs. By testing different sizes of the passage and comparing the results of the simulation, using the level of service indicators, with the desired level of service as formulated by the NS, the density maps of these simulations show that the estimations based on the dimensions of other stations would result in a waste of space as the program was too big for the amount of passengers. Only after the program of the design was reduced by 40%, values were measured close to the maximum allowed values formulated by the NS. The results of the model therefore enforced the spatial requirements to be restated.

Besides answering these explicitly defined questions, this phase was also used to test a wide variety of different spatial layouts to gain an understanding of the possibilities and accuracy of the model and a familiarity with its results. This in addition to finding inspiration and generating ideas concerning the possibilities of different layouts and resolving more detailed questions such as the most beneficial placement of entrances, shops and toilets.
Fig 33: ‘Heat maps’ showing the results of simulations of 2000 seconds.
Fig 34, next page: examples of simulated layouts.
The most important part of this research project has been the design of the passage, connecting both of the station’s entrances and the train platforms. Important restrictions for the design of the passage where the positioning of its entrances, which are not merely defined by their interior passenger flows but perhaps even more by their context, and the possibilities to create the connections between the passage and the train platforms such that passengers would not entirely arrive at the side of the platforms. Besides these two guidelines, the shape of the passage was accepted as fully undefined and open to optimization. This optimization process was executed by testing a wide variety of different layouts created by varying the parameters of the floorplan. Parameters that were altered were, among others: the angle of the passage, the size of the passage, indenting the stairs leading to the train platforms, the angle of the wall of the tunnel and the curvature of the walls of the tunnel. After each simulation the influence of altering the parameter was evaluated and the results of this evaluation were used to create new improved layouts used as input for new rounds of simulation. The goal of this process was to evenly distribute the passenger density across the floorplan.

An interesting observation that can be made from looking at the results from these simulations is how the differences in passenger numbers, approaching the station from different directions and entrances, influences the density of passenger flows in the station.
During the optimization process of the station passage there were two main phenomena contributing to occurring disruptions of the passenger flows.

The first phenomenon derives from the station’s specific location in Eindhoven’s urban context. Because the station needs to make a connection between the 18th of September square and the Kennedy square, which are not directly aligned, the passenger flows between the squares will always be forced to bend, resulting in busy corners inside of the station. These corners can immediately be observed by looking at the density maps produced by the simulation of various layouts. To relief the tension around these corners, layouts were developed focused on guiding the passenger flows around these corners. The model proved to be exceptionally useful in not only clarifying the effect of these changes but more importantly upon clarifying the significant effects of these changes on other parts of the design.

The second phenomenon is more generally applicable as it derives from the human tendency of traversing the shortest path towards a destination. Because the connection between the passage and the train platforms is almost always located at the side of the passage, this results in a lot of traffic alongside the sides of the passage. This is one of the reasons that this space is often used for the placement of elevators and other secondary elements. However, these additional elements increase the crowded feel of the passage.

The morphology of the station has eventually become an optimal balance between both of these variables. As the first phenomenon could not be completely resolved by changing the morphology of the passage it was decided to use the corners, causing the more crowded areas, to resolve the second phenomenon. By using the corners at the beginning of the passage as bottlenecks, the passengers are guided towards the middle of the passage to resolve the phenomena of people walking at the sides of the passage. From the middle of the passage the passengers can walk directly towards their preferred exit. Because these exits are not successively aligned from the middle of the passage, the passenger flows are split rather than merged by their destination. This is visible in Figure 36.
**Magnitude of improvement**

To determine the magnitude of the improvement caused by changing the morphology of the passage, the new passage will now be compared with a straight shaped passage as this is the most generic way of connecting different parts of a station. For this comparison it is important to note that the total area reserved for traffic is exactly the same for both of the floorplans.

A big difference between the average densities represented on the floorplans of the layouts is visible in their ‘heat maps’. By comparing both of the ‘heat maps’ in Figure 37 we can observe how the overall density is reduced by spreading the passenger flows across the floorplan more evenly. Furthermore, it can be observed that the bottleneck at the North-East side of the station is significantly reduced by the design of the corner.

To quantify the improvement achieved by altering the floorplan of the station’s passage the average densities as experienced by the agents can be compared. If we compare both of the density charts of Figure 37 it becomes insightful how the average densities experienced by the agents diverge as the station becomes more and more crowded during the simulation. Eventually the difference between the two designs reaches a magnitude of 8%. For a correct interpretation of this improvement it is important to note that both of the stations have exactly the same size. The improvement can therefore be fully addressed to an improved direction of the passenger flows.

A small downside to the new floorplan is a slight increase in the average walking distance. This is visible in Figure 37. The increase has a magnitude of 0.1% and can therefore be classified as rather insignificant, since the noticeable effects of this increase in walking distance is reduced by a decrease in the ratio of the estimated walking distance and the actual distance. This ratio decreases by 3% as the agents are far less often forced to make detours and avoid collisions caused by high density areas occurring in the station.
These results lead to the conclusion that the model has been very helpful in the design process. Eventually, the model was able to improve the daily functioning of the station when compared to a generic straight hallway. This improvement only becomes bigger as the model supported the ongoing design process, preventing 'wrong' design decisions such as creating two or more smaller hallways. Although it is impossible to quantify the exact magnitude of the model's importance, it is clear how its application is crucial for the design.

Fig 37: Charts showing the different results of the simulation, the black line describes the results of the generic floorplan, the red line describes the results of the improved floorplan.
Transformation into a three dimensional design.

The final design clearly reflects the results obtained from the simulation. The results are visible in the morphology of the floorplan, which influences the flows occurring in the station, but is also visible throughout the design of the station. In the concept developed for the station it is explained how the different parts of the station should all have different means of expressing this movement. Both of the entrances have a context which has been taken into consideration during their design. Because of this context, of which the monumental old station is considered the most imported asset, it is decided to create the outside appearance of the entrances in a conventional architectural language, ensuring the station to blend in with the surroundings.

Southern entrance

The Southern entrance hall of the station makes a grand gesture to the city by the size of its volume. The entrances of the hall are pierced through this volume at exactly the right places, as dictated by the results of the simulations performed to find the optimal placement of these entrances. The entrances of the hall are highlighted by a metal frame. The volume itself is made into an even bigger gesture by a big overhang on all sides of the volume, enhancing the building’s welcoming entrance.

The gesture of the southern entrance and its welcoming appearance are supported by transforming the station square into an arena that is sloping down towards the station’s entrance. This arena enhances the volume of the entrance, removing the need to create a volume so big that it would overpower the entrance hall of the old station. Furthermore, the arena creates a smooth transition between the street and the floor of the station, which has been lowered, allowing the station’s tunnel to have a much higher ceiling height compared to the old station. Another benefit of lowering the ground floor of the station is that it allows for the volume of the South entrances to end at the same height as the volume of the old station. The overhang of the roof of the new entrance is used to create a clear connection between the old and the new entrance, resulting in a harmonious composition. This is visible in Figure 39.
Fig 40:
Southern elevation scale 1:500

CENTRAAL STATION
Fig 41:
Section CC' scale 1:1000
Fig 42:
Section CC' scale 1:200
While approaching the entrance hall, the glass that is used to construct the volume becomes more transparent, enabling passengers to see more and more of the roof inside of the volume. This part of the roof is curved to express the occurring passenger flows inside of the station. Such an expression is created by translating the average densities, mapped to the floorplan by the simulations, into a curved surface. This surface has its highest and lowest points at the local extremes of the occurring densities and its transition from high to low at the average values of the densities as is visible in Figure 38. When the visitor enters the hall, more details of the roof and the performance of the entrance hall become apparent. The hall expresses a distinction between areas for traffic and areas used for secondary functions, such as columns, benches or signs showing train departure times. Because of the results obtained from the simulations this border has not been made by the use of a material intervention, such as fences or height differences, but by far more subtle architectural cues such as the design of the roof and the placement of the NS service desk. The main reason for the absence of need for such a physical barrier is the fact that this border is derived from the usage of space (obtained from the simulations). Rather than to create this border the design therefore only needs to highlight and express its boundary. The usage of space is visible in Figure 43 which shows the movement of the agents in relation to the design of the Southern entrance hall.

The division between the areas used for traffic and areas used for secondary functions is visible in the absence of any unnecessary elements that could obstruct the passenger flows in the areas reserved for traffic. Some of these elements have been transferred to the side of the border between these areas, such as the public transport-check-in/out points, or all the way to the areas sheltered from the passenger flows such as the NS service desk. Another distinctive example of the model’s influence upon the entrance hall is the positioning of the columns supporting its roof. Because of the predicted passenger flows, the columns have been placed a-symmetrically at the sides of the entrance hall. This is visible in Figure 43. This placement ensures that any disruption of the passenger flows caused by the columns is reduced to a minimum. The roof of the entrance halls that is supported by these columns, reflects the division of the entrance hall in the different zones for traffic and secondary activities, as this

Fig 43: Interior rendering of the Southern entrance hall.
division forms the border between the higher and lower parts of the roof. The difference in height between the different parts of the roof reflect the density of the passenger flows of the station. The division between the different parts of the roof is made even more apparent by other aspects of its design. The lower parts of the roof are made out of sandwich elements, composed out of aramid and carbon fibre, with a seamless matt white finish, resulting in a totally smooth curved surface. The structure of the roof is visible in Figure 42. In order to give the higher parts above the passenger flow an even more distinct expression of motion, the curvature of its surface is highlighted by beams supporting the roof. These beams subdivide the surface, making its curvature more perceivable. Finally, beside the border of the higher parts of the roof, a big skylight is added to the roof, as is visible in Figure 45. The light entering through this skylight has multiple purposes. In addition to its effect on the overall ambiance of the hall the light is used to create more equal lighting levels between the interior and exterior of the hall, ensuring the transparency of its glass volume. The third effect of the skylight placement is the effect on the occurring movement, as the light coming from the edge of the busiest areas lures the people towards the side of this area, distributing the passenger density more evenly. This effect is an important benefit of including the agents’ sensitivity for light into the model, as discussed in the section concerned with the simulation of different aspects of human behaviour.

In the new design the old entrance hall at the Southern side of the station is allocated the function of office space for the station. The station needs a relatively large amount of space because for this function the station is the region office for the Southern part of the Netherlands. Between the old and the new entrance halls a restaurant will be located that will both physically and functionally connect the different buildings. This restaurant consist of a glass box underneath the roof that also covers the new entrance hall, as is visible in Figure 41. By extending the roof towards the old entrance the restaurant is sheltered from direct sunlight and the connection between the buildings is highlighted. The interior of the restaurant will consist of three levels that follow the slope of the arena surrounding the Southern entrance. The floorplan of the ground floor is visible in Figure 44.
Fig 44:
Floorplan p = 0 scale 1:1000
Fig 45:
Roof elevation scale 1:2000
Fig 46:
Southern elevation scale 1:1000
Northern entrance

The Northern entrance of the station deals with an entirely different context concerning the spatial distribution of the arriving passenger flows. On the Southern side of the station the station square directs the passenger flows, arriving at the station from different angles, towards the entrance of the station. On the Northern side there is no room to interfere with these flows before they enter the building. The volume of the Northern side is therefore directed towards these passenger flows, with entrances directly facing the flows. After the building is entered there are stairs and a ramp leading to the lower level of the station’s floorplan. Alongside the entrance hall there are several commercial establishments and the entrance of the parking garage. The space at the centre of the hall, in between the main passenger flows, is reserved for bus travellers, in combination with the space just outside of the station underneath the overhang of the station’s roof. These spaces resolve the need for a separate bus station. The triangular shape of the Northern entrance hall, which derives from the arriving passenger flows, fits with its character that is focused on transportation. The focal point of the hall’s triangular shape is focused on the entrance of the passage.

The roof of the entrance hall expresses the usage of space in a similar fashion as the roof of the Southern entrance hall. In the Northern entrance hall the highest parts of the roof are located at the sides of the hall. This is visible in Figure 47. The columns in the middle highlight the transition between the areas reserved for traffic and the waiting area located in the middle of the hall.

On the second and third floor of the Western side of the Northern entrance hall the station houses a ‘NS station2station’ office that offers the passengers the opportunity to rent a temporary workplace inside the station. On the Eastern side the station’s ‘huiskamer’ is located, the huiskamer provides the passengers with the possibility to wait for the arrival of their train in a comfortable ‘home-like’ environment. The floorplans of the second and third floor of the Northern entrance hall are visible in Figure 49.
Passage

The shape of the passage’s floorplan is already discussed during the previous chapter but it is important to note that the workflow, which to a great extend was concerned with an optimal direction of the passenger flows, has created a design that, although the floorplan as it can be seen in Figure 48 may look counter intuitive, has a very smooth transition between both of the entrance halls and the eventual shape of the passage. This smooth transition and the modest curvature of the passage’s walls ensure that the design does not look counter intuitive, as it is viewed from a visitor’s perspective. This can clearly be observed in the rendering shown in Figure 51.

Directly located at the side of the passage are several commercial functions, located behind big glass storefronts. To enhance the expression of movement the trumpery of the storefronts has been reduced to a minimum and any objects that are not essential for the primary functioning of the station that could obstruct the passenger flows have been removed from the passage.

The passage contains six transportation units towards the train platforms. Every platform is accessible by 2 escalators and 1 staircase at the West side of the passage and 2 escalators and an elevator at the East side of the passage. The difference in transportation capacity between the units on the East and West side of the passage corresponds to the size of the available train platform at either side of the passage. The relation between the different levels is visible in Figure 48 and Figure 50.

Between the opposing transportation units, a grid has been created that aligns the different stores and the beams of the passage ceiling. These beams are used to create an expression of movement, in a similar fashion as in the roof of both the entrance halls. To create an optimal balance between expressing the occurring movement and the overall use of the station the beams of the ceiling have been cleverly incorporated into the structure of the passage. This is
Floorplan p = -1700 scale 1:1000

Fig. 48:
Fig 50:
Floorplan p = 4000 scale 1:2000
visible in Figures 52 and 53. This integral design approach ensures both the expression and the ceiling height of the passage as well as the structural integrity of the passage. Because the free workable height is limited by a minimal ceiling height the ceiling creates a strong but subtle effect.

A last important design decision concerning the passage was inspired by the model’s indication that the light coming from the stairwells could tempt the visitors to walk along the sides of the passage. This unwanted effect is countered by incorporating artificial lighting devices into the ceiling and by adding a glass floor to the train platforms. These additional light sources ensure an even distribution of light throughout the whole width of the passage and highlight the beams of the passage serving as flood lighting, the effects of these lights can be seen in Figure 51.
Fig 52:
Section AA’ scale 1:1000
Fig 53:
Section AA' scale 1:500

2 4 6
Train platforms

The train platforms of the station follow the design initiated by the station’s entrance halls. By using the roof to represent the traffic flows in a similar fashion as used in the entrance halls, the roof covers the entire station, ensuring a continuous space throughout the station. Besides the shape of the roof, other aspects of the design such as the design of the columns and the connection between the columns and the roof, have been designed in a similar fashion. The highest parts of the roof located above the platforms, are entirely executed out of glass, allowing a lot of daylight to enter the station. The beams visible underneath the glass of the roof are visible over the entire length of the platform, creating an impressive appearance. This appearance is very important for the train platform’s function as the entrance to the city of Eindhoven. Besides a refurbishment of the actual train platforms their position, and subsequently the position of the railway tracks, are not altered as these parts of the station are able to account for an increase in the predicted passenger numbers.
The main theme of this project was the application of a multi agent simulation model in an architectural design process. At the start of this project several questions were formulated to guide the research process. The answers to these questions can partly be found in the previous chapters, this chapters provides a short summary of these answers and important conclusions for any future research.

How can different aspects of human behaviour be simulated in a multi agent simulation environment?

The findings of this research show that there is a lot of research available concerning the simulation of human behaviour. This information originates from various research fields such as: Architecture, behavioural psychology, emergency egress, and urban planning. These researches provide a wide variety of procedures and implementations suitable for an application in a multi agent simulation environment. By relating aspects from different researches and implementing them in the Netlogo simulation environment, it has become possible to simulate a wide variety of human behaviour. An important conclusion concerning the literature that should ideally be used as the foundation for a model is the recommendation to, if possible, limit the scope of the research to studies that have undergone an extensive validation, as this is the only way, besides performing a validation, to ensure the validity of the model.
A second conclusion is that multi agent systems are able to incorporate aspects that are interesting for the human experience of architecture that are less generally applicable in other research fields. This entails that there exists a lack of previous studies that developed routines to incorporate these aspects of behaviour in a simulation environment. Although this research proves that it is possible to develop new routines, for instance the routines concerned with the agents’ sensitivity for light, the quality of such an implementation is greatly affected by the available literature describing the particular phenomenon. It is important to note that such an implementation can only be developed based on reliable quantitative data that could potentially be hard to find.

Can a model that is able to simulate human behaviour exceed the human ability to predict this behaviour?

The first notion of the model’s ability to exceed the common sense regarding the ability to predict (certain aspects of) human behaviour was proved early on during this research. The common sense for instance showed to lack the ability of accurately predicting human movement as the complexity of a floorplan increased. Especially quantifying the effect of variations in the intensity of people arriving at the station from multiple entrances proved to result in unexpected outcomes, that could only be explained after reviewing the results of the simulation. Furthermore, quantifying the effects of changing the spatial layout of a station and making choices concerning this layout can impossibly be done by the use of one’s common sense. The limits of one’s common sense became even more apparent during the research phase focused upon improving the morphology of the station, a process which without the use of the application would have been impossible. As the relationship between the morphology of the station and its effect on the occurring passenger flows is to complex to predict.

How does making a model that is able to predict the future behaviour of a building’s visitors influence an architectural design process?
The design process that was part of this research consisted of several steps focused on the creation of different design alternatives and their evaluation. This process works very well in collaboration with the application of the model used to during the evaluations. By comparing this process to a more conventional design process it becomes possible to conclude that there is quite some familiarity between the processes, as the creation of alternatives with different strengths and weaknesses and their evaluation is an important part of almost any design process. The additional effect of the application of the model in the design process is therefore limited.

One of the most obvious results of using a simulation model as an integral part of an architectural design process is that the application of the model requires time. Although this may seem like an obvious statement the simulation of complex phenomena, for which human behaviour definitely qualifies, is quite a time consuming process. This downside to the models is not only present in the model developed as a part of this research but even in commercial software packages[5]. The simulation of different layouts therefore often becomes a matter of hours rather than minutes. Although in itself a longer waiting time is not that big of a deal, as the same goes for instances for the process of rendering high quality images, a process that involves these kind of simulations encourages a designer to test a wide range of different designs. This could potentially delay the design process for quite some time.

What implications does using a model that is able to predict the future behaviour of a building’s visitors entail on an architectural design?

This research shows how involving a multi agent model in the design process can have a significant impact on architectural design. The model has proved its ability to support the process of determining the optimal spatial layout for a train station and during the optimization of the station’s floorplan. Furthermore, the design accompanying this research shows how the results obtained from the simulation can serve as an initiator for the space and shape of a station.
Although for the design, the model was used in multiple stages of the design process, it is important to note that the extent to which the results of the simulation are used are always determined by the designer. This is an important notion as certain building types are less dependent on the variables that the model is able to clarify. This effect is even visible in the design of the station as different parts of the station have different levels of expressing the predicted passenger flows. Although using the results of the system to create an expression of movement could potentially be classified as unwanted, testing the functionality by use of the model will always supply useful information.

To what extent should a model be validated in order to be of use in an architectural design process?

During this research the importance of validating a model used for an application in a design process has become abundantly clear. To base the design of any type of building upon the results of the model, the accuracy of these results should of course be known. Although several pieces of literature have been studied to investigate the possibility of performing a validation of the model developed during this research, the limited time frame forced the decision to leave an extensive validation out of the scope of this research[31][32][33]. The validation of the model therefore mainly consists of the user’s experience with the model. The results presented in this report concerning the functioning of the station, its spatial layout, and the morphology of the passage should therefore be verified before they can be applied on a wider scale.

Although the validity of the results cannot completely be guaranteed, taking the results of the model into account and investigating passenger flows has definitely resulted in an improvement of the design. The optimization process of the passage, which would not have been possible without the application of the model, has for instance resulted in a supposedly better direction of the passenger flows inside of the passage, which definitely seems plausible.
How can simulations of the human experience of architecture improve an architectural design process for a new train station in the city of Eindhoven?

Throughout the design process of the design presented in this research there were several phases during which the model was able to support the process and improve the design. The first phase was focused on answering questions related to the spatial layout of a station. The model proved how creating one big passage resulted in better evaluations concerning the average density of the station and walking distance of the agents, compared to other design alternatives. Although these results definitely support the design process, the application of the model could perhaps have been even more useful for a more complex building type, such as an airport. This is because such a building has more variables concerning the building program and the direction of passenger flows.

A second benefit of the application of the model was a significant reduction of the building program. The initial program, based on estimations derived from other stations such as the station of Rotterdam, proved to be too large. This was caused by a very different balance of space between the stations, as the balance of space of the station presented in this research is shifted towards the space of the passage.

The second phase of the research was focused on optimizing the generic solution of using a straight hallway between the station’s entrance halls. The results of this part of the project are very exciting as they showed how an improvement upon a straight hallway can be made by the use of the passage morphology. This improvement would not have been possible without the application of the model as the passenger flows would have remained a concept far too abstract to influence. The model is definitely capable of making the effect of actively steering the passenger flows more insightful, allowing the designer to supersede just the creation of a space for movement and to achieve the shaping movement by the design of space. The eventual improvement would definitely make an impact upon the user’s experience of the model as the overall experienced density decreases by 8%. By using a design concept
that allocates different levels of the model’s influence to different parts of the station it was ensured that the influence on the user’s experience remains solely positive. This is because design decisions not only concerned with the passenger flows could easily outweigh the result obtained from the model in certain parts of the design.

After the layout and floorplan of the station were for a large part determined, the results of the model were used for the transformation of the floorplan into a three dimensional design. The model was able to provide valuable data about the usage of the different parts of the station. The data was for instance used to substantiate the positioning of the columns in the entrance halls. During this phase it was discovered how the results of the model could be used to create an expression of movement that fits very well with the character of a train station. This expression was obtained by shaping the station’s roof to the exact ‘needs’ of the station, enforced by the usage of the different spaces. This becomes especially visible in the roof of the Northern entrance. This roof would probably have a symmetrical curve without the results of the simulation as people enter the hall from equal angles. With the use of the model however, it became clear that the occurring passenger flows would not be equal, therefore requiring different representations into the roof of the entrance hall. The model therefore allows a new balance, not in the exact geometrical shape of the roof but a balance between the shape of the roof and the internal usage of space by the station’s visitors. The result of this new balance, apparent in the roof of the station, leads to several impressive spaces.

Eventually this has led to a design that is able to fulfill all the requirements of a contemporary train station. Furthermore, the station will excel in the direction of the passenger flows which is still one of the most important functions of a train station. It is therefore safe to conclude that the application of a model, capable of simulating human behaviour, can improve an architectural design process in a variety of ways and with significant results.
Conclusions regarding the model

The model developed during this research is focused on supporting an architectural design process. Although a lot of aspects of the model have been based on existing research, the development of the model was started from scratch. This allowed the creation of a model tuned to the specific needs of an architect. For the model, this means that the agents have been equipped with procedures that are able to provide data about variables important for the design. The architectural viewpoint holds a closer relationship with modelling approaches that are psychologically driven rather than modelling approaches applied in other studies, which are more epistemologically driven. In the model this becomes apparent in, for instance, the avoidance procedures that are reminiscing a human thought process but also in the route selection procedures, that do not only take into account statistics but also the agents’ preferences and a choice between different alternatives based on several variables. This decision process, that uses a k shortest path algorithm to find multiple solutions, is one of the aspects of this research that could perhaps improve other simulation models. The behaviour that the model produces concerned with the agents’ wayfinding and collision avoidance is life like and further developing the model based from this architectural point of view therefore seems interesting.

The model shows how it is possible to include the results of external simulation software into the simulations and into the behaviour of the agents. For this research it was chosen to include the results of daylight simulations and make the agents reactive of light. In future research other phenomena could be included such as evaluations of temperature and sound levels to provide valuable data for the design process.

As mentioned before, the model is able to support the design process in a variety of ways and therefore proved to be a valuable addition to the design process.
After this project has been completed it is important to reflect on the process that led to this research. At the beginning of the project I had quite a clear image of the model that I wanted to develop and how such a model would be able to support the design process. This image was altered during the development of the project in several ways. At the beginning of the project I thought that altering the spatial layout of a station would provide results that would exceed the evaluation of a layout using one big passage, failing to find such a new layout was therefore a bit of a disappointment. This result however, was easily compensated by the other results of the project. The improvement of obtaining a 8 % decrease in the overall experienced density by changing the morphology of the passage, is in my opinion a very exiting result. Furthermore, the application of the results of the simulations into the design of the station has resulted in several impressive spaces. I therefore think that the process of applying the model and using the results in the design process worked very well.

A possible downside to the presentation of the design is that it proved to be impossible to create a physical scale model that is able to display the curved shapes of the design, the overall shape of the design, and the much smaller but very important beams and columns that support the roof of the station. The difference in size of these elements is too big to accurately display the elements in the same scale.
A possible downside to the process of this project was that it perhaps deserved some more time that could be used to test a wider variety of design alternatives both concerning the floorplan of the station as well as its transformation into a spatial design. Extending the part of the project concerned with the design of the station would leave more time to give every aspect of the design the attention it deserves.

The reason for the limited amount of time available for the design process was that, before the model could be used, it had to be completed to a large extent. Although the development of the model had already started during the M3 research project, it was a very time consuming process. During the development of the model I often thought about the advice of mr. de Vries who encouraged me to use as much research that had already been conducted as possible. Although a lot of aspects of the model have been based on existing research I did start the development of the model from scratch. This has eventually resulted in a code of which the length slightly exceeds the length of this report and a model that is very well capable of supporting a design process. I am therefore very satisfied with both the model as well as the design developed during this project which has exceeded my own expectations of what would be possible within a one year time frame.
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**Figures**

Figures are a result of own production, unless mentioned below.


Figure 26: Linders, J. (2014). Retrieved February 23, http://www.gebouwvanhetjaar.nl/entry/rotterdam-centraal/