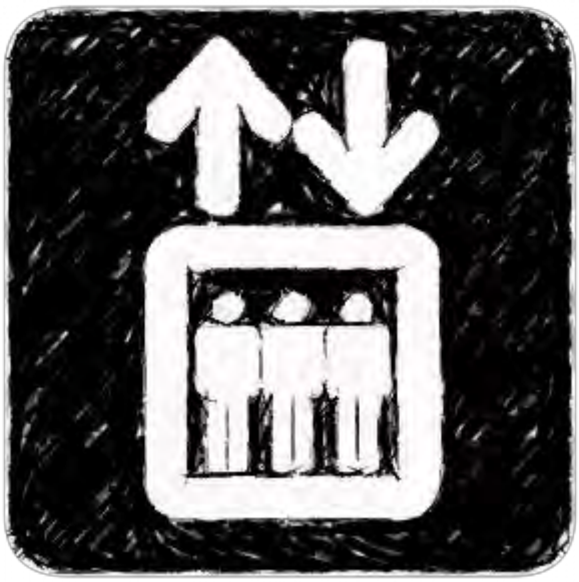
Reducing passengers waiting time in elevator traffic by adding information about passengers arrivals



Research Paper Business Analytics

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PREFACE

Writing a research paper is a compulsory part of the Master program Business Analytics at the VU University. The purpose of the research paper is to use your knowledge and capabilities to perform an individual research and describe the findings in a clear manner.

The subject of this paper is elevator traffic and the possibilities of improving this in terms of waiting time and energy consumption. The reason why I chose this subject is that traveling with an elevator is a day-to-day activity for many people and waiting to be served is an annoying aspect of elevator traffic. I wondered if it is possible to decrease waiting times and energy consumption by adapting the movement rules of an elevator.

My supervisor during this research was Prof. R.D. van der Mei of the VU University. I want to thank him for all the help and support.

Amsterdam, February 2015
Leonie Beers

SUMMARY

In elevator traffic the time between the arrival of a passenger at the front of an elevator and the moment the passenger enters the elevator is called the waiting time. This moment of time is a factor of frustration for many (business) people. The goal of this paper is therefore to try to reduce this waiting time. This is done by adapting the movement of the elevator with the use of upfront information about passengers.

Besides the passenger waiting time, the riding time and the service time are measured. These three together form the results from the passengers' perspective. For the elevator's perspective the performance metrics are the number of stops, the maximum number of passengers in the elevator and the energy consumption. The movement of the elevator is simulated as well as the arrival of the passengers. A set of rules about the movement of the elevator is called a policy. In this paper 2 different policies with different settings are evaluated for both up-peak and down-peak traffic. Several realistic scenarios are simulated. In all scenarios the building consist 11 floors and one elevator with unlimited capacity. Other specifics of the simulation vary across the scenarios. This simulations resulted in the following conclusions.

The conclusion for up-peak traffic are:

- For a low arrival rate it is preferred to not take reservations into account.
- For a medium arrival rate the reduction on waiting time is maximal 8.3% but this results in an increase in service time by 11.3%. So also for a medium arrival rate the policy without reservations is preferred.
- For a high arrival rate it is preferred to take the reservations into account. The optimal time the elevator should wait is 7 seconds. In this case the waiting time is reduced by 35.4%, the service time is reduced by -1.2% and the energy consumption is reduced by 10.8%.

For down-peak traffic the conclusions are:

- For each arrival rate the policy which uses reservations is preferred.
- For a low arrival rate the optimal time for the elevator to wait is 11 seconds, the results are -30.6%, -8.8% and -3.1% for EW, ES and the energy consumption respectively.

- For a medium arrival rate the optimal time for the elevator to wait is 9 seconds. This results in -21.5% for EW, -0.8% for ES and -4.1% for the energy consumption.
- For a high arrival rate the optimal time for the elevator to wait is 5 seconds, it should be noticed that this is for the perspective of lower the waiting time. For 5 seconds the effect on ES and the energy consumption is negative. The results in this case are -11.5% for EW, +4.5% for ES and +1.0% for the energy consumption.
- When the average amount of time between the reservation and arrival of a passenger is doubled, the optimal value of the time the elevator should wait is not changed.

CONTENTS

LIST OF TABLES AND FIGURES

1 INTRODUCTION

Time is money they say. For most businessman and –woman this results in a lifestyle full of haste. Running to get to the train station, working while driving and making business calls everywhere where possible. When arriving at the office there is that moment of waiting, waiting for the elevator to arrive at the ground floor. This moment of waiting can be only a few seconds, but it might be a minute, no one knows this in advance. However, for many people this waiting time is a cause of frustration. Not only businessmen and –women experience this kind of waiting. Many people use an elevator now and then, but how many of those do not care waiting?

This research paper is focused on this particular kind of waiting, waiting for the elevator to arrive. For most people the time before the elevator arrives is the most frustrating part, but waiting in a crowded elevator for the elevator to arrive at your destination floor is not comfortable as well. In this paper, both the waiting time and the riding time are taken into account. Besides the performance metrics based on the passengers the energy consumption of the elevator is calculated. This is done because energy conservation is getting more and more important nowadays. However, the main goal of this research is to lower the waiting time of the passengers. Therefore the main question in this paper is:

Is it possible to reduce waiting time in elevator traffic by making use of information on arrivals of passenger?

If the answer to this question is yes, the follow-up questions are:

1. *By what percentage can the waiting time be reduced, and how?*
2. *What is the influence on the other performance metrics, especially the service time and energy consumption?*

Within the field of elevator traffic there are three different traffic patterns: Up-peak-traffic, down-peak-traffic and interfloor traffic. Up-peak and down-peak are quite naturally but the definitions of these two patterns according to Barney in *Elevator Traffic Handbook* pp. 87 (2003):

Up-peak-traffic: An up-peak-traffic condition exists when the dominant traffic flow is in upward direction, with the majority of passengers entering the system at the main terminal of the building.
Down-peak-traffic: A down-peak-traffic condition exists when the dominant traffic flow is in a downward direction with the majority of passengers leaving the lift system at the main terminal of the building.

Interfloor traffic consist of all movements which does not belong to either up-peak or down-peak traffic. In this paper two of the three patterns are analyzed, namely up-peak-traffic and down-peak-traffic. Besides two traffic patterns, two different policies are analyzed and three different arrival rates of passengers are taken into account. Each policy contains a number of rules for the movement of the elevator. These policies and arrival rates are described in chapter 3.

Multiple studies about elevator traffic are performed with different objectives, an overview of the literature is given in chapter 2. In chapter 3 the methods used in this research are explained followed by the results in chapter 4. The final chapter contains the conclusion and discussion.

2 LITERATURE

In this chapter an overview of previous research in the field of elevator traffic is given. In the history of elevator traffic there have been a variety of studies on different aspects, such as reducing passengers waiting time, car-call allocation, optimizing parking of empty elevators and so on.

2.1 STOPPING POLICIES

One of the subjects of previous research is stopping policies. This deals with decisions about which elevator should stop at which floor. Sometimes it is not optimal for elevators to stop at each desired destination floor. Shearn (1983) developed an algorithm for determining an optimal stop schedule for one elevator with traffic from the ground floor to higher floors only. Newell (1998) states that for tall buildings, with more than one elevator, zoning is useful. Zoning means dividing the floors into different zones and each elevator then serves one zone. Even assigning one floor per trip to each elevator might be the optimal strategy, in case of very heavy traffic.

2.2 PARKING EMPTY ELEVATORS

A second subject is optimizing the policy for parking empty elevators. One can imagine the huge number of possibilities, especially when the number of (empty) elevators increases. If there is only one elevator, the possibilities for parking are quite simple. But what if there are for example 15 elevators in the building? Should they all be parked at the ground floor once they get empty? This kind of questions are not easily answered. Brand et al. (2004) showed that "matching the distribution of free cars to the arrival distribution of passengers is sufficient to produce savings of up to 80% in down-peak traffic". However, for the harder case of up-peak traffic they used dynamic programming on a Markov Decision Process. An article of Parlar et al. (2006) is very theoretic, with formulae and proofs. It focuses on a situation with a single elevator, which is not the most interesting situation for parking issues. For a situation with multiple elevators they assume that "parking takes place when all the elevators become idle".

2.3 CAR-CALL ALLOCATION

In a system with multiple elevators which serve the same floors the allocation of an elevator or car to a call can be done based on many different rules. It can be done random, but this will probably not be the optimal way. This aspect of elevator traffic is very popular, many different approaches has been studied. A few of the most recent articles are presented in this section to illustrate the widely spread possible methods. Besides these methods there are of course many others. P. Cortés is one of the authors in all three articles discussed below, for that reason they are compared to one another. Cortés et al. (2004) evaluated a building with 2 elevators and 12 floors. They used genetic algorithms for assigning cars to calls during lunch break. Bolat et al. (2013) allocated cars to calls with a particle swarm algorithm, in a situation with 10 - 24 floors and 2 - 6 elevators. This resulted in faster and better results than the genetic algorithm. A viral system algorithm is the method used in the third article. Cortés et al. (2013) tested this method for the same situations as used for the particle swarm algorithm, with 10 - 24 floors and 2 - 6 elevators. The viral system method outperforms the genetic algorithm is various (almost all) settings of the number of floors and elevators.

Besides all these articles, there are two recent articles which were the inspiration for this research. The inspiration for using reservations in elevator traffic comes from Kwon et al. (2014). They developed an elevator scheduling system that uses information provided by different sensors such as cameras and floor sensors. Each of these sensors detects passengers and sends this information to the controller of the elevators. The second article by Zhang et al. (2013) is about energy consumption in elevator traffic. This article formed the inspiration for taking energy consumption as performance metric in this research.

3 MODEL

This chapter is the main body of this paper, first of all a problem description will be presented in which the reasoning behind this paper is explained. After this the model is further clarified by means of the chosen methods, model details, assumptions and implementation. In section 3.5 multiple policies which will be evaluated are given.

3.1 PROBLEM DESCRIPTION

The main question in this paper is: *Is it possible to reduce waiting time in elevator traffic by making use of information on arrivals of passenger?* The possible reduction is measured by comparing two policies, the first is a general policy which does not use information about arrivals and the second one does use this information. The term *waiting time* refers to the time passengers are waiting for an elevator to arrive. The time spent while riding is also taken into account as well as the energy consumption of the elevator. As seen in chapter 2 there is done quite some research on improving elevator traffic in different ways. So, reducing the waiting time in elevator traffic is too general and therefore the part of *making use of information on arrivals of passengers* is added to the question. Information on arrivals is vague and could mean anything. In this paper information on arrivals is referring to information about arrival times of passengers. This can be obtained in different ways, Kwon et al. (2014) described the use of sensors to locate passengers before arriving in front of the elevators. But another possibility might be an application for mobile devices which is communicating with the controller of the elevator. If passengers let the elevator know they are arriving, the elevator has information which can be taking into account while moving. The way this information is obtained is not part of this research, the possibilities of using this information is. If the answer to the main question is yes, more detailed results are analyzed. This is done to see how big the reduction is and what the impact is on other performance metrics, especially the service time of passengers and the energy consumption of the elevator.

3.2 METHODS

To analyze a system there are multiple possibilities, see figure 1[1]. Experiments with the actual system is often too complicated, too expensive or not possible at all. For this research

[1] Eduard Babulak and Ming Wang (2010). Discrete Event Simulation: State of the Art, Discrete Event Simulations, Aitor Goti (Ed.), ISBN: 978-953-307-115-2, InTech, Available from:

simulation is chosen as the method for analyzing the elevator system. Simulation is a strong tool because adapting the system or the situation can be done in a short manner of time. With simulation the same situation can be evaluated many times under different sets of rules, or the other way around, testing the same set of rules under different situations. Results of the simulation can give insight in which set of rules is preferred in each of the situations. These sets of rules are called policies in this paper. Each policy can be seen as a set of rules about the movement of the elevator, rules about where the elevator should stop if it becomes idle or at which floor it should stop next. The policies evaluated in this paper are further explained in section 3.5.

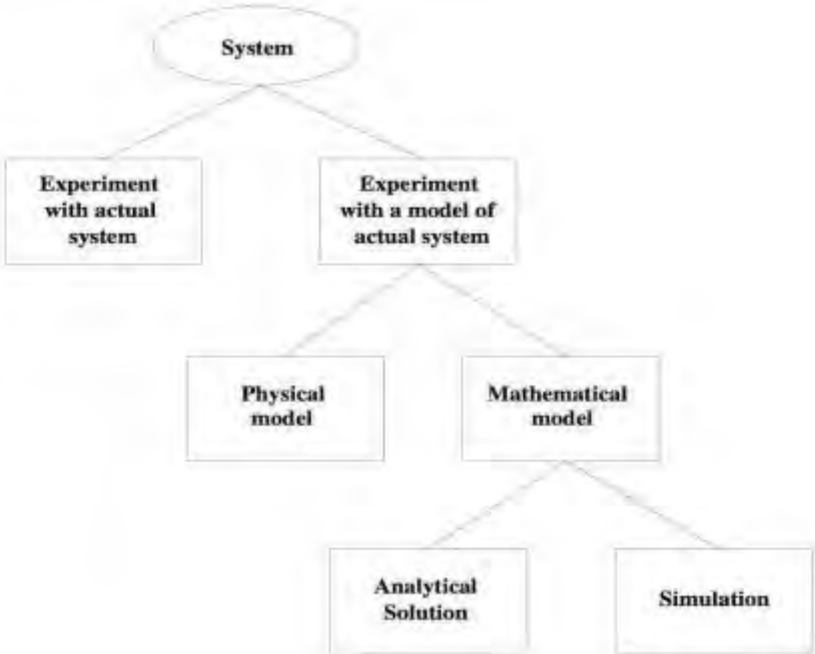

Figure 1: Ways to analyze a system

Within simulation there are different options, see figure 2[2]. In this paper discrete-event simulation is used. Discrete-event simulation represents the real world, the state of the system changes each time an event takes place. Examples of events in elevator traffic are the arrival of a passenger at a specific floor, the movement of an elevator and the entry of a passenger in an

http://www.intechopen.com/books/discrete-event-simulations/discrete-event-simulation-state-of-the-art

[2] Eduard Babulak and Ming Wang (2010). Discrete Event Simulation: State of the Art, Discrete Event Simulations, Aitor Goti (Ed.), ISBN: 978-953-307-115-2, InTech, Available from: http://www.intechopen.com/books/discrete-event-simulations/discrete-event-simulation-state-of-the-art

elevator. Besides the events the simulation consist of entities, results and time. Keeping track of time is important for calculating the performance metrics. The results are based on the measures of all simulation runs and these results show information about the entities. In this research the passengers and elevators. All specifications of the model are described in the next section.

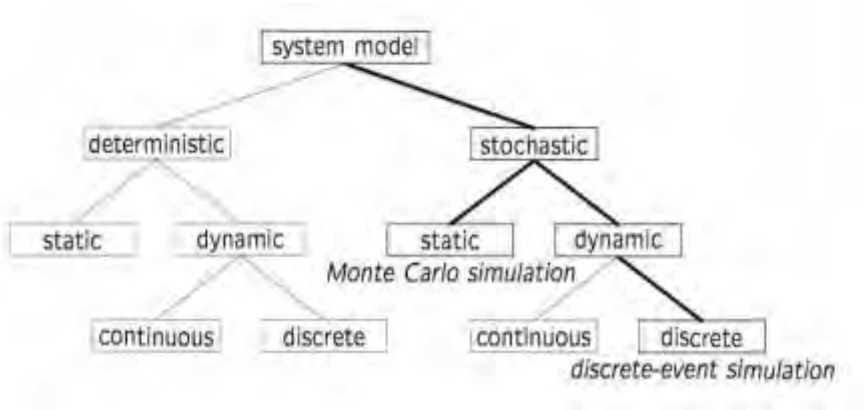

Figure 2: Different options within simulation

3.3 MODEL DETAILS & ASSUMPTIONS

As explained in the previous section, a discrete-event simulation consist of events, entities, results and time. In this section the general description of the model is followed by the specifics of the experiment and a description of each aspect of discrete-event simulation and the assumptions.

3.3.1 General model

In this subsection the general model of this research is described. In the next subsection the specific set-up of the experiment is given. The model consist of a number of parameters, namely:

$F: The\ number\ of\ floors$

$E: The\ number\ of\ elevators$

$Q: The\ total\ number\ of\ passengers$

$Q_k: The\ number\ of\ passengers\ working\ on\ floor\ k$

$p_k: The\ percentage\ of\ passengers\ who\ travel\ to\ or\ from\ floor\ k$

$\lambda: The\ arrival\ rate\ of\ the\ passengers$

$o: Time\ in\ seconds\ it\ takes\ to\ open\ or\ close\ the\ doors$

$m: Time\ in\ seconds\ it\ takes\ to\ travel\ one\ floor\ up\ or\ down$

$T: Time\ in\ seconds\ an\ elevator\ waits\ in\ case\ of\ an\ reservation - call$

$R: Time\ between\ a\ reservation\ and\ the\ arrival\ of\ a\ passenger$

$N: The\ total\ number\ of\ simulation\ runs\ performed$

Besides these parameters the state of the system is important for the model description. In discrete-event simulation the state of the system changes when an event takes place. The events are described in subsection 3.3.3. Here the state of the system is further explained. In the simulation the following aspect are remember at each time step:

$K(e): The\ current\ floor\ at\ which\ elevator\ e\ is\ positioned$

$S(e): The\ current\ state\ of\ elevator\ e, active\ or\ idle$

$Q(e): The\ number\ of\ passengers\ in\ elevator\ e$

$D(e): The\ direction\ of\ movement\ of\ elevator\ e, up\ or\ down$

$up_q: A\ list\ of\ floors\ at\ which\ an\ up\ call\ is\ performed\ by\ a\ passenger$

$down_q: A\ list\ of\ floors\ at\ which\ a\ down\ call\ is\ performed\ by\ a\ passenger$

$dest_q(e): A\ list\ of\ floors\ at\ which\ elevator\ e\ should\ stop\ to\ serve\ a\ passenger$

3.3.2 Set-up of the experiment

In this subsection each parameter of the model is specified for this specific experiment. First of all the number of elevators $E = 1$. The simulation is performed in an imaginable building, which consists of $F = 10$ floors. On each of these floors there work 30 passengers. This means a total of 300 possible passengers for the elevator system. However not everyone will use the elevator, some of them take the stairs. In this paper up-peak traffic and down-peak traffic are considered. During up-peak traffic all passengers arrive at the ground floor and the distribution of the destination floor is as follows:

Floor number: k	1	2	3	4	5	6	7	8	9	10
Number of employees who use the elevator: $Q(k)$	10	15	20	25	30	30	30	30	30	30
Percentage of total passenger population: $p(k)$	4%	6%	8%	10%	12%	12%	12%	12%	12%	12%

Table 1: Distribution of passengers

In table 1 it can be seen that everybody who works on floor 5 to 10 will use the elevator. Below these floors some of the employees take the stairs. Out of the 30 employees who work on the first floor 10 of them make use of the elevator. In total 250 out of the 300 will use the elevator, so $Q = 250$ in this experiment. During down-peak traffic all passengers go to the ground floor and the same number of employees use the elevator. So the arrivals of passengers is divided among floors 1 to 10 according to the distribution in table 1. The arrivals of passengers is according to a homogeneous Poisson process. A Poisson process is characterized by the intensity rate, notated with λ. In order to select values for λ assume that all employees arrive within 3 hours. This means that on average $250/3/60/60 = 0.0231$ employees arrive each second and the average time between two arrivals is $1/0.0231 = 43.3$ seconds. But instead of arriving within 3 hours all employees might arrive within one and a half hour or within half an hour, then the parameter changes to $250/1.5/60/60 = 0.0463$ or $250/0.5/60/60 = 0.1389$. This corresponds to an average time between two arrivals of $1/0.0463 = 21.6$ seconds and $1/0.1389 = 7.2$ seconds respectively. In the experiment these three values of λ are evaluated, so $\lambda = 0.1389$, $\lambda = 0.0463$ and $\lambda = 0.0231$. For down-peak traffic the same values are used, so all employees leave the office either within half an hour, within one and a half hour or within 3 hours. This arrival rate is used to generate arrivals, the exact time it takes for all 250 passengers to arrive can therefore be different than the times used for calculation. However, on average the times (0.5 hours, 1.5 hours and 3 hours) are correct. A few parameters are not yet specified. The time it takes to open or close the doors $o = 2$ and the time of moving one floor up or down $m = 2$. The parameters T, R and N are specified further on in this section.

3.3.3 Events

The simulation model distinguishes 5 different events, each event means a significant change in the state of the system. This can be adding or removing floors from a queue, changing the direction or state of the elevator, moving the elevator to the next floor or the entrance or exit of a passenger. These are the events used in the simulation:

1. **Movement of elevator:** Each time the elevator moves one floor up or down the state of the system changes, the elevators current positions is changed. The simulation checks whether or not the elevator should visit this floor. The next event is either visit the current floor or moving on to the next floor.
2. **Visit floor:** When the elevator stops at its current floor, the doors open, passengers with this floor as destination floor leave the elevator and passengers that are waiting enter the elevator, the door closes and the elevator moves on. If there is a reservation call which came from this floor the elevator waits during a short moment for the passenger to arrive and then moves on. This time is called the elevator waiting time and is notated with T.

3. **Hall-call:** A hall-call takes place if a passenger presses the up or down button outside the elevator, so in the waiting room. The floor at which this happens is added to the list of stops of the elevator.
4. **Car-call:** A car-call takes place when a passenger who entered the elevator presses the button of his destination floor. This floor is added to the list of stops of the elevator.
5. **Reservation-call:** If the reservations are taken into account the simulation generates a reservation-call for each passenger. This reservation-call is passed on to the elevator some time before the passenger will arrive in the waiting room. This time R follows a Normal distribution $\mathcal{N}(\mu = 20\ seconds, \sigma^2 = 5\ seconds)$. This implies that r could be negative, but the chance of this to happen is only 1%. If this happens r is set to 0. When a reservation-call reached the elevator, the elevator knows it should stop at this floor within a limited time period.

3.3.4 Entities

As explained before, there are two entities in the simulation. Elevators and passengers. There is only 1 elevator and there are 250 passengers. For each of these two entities some measures are calculated, these are explained in subsection 3.3.4.

3.3.5 Performance metrics

For each passengers three performance metrics are calculated by the simulation:

- The waiting time (WT), this is the time a passengers waits before the elevator arrives.
- The riding time (RT), this is the time a passenger spends in the elevator.
- The service or journey time (ST), this is the total time the passenger spends in the system, from arriving at the front of the elevator until leaving the elevator.

Eventually the results for one simulation run is a summation over all passengers and then divided over the total number of passengers. Below the formulas of the actual results of the simulation are given.

$$Expected\ passenger\ waiting\ time = EW = \frac{\sum_{i=1}^{N} WT(i)}{N}$$

$$Expected\ passenger\ riding\ time = ER = \frac{\sum_{i=1}^{N} RT(i)}{N}$$

$$Expected\ passenger\ service\ time = ES = \frac{\sum_{i=1}^{N} ST(i)}{N}$$

In these formulas N is the total number of passengers and $WT(i)$, $RT(i)$ and $ST(i)$ stands for waiting time of passenger i, riding time of passenger i and service time of passenger i respectively.

For the elevator there are also three performance metrics:

- The number of stops the elevator has performed during the simulation time.
- The maximum number of passengers which are in the elevator at the same time.
- The energy consumption, this is the total energy used by the elevator during the simulation time.

Because there is only one elevator in this experiment there is no further calculation needed for these metrics.

3.3.6 Time & Results

Each simulation ends when the last passenger is served, this is when there are no more events to handle. This time can differ between runs due to the arrival moments of the passengers, but the performance metrics take the running time into account so this is no problem. Each policy is tested with all three arrival rates (values of λ). Because the specific arrival moments of passengers are different each run it is important to run the same combination (policy with arrival rate) multiple times. To get reliable results within a short time period each combination is simulated $N = 1000$ times. The performance metrics described above are evaluated each of these 1000 runs. The actual results are the average, standard deviation, maximum and minimum values of these 1000 runs. This makes sure the results are comparable and show not only the average but also the spread.

3.3.7 Assumptions

- During up-peak traffic each passenger arrives at the ground floor and during down-peak traffic each passenger goes to the ground floor
- The elevator does not have a limitation based on capacity
- The maximum speed of the elevator is achieved within one floor, so traveling more floors at once is not faster than traveling each floor one by one (except for the time it takes to stop at a floor)

3.4 IMPLEMENTATION

The implementation of the simulation is divided in two parts. First the arrivals of the passengers are generated with and then the actual simulation takes place. Both parts are programmed in JAVA with use of Eclipse.

3.4.1 Validation and Verification

Before running the experiment to generate the results it is important to verify and validate the model. For verification of the model, small tests have been performed to check for errors in the implementation. Eventually all error have been fixed, this completed the verification phase. Validation is based on comparing the model to the real world, this is difficult to test. Especially in this case, with a building consisting of 11 floors and only one elevator. However, most specifics about the elevator, such as speed of moving and open/closing times of doors, are often used numbers in literature.

3.5 POLICIES

The different policies which are evaluated in the experiment are described below. Policy 1 does not take reservations into account, this one is created to form a basis for comparison to policy 2. Policy 2 does take the reservations into account and is tested with different settings for the parameter T, specific values for this parameter are expressed in chapter 4.

Policy 1, without reservations

- When the elevator becomes idle, it stops at the current floor
- When there is a hall-call and the elevator is idle, the elevator moves to the source floor
- When there is a hall-call and the elevator is active, the elevator stops at the source floor if it is on the current route otherwise the source floor is saved in the queue
- When there is a car-call, the pressed floor number is added to the list where the elevator is going to stop
- When the elevator stops at a floor, passengers enter/leave the elevator

Policy 2, with reservations (moving direction and source floor is known)

- When the elevator becomes idle, it stops at the current floor
- When there is a reservation-call and the car is idle the elevator waits until the last possible moment of movement
    - If this moment arrives and this call is still the only request, the elevator moves to the source floor
    - If this moment arrives but there are multiple requests, the elevator moves to the closest floor with a request
- When there is a hall-call and the elevator is idle, the elevator moves to the source floor

- When there is a hall-call and the elevator is active, the elevator stops at the source floor if it is on the current route otherwise the source floor is saved in the queue
- When there is a car-call, the pressed floor number is added to the list where the elevator is going to stop
- When the elevator stops at a floor, passengers enter/leave the elevator. If there is a reservation call at this floor and the passenger did not arrive jet then the elevator waits during T seconds before moving on

4 RESULTS

In this chapter the results of the simulation are evaluated. The results of up-peak traffic are shown in section 4.1 and the results of down-peak traffic are shown in section 4.2. It is not useful to compare the two. In up-peak traffic all passengers arrive at the same floor, while in down-peak traffic the arrivals are distributed over all floors.

4.1 UP-PEAK TRAFFIC

In this section the results of up-peak traffic are presented. First the main question is answered, is it possible to reduce waiting time in elevator traffic by making use of information on arrivals of passenger? If the answer to this question is yes for one or more situations, the result of these situation are further analyzed.

4.1.1 Is it possible to reduce waiting time for up-peak traffic?

To answer this question 9 combinations of policies and arrival rates are analyzed. For each combination of policy (1 or 2) and arrival rates ($\lambda = 0.0231$, $\lambda = 0.0463$ or $\lambda = 0.1389$) the results are shown in tables 2 to 5. For policy 2, three different setting for the parameter T are used. These policies are called 2a, 2b and 2c, with $T = 5/10/15$ seconds respectively.

Table 2 shows the results of policy 1 for different arrival rates. For each performance metric the average, standard deviation, maximum value and minimum value over 1000 simulation runs are given. Some performance metrics are closely related to one another. For example, the number of stops, the maximum number of passengers in the elevator and the energy consumption. If there are more stops needed to serve all passengers the elevator needs to move up and down more often so the energy consumption will increase and the maximum number of passengers in the elevator will decrease. This can be seen by comparing these three performance metrics for the low and high arrival rate. When increasing the arrival rate the number of stops and energy consumption decrease while the maximum number of passengers in the elevator increases.

POLICY 1	λ=0,0231 (LOW)				λ=0,0463 (MEDIUM)				λ=0,1389 (HIGH)			
	Avg.	St.Dev.	Max	Min	Avg.	St.Dev.	Max	Min	Avg.	St.Dev.	Max	Min
Number of stops	423.67	8.39	447.00	393.00	361.25	10.03	393.00	334.00	227.38	9.28	255.00	195.00
Max number of passengers in the elevator	4.32	0.74	8.00	3.00	6.17	0.98	11.00	4.00	13.52	1.82	20.00	9.00
Energy consumption	2368.32	86.12	2678.00	2121.00	1776.08	79.88	2051.00	1573.00	889.76	47.82	1058.00	555.00
Expected passenger riding time (s)	15.15	0.35	16.22	14.23	15.99	0.39	17.18	14.61	19.48	0.57	21.60	17.76
Expected passenger waiting time (s)	14.29	0.60	16.07	12.37	16.37	0.79	19.99	14.26	22.25	1.11	26.81	19.00
Expected passenger service time (s)	29.44	0.85	32.02	26.78	32.37	1.01	36.76	29.43	41.73	1.33	47.40	37.84

Table 2: Results of policy 1 with different arrival rates for an up-peak traffic pattern

For the maximum number of passengers in the elevator the highest value is 20. So in 3000 runs with different arrival rates there is a maximum of 20 passengers in the elevator all together. This shows that the assumption of an unlimited capacity of the elevator is not completely unrealistic for the current parameter set. An elevator with a capacity of 20 passengers might not be very common, but is not impossible. To get more insight in this value, a 95%-confidence interval can be calculated. This gives an interval such that in 95% of the time the values lies in this interval. The formula for this interval is:

$$\left[\overline{x} - z\frac{\sigma}{\sqrt{n}};\ \overline{x} + z\frac{\sigma}{\sqrt{n}}\right]$$

In which $\overline{x}$ is the average value, σ is the standard deviation, n is the number of evaluations (1000 in this case) and z is a specific value which belongs to the interval that is calculated, for a 95%-interval this value is 1.96. Calculating this interval gives more information about the average, standard deviation or maximum on itself. For example the 95%-confidence interval for the maximum number of passenger in the elevator for a high arrival rate is:

$$\left[13.52 - 1.96\frac{1.82}{\sqrt{1000}};\ 13.52 + 1.96\frac{1.82}{\sqrt{1000}}\right] = [13.41;\ 13.63]$$

So in 95% of the runs the maximum number of passengers in the elevator lies between 13.41 and 13.63. This is close to the average because the value for the standard deviation is low.

These performance metrics about the elevator are interesting to check but the three performance metrics about the passengers, the expected riding time (ER), the expected waiting time (EW) and the expected service time (ES) are the most important. Also for these three there is some correlation. For one passenger the service time is a summation of the riding time and waiting time. In these results this relation is not completely visible because they are all measured over all passengers and simulation runs. However, it can still be seen in the table. If the riding time and the waiting time increases, the service time will increase also. Important about these results is that the increase in the arrival rate is clearly visible in the table. All three measures are increasing when increasing the arrival rate. This is as expected, when there are more passengers arriving at the elevator it takes longer to serve all passengers in the elevator before getting back to the ground floor. So the passengers need to wait longer before the elevator to arrive and the riding time will increase also. These results of policy 1 will be used as starting point, the results of policy 2 will be compared to these results. Before this comparison the results of all three situations of policy 2 will be shown in table 3, 4 and 5. These are separated in the arrival rates, so for each value of λ there is one table. Table 3 shows the results for a low arrival rate, table 4 shows the results for a medium arrival rate and table 5 shows the results for a high arrival rate. A short recap about the difference between policy 2a, 2b and 2c. When there is a reservation for a specific floor and the elevator arrives at this floor it waits for T seconds for the passenger to arrive. For 2a this is 5 seconds and for 2b and 2c this is 10 and 15 second respectively.

POLICY 2 (a, b & c)	**2a (T = 5 seconds)**				**2b (T = 10 seconds)**				**2c (T = 15 seconds)**			
λ=0,0231 (LOW)	**Avg.**	**St.Dev.**	**Max**	**Min**	**Avg.**	**St.Dev.**	**Max**	**Min**	**Avg.**	**St.Dev.**	**Max**	**Min**
Number of stops	456.13	8.99	485.00	427.00	437.30	9.66	464.00	405.00	422.20	9.02	455.00	392.00
Max number of passengers in the elevator	5.14	0.93	10.00	3.00	5.55	1.02	10.00	4.00	5.34	0.98	10.00	4.00
Energy consumption	2462.69	94.01	2736.00	2171.00	2376.06	93.33	2664.00	2040.00	2401.12	87.68	2711.00	2136.00
Expected passenger riding time (s)	20.50	2.08	28.87	15.57	23.53	2.39	32.49	17.90	20.90	1.86	27.48	16.23
Expected passenger waiting time (s)	14.93	1.52	20.42	11.09	18.47	2.35	25.81	12.13	21.11	2.50	31.45	14.43
Expected passenger service time (s)	36.08	3.47	50.57	27.43	42.40	4.38	58.03	31.78	42.45	3.86	56.16	32.12

Table 3: Results of policy 2 with a low arrival rate for an up-peak traffic pattern

POLICY 2 (a, b & c) λ=0,0463 (MEDIUM)	2a (T = 5 seconds)				2b (T = 10 seconds)				2c (T = 15 seconds)			
	Avg.	St.Dev.	Max	Min	Avg.	St.Dev.	Max	Min	Avg.	St.Dev.	Max	Min
Number of stops	390.00	11.76	429.00	352.00	370.65	11.89	412.00	329.00	357.00	10.78	390.00	324.00
Max number of passengers in the elevator	7.25	1.26	14.00	5.00	8.46	1.77	18.00	5.00	7.99	1.45	17.00	5.00
Energy consumption	1820.81	91.90	2120.00	1519.00	1702.88	91.82	2026.00	1422.00	1793.79	88.38	2087.00	1550.00
Expected passenger riding time (s)	20.89	1.78	28.82	16.96	25.97	2.37	37.60	20.26	22.88	2.03	29.96	17.06
Expected passenger waiting time (s)	15.01	1.09	19.67	10.60	16.35	1.26	20.95	12.68	17.60	1.43	23.29	13.91
Expected passenger service time (s)	36.04	2.41	47.03	30.22	42.41	3.12	54.90	34.63	40.41	2.84	47.92	31.17

Table 4: Results of policy 2 with a medium arrival rate for an up-peak traffic pattern

POLICY 2 (a, b & c) λ=0,1389 (HIGH)	2a (T = 5 seconds)				2b (T = 10 seconds)				2c (T = 15 seconds)			
	Avg.	St.Dev.	Max	Min	Avg.	St.Dev.	Max	Min	Avg.	St.Dev.	Max	Min
Number of stops	256.17	12.25	294.00	218.00	235.63	12.09	274.00	198.00	240.36	11.39	280.00	204.00
Max number of passengers in the elevator	16.65	2.77	29.00	10.00	22.75	5.40	46.00	12.00	19.60	4.24	40.00	11.00
Energy consumption	791.07	68.30	1022.00	585.00	770.41	55.31	879.00	590.00	706.48	70.44	1107.00	614.00
Expected passenger riding time (s)	23.78	2.41	33.08	17.52	40.99	6.97	75.10	26.65	30.99	5.28	53.17	19.48
Expected passenger waiting time (s)	16.25	1.52	21.28	11.56	14.29	1.38	19.47	10.00	13.84	1.24	18.63	9.22
Expected passenger service time (s)	40.02	3.11	50.73	31.36	55.35	6.74	90.61	39.83	44.66	5.38	68.35	32.05

Table 5: Results of policy 2 with a high arrival rate for an up-peak traffic pattern

Remarkable about these three tables is the performance metric expected passenger waiting time. This is an important aspect because the focus of this paper is decreasing the waiting time by adding information about passengers to the movement of the elevator, i.e. taking reservation into account. For the low and medium arrival rates the waiting time is increasing when the time an elevator waits is increasing. So from 2a to 2c the waiting time of passengers is increasing. For the high arrival rate this is decreasing. An explanation for this is that when the arrival rate is high, there are more passengers arriving while the elevator is waiting due to a reservation call. So many passengers benefits from this situation. For low and medium arrival rates the number of passengers which arrive during this moment is lower. However, in case of a high arrival rate, many passengers enter the elevator during this moment and this is also reflected in the maximum number of passengers in the elevator. For policy 2c with a high arrival rate the average is 19.60 but the maximum is 40. This means in at least one of the 1000 simulation runs there have been 40 passengers in the elevator at the same time. A 95%-confidence interval for this performance metric is [19.34; 19.86]. For policy 2b this is even worse, with an average of 22.75 and a maximum of 46, the interval is [22.42; 23.08]. This means that almost all runs the elevator is at least ones filled with more than 20 passengers. So the elevator should have a capacity which exceeds 20, this is of course not very common. Apparently for this situation in combination with a high arrival rate one elevator is not enough to serve all passengers.

To compare all policies, for each arrival rate the results of policy 1 is compared to the best performing situation of policy 2. For the low and medium arrival rate policy 2a is selected based on the fact that these give the lowest results for ER, EW and ES. For a high intensity rate policy 2c is selected despite the high maximum number of passengers in the elevator. Not all results are shown, only the average values are shown in table 6. This is done because almost all values of the standard deviation are low with respect to the average. Calculating a 95%-confidence interval would show a small interval around the average, so the average itself is quite accurate for comparison.

Arrival rate:	**λ=0,0231 (LOW)**		**λ=0,0463 (MEDIUM)**		**λ=0,1389 (HIGH)**	
Policy:	**1**	**2a**	**1**	**2a**	**1**	**2c**
Number of stops	423.67	456.13	361.25	390.00	227.38	240.36
Max number of passengers in the elevator	4.32	5.14	6.17	7.25	13.52	19.60
Energy consumption	2368.32	2462.69	1776.08	1820.81	889.76	706.48
Expected passenger riding time (s)	15.15	20.50	15.99	20.89	19.48	30.99
Expected passenger waiting time (s)	14.29	14.93	16.37	15.01	22.25	13.84
Expected passenger service time (s)	29.44	36.08	32.37	36.04	41.73	44.66

Table 6: Results of policy 1 and 2 for different arrival rates for an up-peak traffic pattern

This table gives a good idea about the impact of reservations. For a low arrival rate the addition of reservations in slightly negative, about +4.5%. For a medium and high arrival rate the impact is positive for the waiting time, -8.3% and -37.8% respectively. But for the overall service time the impact is also slightly negative, +11.3% for a medium arrival rate and +7.0% for a high arrival rate. So for up-peak traffic the standard movement rules, without taking reservations into account performs better for a low arrival rate. For a medium arrival rate the waiting time can be reduced by 8.3% but then the service time increases by 11.3%. Only for a high arrival rate the results are positive, the waiting time can be reduced with 37.8% while the service time increases only by 7% in this case. For a high arrival rate a new simulation is performed in which the value of T runs from 1 to 15. This is done to get more insight in the results, maybe there is a specific setting in which not only the waiting time reduces but the service time also. The results of this simulation are shown in the next subsection.

4.1.2 Detailed results for up-peak traffic with a high arrival rate

As explained above, in this subsection the results for a high arrival rate are analyzed in more detail. The same simulation as before is performed, this time with T running from 1 to 15 with steps of 2. The complete table with results is shown in the appendix in table 12. In figure 3 the results of the EW and ES are shown for both policy 1 and policy 2. Policy 1 is of course a straight line because this policy does not have the parameter T. It is shown as dotted line and is only added for comparison.

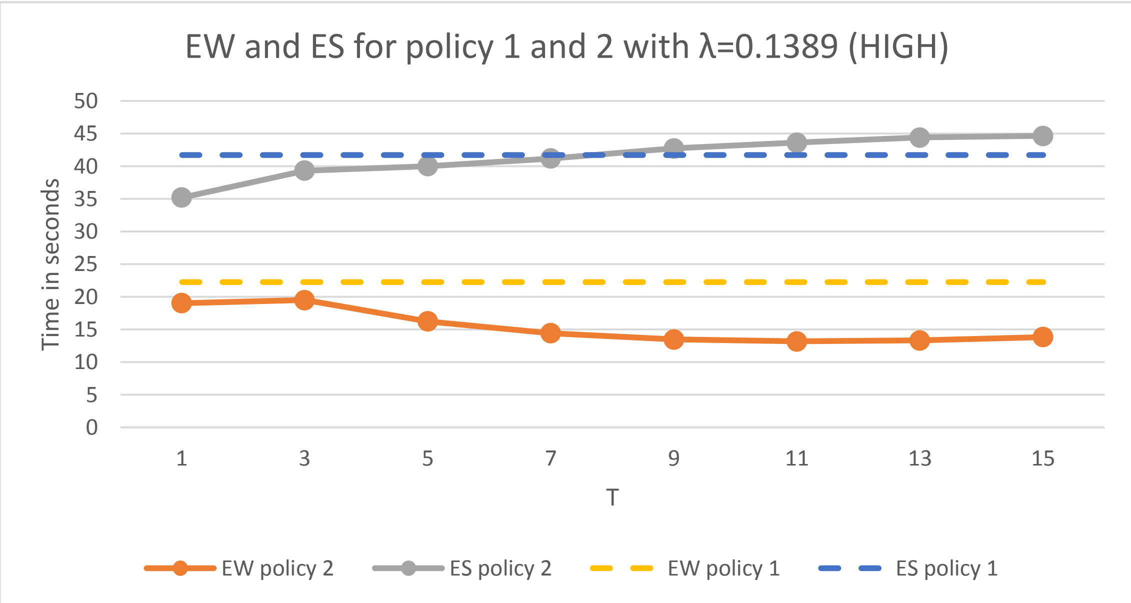

Figure 3: EW and ES for policy 1 and 2 with λ=0.1389 (HIGH)

This figure shows some important results. First of all it is shown that policy 2 outperforms policy 1 for the EW. For all values of T, the line of policy 2 lies below the dotted line of policy 1. Second of all, for policy 2 the ES is increasing when increasing T. However, there are cases in which both EW and ES of policy 2 lie below the values of policy 1. This means that indeed policy 2 performs better for a high arrival rate. The optimal value of T is depending on the goal. If the goal is to serve passengers as quick as possible the optimal value might be $T = 1$. In this paper lower the waiting time is the main goal but the other performance metrics are also important, so $T = 7$ would be the optimal choice. In this case the waiting time is reduced as much as possible while keeping ES a least as good as in policy 1. For $T = 7$ the results are a decrease in EW with 35.4% and a decrease in ES with 1.2%. Besides these positive results for

the performance metrics of the passengers the performance metrics of the elevator are calculated. The energy consumption decreases from 889.8 (policy 1) to 793.9 (policy 2). This implies that the improvements for the passengers result in lower cost on energy by 10.8%. A check on the assumption of unlimited capacity of the elevator is done by calculation of a 95%-confidence interval for the maximum number of passengers in the elevator. For $T = 7$ the average is 17.0 and the standard deviation is 3.3, then the interval becomes [16.8; 17.2]. This is an acceptable number of passengers in the elevator.

4.2 DOWN-PEAK TRAFFIC

In this section the results for down-peak traffic are presented. The structure of this section is the same as in section 4.1. First the main question is answered by analyzing four policy settings for all three arrival rates. Then more detailed results are shown for the cases in which reduction is possible.

4.2.1 Is it possible to reduce waiting time for down-peak traffic?

In this subsection the results for policy 1 are evaluated, followed by one table per arrival rate which show the results of policy 2a, 2b and 2c (with $T = 5/10/15$ respectively) and this subsection ends with a comparison between the different policies.

Table 7 shows the results of policy 1 for down-peak traffic with different arrival rates. The same performance metrics as before are shown and again the average, standard deviation and maximum and minimum value are given as results.

POLICY 1	**λ=0,0231 (LOW)**				**λ=0,0463 (MEDIUM)**				**λ=0,1389 (HIGH)**			
	Avg.	**St.Dev.**	**Max**	**Min**	**Avg.**	**St.Dev.**	**Max**	**Min**	**Avg.**	**St.Dev.**	**Max**	**Min**
Number of stops	379.82	8.08	403.00	352.00	318.96	7.99	345.00	295.00	212.37	7.84	237.00	190.00
Max number of passengers in the elevator	4.98	0.82	9.00	3.00	6.92	1.01	11.00	5.00	13.95	1.78	24.00	10.00
Energy consumption	2884.26	124.32	3259.00	2479.00	1911.79	102.00	2245.00	1555.00	697.07	48.62	881.00	519.00
Expected passenger riding time (s)	15.38	0.34	16.67	14.35	16.26	0.36	17.30	14.89	19.22	0.47	21.24	17.58
Expected passenger waiting time (s)	24.53	0.64	26.60	22.46	23.72	0.74	25.87	21.34	25.20	1.01	29.91	22.28
Expected passenger service time (s)	39.91	0.60	41.92	38.22	39.98	0.78	42.50	37.81	44.42	1.16	47.88	40.83

Table 7: Results of policy 1 with different arrival rates for a down-peak traffic pattern

For the performance metrics about the elevator as well as for those about the passengers the same correlations between the metrics can be seen as for up-peak traffic. The number of stops, maximum number of passengers in the elevator and the energy consumption are related in the same way. Of course also the ER, EW and ES are correlated because of their definition. For the ER, EW and ES it can be seen that the results again are depending on the value of λ. When there are more passengers in the system, all three increase. This is logical of course, everybody knows it takes longer to arrive at the destination floor when it is crowded. Remarkable is the increase in maximum number of passengers in the elevator. For a high arrival rate the maximum value is 24, which is quite high. However, the average is 13.95 and the 95%-confidence interval is [13.84; 14.06]. This is a very acceptable interval, it gives no sign of unrealistic situations. For the passengers performance metrics all standard deviations are small so the average values give an accurate view of the results.

For the results of policy 2a, 2b and 2c the tables are sorted based on the arrival rate as in section 4.1. Table 8 shows the results for a low arrival rate, table 9 shows the results for a medium arrival rate and table 10 shows the results for a high arrival rate.

POLICY 2 (a, b & c)	**2a (5 seconds)**				**2b (10 seconds)**				**2c (15 seconds)**			
λ=0,0231	**Avg.**	**St.Dev.**	**Max**	**Min**	**Avg.**	**St.Dev.**	**Max**	**Min**	**Avg.**	**St.Dev.**	**Max**	**Min**
Number of stops	447.52	9.61	478.00	413.00	419.45	9.36	450.00	392.00	392.47	8.70	423.00	367.00
Max number of passengers in the elevator	5.26	1.02	10.00	3.00	6.05	1.32	14.00	4.00	6.87	1.56	18.00	4.00
Energy consumption	3045.24	133.33	3468.00	2626.00	2837.27	135.64	3358.00	2388.00	2637.18	136.69	3125.00	2254.00
Expected passenger riding time (s)	16.83	1.16	21.65	14.60	19.26	1.76	26.52	15.43	21.98	2.33	33.60	17.01
Expected passenger waiting time (s)	17.87	0.83	22.24	15.17	17.07	0.94	21.23	14.50	17.53	1.13	22.10	14.42
Expected passenger service time (s)	34.54	1.49	40.97	30.63	36.16	2.20	44.60	31.89	39.29	2.86	51.88	32.61

Table 8: Results of policy 2 with a low arrival rate for a down-peak traffic pattern

POLICY 2 (a, b & c)	2a (5 seconds)				2b (10 seconds)				2c (15 seconds)			
λ=0,0463	Avg.	St.Dev.	Max	Min	Avg.	St.Dev.	Max	Min	Avg.	St.Dev.	Max	Min
Number of stops	399.19	9.69	429.00	362.00	366.85	9.27	393.00	339.00	336.66	8.05	360.00	314.00
Max number of passengers in the elevator	7.81	1.54	17.00	5.00	9.56	2.16	20.00	6.00	11.35	2.67	24.00	6.00
Energy consumption	1973.65	108.87	2325.00	1570.00	1781.36	113.48	2131.00	1388.00	1584.30	106.17	1925.00	1268
Expected passenger riding time (s)	18.30	1.21	24.74	16.01	22.53	2.22	32.74	17.29	27.58	3.31	47.38	20.36
Expected passenger waiting time (s)	19.14	0.90	22.03	16.59	18.81	1.08	22.88	15.97	20.44	1.35	27.48	16.30
Expected passenger service time (s)	37.39	1.60	43.47	32.86	41.25	2.75	53.15	35.05	47.88	3.97	68.50	38.94

Table 9: Results of policy 2 with a medium arrival rate for a down-peak traffic pattern

POLICY 2 (a, b & c)	2a (5 seconds)				2b (10 seconds)				2c (15 seconds)			
λ=0,1389	Avg.	St.Dev.	Max	Min	Avg.	St.Dev.	Max	Min	Avg.	St.Dev.	Max	Min
Number of stops	308.49	9.29	339.00	282.00	277.88	8.33	307.00	248.00	255.09	8.65	282.00	222.00
Max number of passengers in the elevator	19.19	4.30	42.00	11.00	30.11	8.63	75.00	15.00	39.43	11.75	104.00	17.00
Energy consumption	703.86	61.75	982.00	541.00	557.33	50.33	741.00	404.00	467.41	51.18	658.00	321.00
Expected passenger riding time (s)	24.15	3.03	38.00	16.59	40.86	8.85	89.97	25.02	57.08	15.31	150.13	30.09
Expected passenger waiting time (s)	22.28	1.31	27.05	17.37	25.92	1.97	32.73	20.26	32.04	3.38	49.32	22.85
Expected passenger service time (s)	46.41	3.52	60.11	36.92	66.78	9.76	122.37	47.61	89.15	17.22	190.43	57.25

Table 10: Results of policy 2 with a high arrival rate for a down-peak traffic pattern

For the tables of the low and medium arrival rate there are no strange results. The performance metrics about the elevator show the same pattern as seen before, the longer the waiting time of the elevator, the lower the number of stops and energy consumption. In relation to this the maximum number of passengers increases. For the performance metrics about the passengers it is remarkable to see that for policy 2b the EW is lower than for policy 2a. So indeed by increasing this stopping time of the elevator the waiting time decreases. However, further increasing this time, to 15 seconds in policy 2c, has a negative effect. Also for the riding time and service time it is negative to increase the stopping time of the elevator. For both, low and medium arrival rate, policy 2b shows the best results for the performance metric EW. These are compared to the results of policy 1 in table 11.

For up-peak traffic the maximum number of passengers in the elevator was acceptable in almost all cases. Table 10 shows that for down-peak traffic there are very high averages for policy 2b and 2c. The 95%-confidence intervals are [29.57; 30.64] and [38.70; 40.16] respectively. This is very unrealistic, an elevator with a capacity of 30 or even more. For policy 2a the average is around 20, this might be possible but is also quite a lot. For down-peak traffic an (high) arrival rate of 0.1389 seems to be too high. For a high arrival rate in the comparison of policy 1 and 2 the results of policy 2a are taken, because this policy shows the lowest waiting time.

Table 11 shows the results of policy 1 for all arrival rates and the results of policy 2b for the low and medium arrival rates and the results of policy 2a for the high arrival rate. As for up-peak traffic, only the average values are presented in this table.

Arrival rate:	**λ=0,0231 (LOW)**		**λ=0,0463 (MEDIUM)**		**λ=0,1389 (HIGH)**	
Policy:	**1**	**2b**	**1**	**2b**	**1**	**2a**
Number of stops	379.82	419.45	318.96	366.85	212.37	308.49
Max number of passengers in the elevator	4.98	6.05	6.92	9.56	13.95	19.19
Energy consumption	2884.26	2837.27	1911.79	1781.36	697.07	703.86
Expected passenger riding time (s)	15.38	19.26	16.26	22.53	19.22	24.15
Expected passenger waiting time (s)	24.53	17.07	23.72	18.81	25.20	22.28
Expected passenger service time (s)	39.91	36.16	39.98	41.25	44.42	46.41

Table 11: Results of policy 1 and 2 for different arrival rates for a down-peak traffic pattern

Looking at the EW, policy 2 performs better than policy 1 for all arrival rates. This implies that taking reservations into account results in a decrease in passengers waiting time. For a low arrival rate the result of EW is -30.4%, for a medium arrival rate it is -20.7 and for a high arrival rate it is -11.6%. So for all arrival rates the reduction is significant. However, for the riding time and service time the results are negative for a medium or high arrival rate, +3.2% and 4.5% respectively. Adding reservations to the system has a slight positive impact on the energy consumption of the elevator in case of a low or medium arrival rate. It reduces with 1.6% for a low arrival rate and with 6.8% for a medium arrival rate. For a high arrival rate the energy consumption increases by adding reservations to the system. Because the accent of this paper is on the waiting times, the conclusion for down-peak traffic is that it is good to take reservations into account. To evaluate these results in more detail the simulation is performed again, for more values of T. The next three subsections described these detailed results, one subsection for each value of λ.

4.2.2 Detailed results for down-peak traffic with a low arrival rate

In the previous subsection it was shown that the waiting time as well as the service time were lower for policy 2 with $T = 10$ than for policy 1. The question that is raised is, is 10 the optimal value for T or is there another value which gives even better results? To answer this question the simulation is run with all values for T between 0 and 15. The complete results can be seen in the appendix in table 13. In figure 4 the results of EW and ES are shown. Again the dotted line is added for comparison with policy 1.

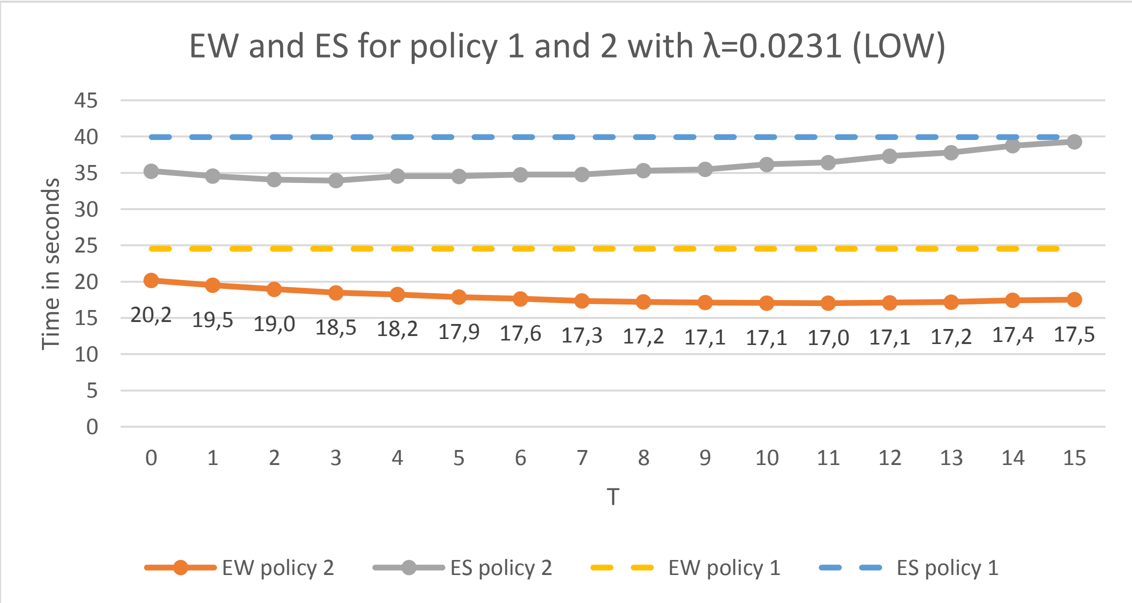

Figure 4: EW and ES for policy 1 and 2 with λ=0.0231 (LOW)

In figure 4 we see that both EW and ES are always better for policy 2 than for policy 1. This means that adding reservation to the system is preferred, but selecting a value for T is depending on the goal. The waiting time is optimal for $T = 11$. In this case the waiting time is 17.0 and this means it is reduced by 30.6% with respect to policy 1. For this value of T, ES is reduced by 8.8%. Not only is the impact on EW and ES analyzed, the energy consumption of the elevator is also taken into account. In figure 5 the results for the energy consumption are shown for different values of T.

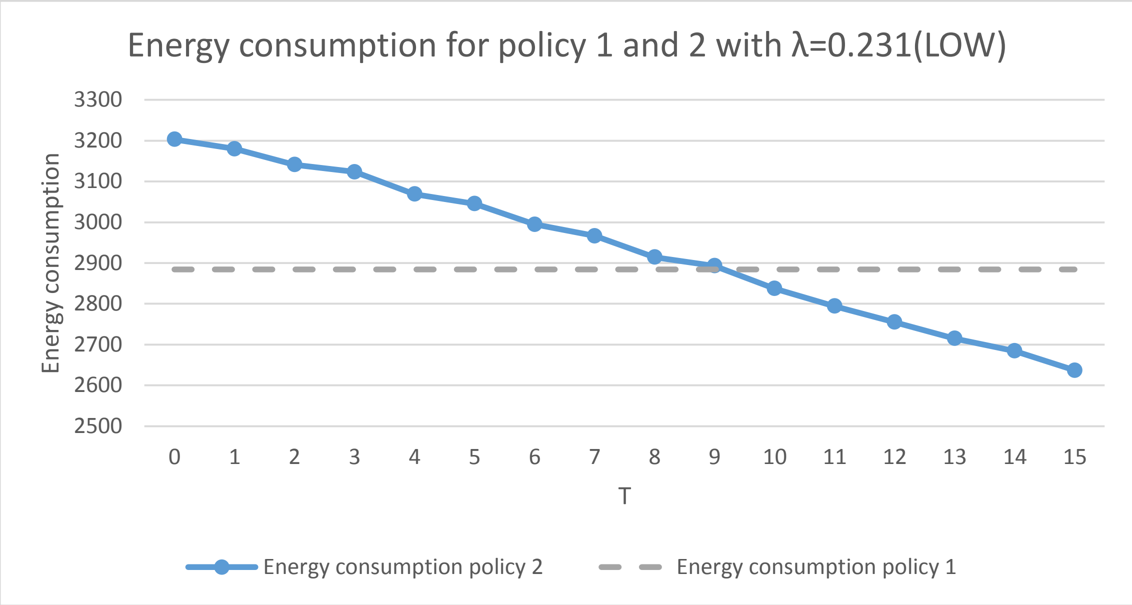

Figure 5: Energy consumption for policy 1 and 2 with λ=0.0231 (LOW)

In this figure it can be seen that from $T = 10$ up to $T = 15$ the impact of adding reservation to the system is positive for the energy consumption. So by taking policy 2 with $T = 11$ the changes in elevator movement are positive for the passengers as well as for the owners that pay the energy bills. In this situation the energy consumption is reduced by 3.1%.

Besides changing the value of T, a second simulation is performed. In this simulation the time between a reservation call and the arrival time of the passengers is doubled. In the previous simulation the time between the reservations and the arrivals, called R, was according to a Normal distribution $\mathcal{N}(\mu = 20\ seconds, \sigma^2 = 5\ seconds)$. Now the distribution is changed to $\mathcal{N}(\mu = 40\ seconds, \sigma^2 = 5\ seconds)$. In the first situation the elevator got a sign of an arriving passenger about 20 seconds before the passenger arrived. In the second situation this is 40 seconds. The complete results are shown in the appendix in table 14. The question is whether the optimal value of T will change by this adaption. This is shown in figure 6.

The figure look quite the same as figure 5. The values of EW and ES are a little higher, but the curve of the lines is almost equal. It is shown that the optimal value of T is still 11. So the conclusion about adapting the distribution of the reservation time R is that is does not influence the optimal value of T.

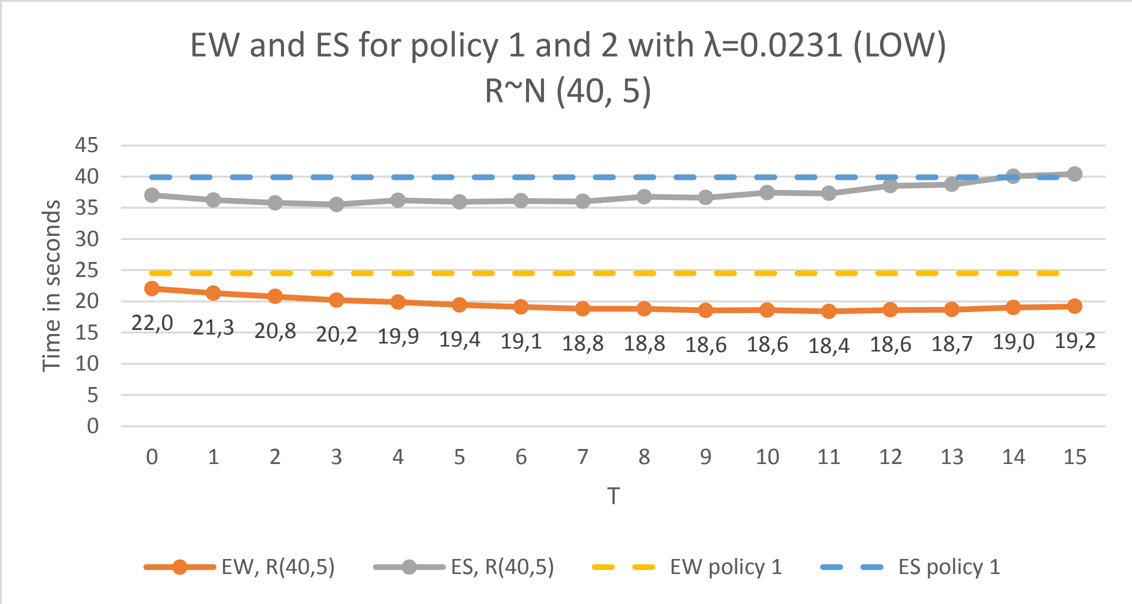

Figure 6: EW and ES for policy 1 and 2 with λ=0.0231 (LOW), R~N (40, 5)

4.2.3 Detailed results for down-peak traffic with a medium arrival rate

In this subsection the same values of T are analyzed, but with a medium arrival rate. The complete table of results are presented in the appendix in table 15. Figure 7 shows the results of EW and ES for policy 1 and 2 with a medium arrival rate.

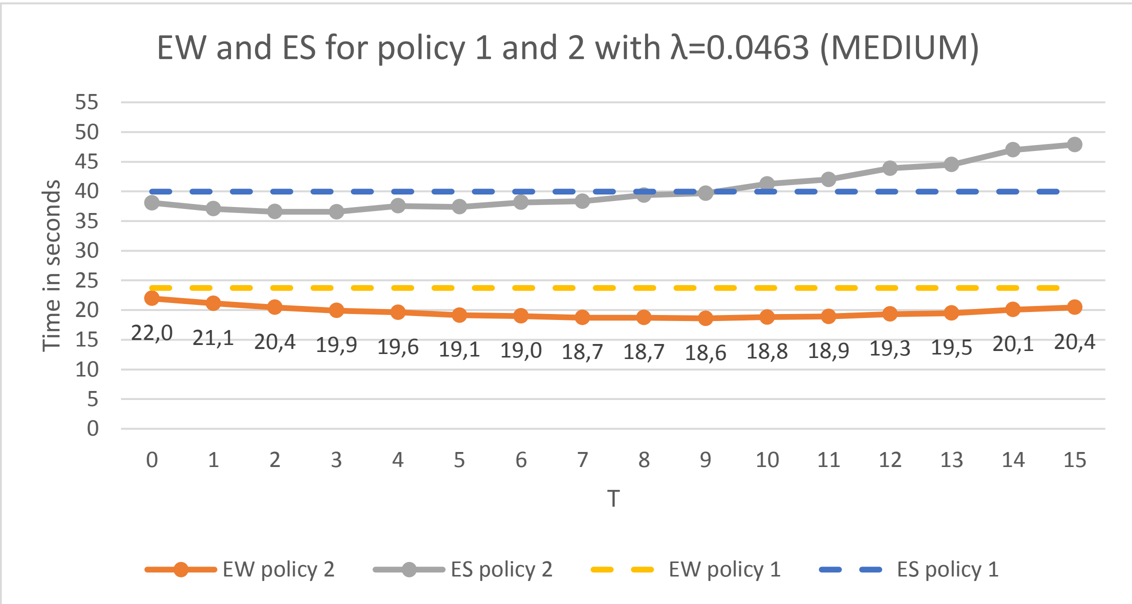

Figure 7: EW and ES for policy 1 and 2 with λ=0.0463 (MEDIUM)

The optimal value of T is 9. In that situation the waiting time is minimal and the service time is almost equal to the service time of policy 1. This means the waiting time is reduced by 21.5% while the service time stays equal, -0.8%. For the passengers this means shorter waiting times but it takes the same amount of time before arriving at the destination floor. This may seem as no improvement, but the assumption is that passengers get more frustrated if they need to wait. Riding in the elevator is not seen as waiting but as being served so this is less frustrating. To see if the results are also positive on the energy consumption figure 8 is presented.

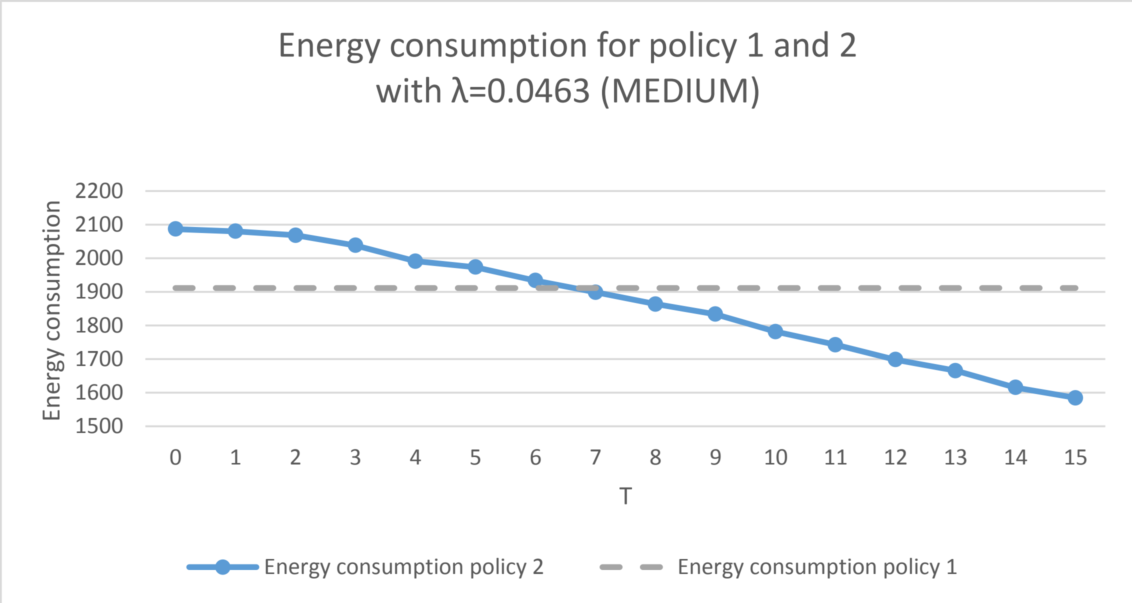

Figure 8: Energy consumption for policy 1 and 2 with λ=0.0463(MEDIUM)

For $T = 9$ the impact on the energy consumption is positive. The reduction is 4.1%, a small reduction. The conclusion after evaluation of these detailed results is that policy 2 is preferred for a medium arrival rate in down-peak traffic.

4.2.4 Detailed results for down-peak traffic with a high arrival rate

For a low or a medium arrival rate policy 2 is preferred. To see if this conclusion is true for a high arrival rate as well the same simulation is performed for a high arrival rate. The result are described in this subsection and the complete results are shown in the appendix in table 16. Figure 9 shows the results of EW and ES for this situation.

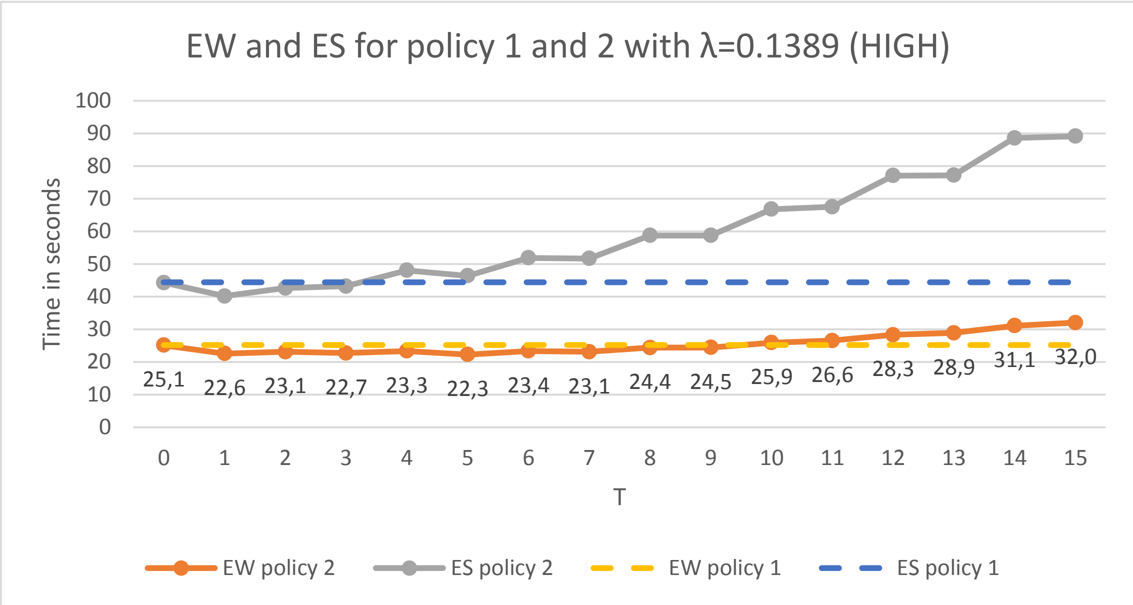

Figure 9: EW and ES for policy 1 and 2 with λ=0.1389 (HIGH)

For a high arrival rate the results are less consistent, the values of EW are fluctuating a little bit. The lowest value is reached for $T = 5$. But in this case ES is increased in comparison with policy 1. This means the passengers waiting time is shorter but it takes a longer time to arrive at the destination floor. The question is whether this is optimal. If the service time should be less or equal to policy 1 the optimal value of T is 1. In that case EW is as low as possible while ES stays below the value of policy 1. To select the optimal value of T the energy consumption is shown in figure 10. This might give more insight in which value should be selected.

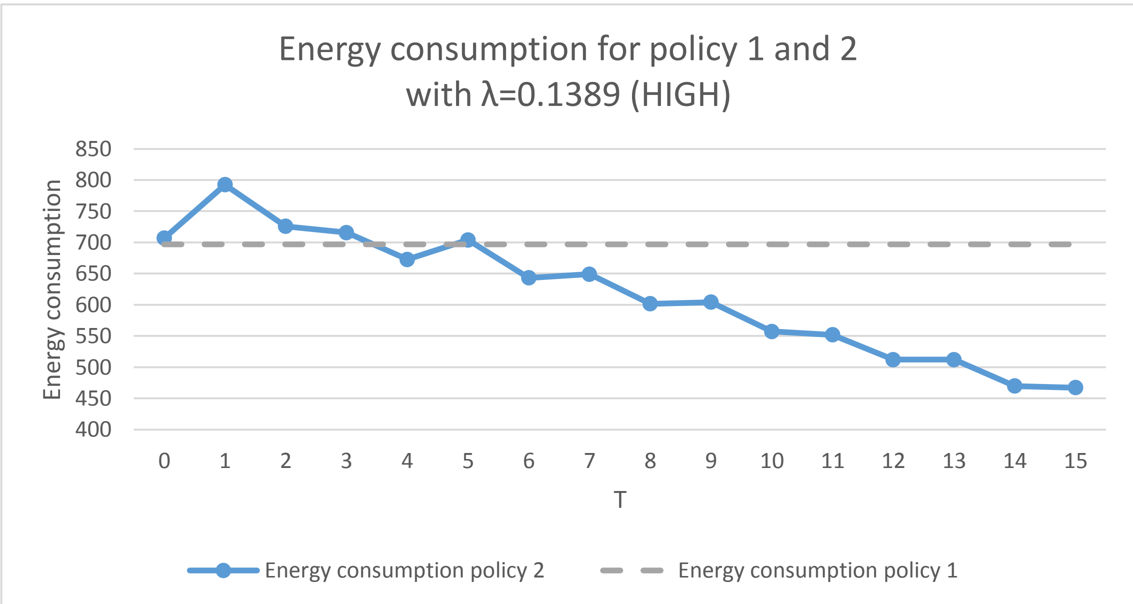

Figure 10: Energy consumption for policy 1 and 2 with λ=0.1389 (HIGH)

From the perspective of energy consumption $T = 1$ is not a very good choice. For $T = 5$ the figure shows a slightly higher value for policy 2 than for policy 1. Besides, it is not possible to select a value for T in which all three metrics are reduced. If the waiting time is reduced, one of the other two, energy consumption or service time, is increased. So selecting the optimal value of T is not easy for a high arrival rate. It strongly depends on the requirements of the performance. But also for a high arrival rate it can be concluded that policy 2 is preferred. The maximum decrease in waiting time is 11.5%. This implies an increase of 4.5% in service time and an increase of 1.0% in energy consumption.

5 CONCLUSION & DISCUSSION

5.1 CONCLUSION & DISCUSSION

In this section the conclusion for both up-peak and down-peak traffic are presented, including some possible reasons for these conclusions.

5.1.1 Up-peak traffic

In section 4.1 the results of the experiment with an up-peak traffic pattern were presented. The conclusion after analyzing the results is that for up-peak traffic with a low arrival rate the policy that does not take reservations into account performs better than the policy which does take reservations into account. For a medium arrival rate, the waiting time can be reduced with 8.3% but then the service time increases with 11.3%. This is reached with $T = 5$. Because these results are not positive (the increase in ES is bigger than the decrease in EW) and increasing T only result in worse values, it is concluded that for a medium arrival rate also policy 1 is preferred. For a high arrival rate the first results showed positive results. With $T = 15$ the reduction for EW was 37.8% while the increase in ES was only 7%. Because these positive results the simulation was performed again to get more detailed results. These results showed a positive impact on both EW and ES for $T = 1$ up to $T = 7$. After this the impact on ES becomes negative. For $T = 7$ the impact is -35.4% on EW and -1.2% on ES. Even though the results for the passengers are positive the results about the performance of the elevator should be taken into account. For $T = 7$ the energy consumption of the elevator decreases with respect to policy 1 with 10.8%. Furthermore it is shown that the assumption of unlimited elevator capacity is no source of troubles. The maximum number of passengers in the elevator is evaluated for every situation and does not show unrealistic values.

These conclusions about the impact of reservations in up-peak traffic might become even better by further increasing the arrival rate or adding a second elevator. Increasing the arrival rate might result in unrealistic values for the maximum number of passengers in the elevator, but the effect of adding reservations to the system could become bigger. With a second elevator the information about the arrivals can be used with greater benefit. In this case it is not profitable to have both elevators waiting for reservations, so most of the time only one elevator waits at the ground floor while the other one is serving passengers. This will most likely lower the waiting time and riding time of the passengers. In the situation without reservations the elevators will start riding when only one passenger arrived at the ground floor, which probably will result in lower performance in comparison to the policy which uses reservations.

5.1.2 Down-peak traffic

The results for down-peak traffic were shown in section 4.2. The main conclusion for this traffic pattern is that for the expected passenger waiting time it is positive to use reservations. For a low or a medium arrival rate this means a decrease in energy consumption and service time as well. For a low arrival rate the reduction percentages are 30.6, 8.8 and 3.1 for EW, ES and the energy consumption respectively. For a medium arrival rate these percentages are 21.5, 0.8 and 4.1. For a high arrival rate it is possible to lower the waiting time and the service time, but then the energy consumption increases. Or the waiting time and energy consumption are reduced, but this results in an increase in service time. About the optimal value of T it can be concluded that a higher arrival rate result in a lower optimal value of T. For a low arrival rate the optimal value is 11, for a medium arrival rate the optimal value is 9 and for a high arrival rate the optimal value from the perspective of lower the waiting time the optimal value is 5. For a high arrival rate with $T = 5$ the result on the waiting time is -11.5%, on the service time +4.5% and on the energy consumption +1.0%.

An explanation for the optimal value of T by changing the arrival rate is that when the arrival rate becomes higher there are more passengers waiting at the same time, so if the elevator waits at a specific floor there are more passengers who experience a negative influence on their waiting time. It is possible that the number of passengers who experience a positive influence on their waiting time increases because the elevator waits for them to arrive. But when the arrival rate becomes higher the increase in the number of passengers who arrive at the floor at which the elevator waits is lower than the increase of passengers who arrive at all the other floors. At each floor the arrival of passenger is increased, but the elevator is just waiting at one floor at the same time.

Besides the results for different values of T a simulation is performed with a different distribution for the time between reservations and arrivals of passengers. This was performed for a low arrival rate and did not result in a different optimal value for T.

5.2 FURTHER RESEARCH

In this section some possibilities for further research are given. Most of them are quite logical and have been discussed in the previous section.

- Increasing the number of elevators. The additional information about arrivals can be used more adequate. Two elevators can work together on the same set of passengers. The expectation is that two elevators are smarter than one.
- Taking interfloor traffic into account. For example running the simulation for a whole day, instead of a short period (up-peak traffic or down-peak traffic only).
- Changing the movement rules of the elevator(s) such that the information about reservations is even more beneficially used. In this research the elevator waits for some seconds on a floor with a reservation and when the elevator is idle it calculates the time it can wait before moving to the source floor. It might be profitable to adapt these methods or create new methods which uses the information about arrivals.

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7 APPENDIX

7.1 UP-PEAK TRAFFIC

Arrival rate:	Policy 2 with λ=0,1389 (HIGH)							
T:	**1**	**3**	**5**	**7**	**9**	**11**	**13**	**15**
Number of stops	256.9	247.5	256.2	254.9	250.8	246.0	244.0	240.4
Max number of passengers in the elevator	12.7	13.7	15.6	17.0	18.4	19.3	19.7	19.6
Energy consumption	855.2	844.9	791.1	793.9	806.1	770.4	732.0	706.5
Expected passenger riding time (s)	16.2	19.8	23.8	26.8	29.3	30.6	31.2	31.0
Expected passenger waiting time (s)	19.0	19.5	16.2	14.4	13.5	13.2	13.3	13.8
Expected passenger service time (s)	35.2	39.3	40.0	41.2	42.7	43.6	44.4	44.7

Table 12: Policy 2 for up-peak traffic with a high arrival rate

7.2 DOWN-PEAK TRAFFIC

Arrival rate:	Policy 2 with λ=0,0231 (LOW) and R~N (20, 5)															
T:	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Number of stops	475.0	469.9	464.2	459.3	453.5	447.5	442.0	436.3	430.2	425.4	419.4	413.6	408.0	403.3	397.9	392.5
Max number of passengers in the elevator	4.8	4.7	4.8	4.9	5.2	5.3	5.5	5.5	5.7	5.8	6.1	6.1	6.3	6.5	6.6	6.9
Energy consumption	3203.2	3179.9	3140.8	3123.4	3069.0	3045.2	2994.6	2966.3	2914.2	2893.2	2837.3	2794.2	2755.2	2715.1	2684.5	2637.2
Expected passenger riding time (s)	15.2	15.2	15.3	15.6	16.5	16.8	17.3	17.6	18.2	18.5	19.3	19.6	20.4	20.8	21.5	22.0
Expected passenger waiting time (s)	20.2	19.5	19.0	18.5	18.2	17.9	17.6	17.3	17.2	17.1	17.1	17.0	17.1	17.2	17.4	17.5
Expected passenger service time (s)	35.2	34.6	34.1	33.9	34.6	34.5	34.7	34.8	35.3	35.5	36.2	36.4	37.3	37.8	38.7	39.3

Table 13: Policy 2 for down-peak traffic with a low arrival rate and R~N (20, 5)

Arrival rate:	Policy 2 with λ=0,0231 (LOW) and R~N (40, 5)															
T:	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Number of stops	551.8	545.3	539.5	532.1	523.8	517.0	508.1	501.2	493.3	486.1	478.6	472.2	463.5	457.1	449.6	443.5
Max number of passengers in the elevator	4.8	4.7	4.9	4.9	5.3	5.3	5.5	5.5	5.8	5.9	6.0	6.1	6.5	6.5	6.8	6.9
Energy consumption	3241.6	3226.9	3191.9	3155.2	3112.6	3086.1	3033.0	2994.7	2939.0	2914.5	2858.6	2829.4	2768.7	2730.4	2684.2	2637.1
Expected passenger riding time (s)	15.2	15.2	15.3	15.6	16.6	16.8	17.3	17.5	18.2	18.3	19.1	19.2	20.2	20.3	21.4	21.5
Expected passenger waiting time (s)	22.0	21.3	20.8	20.2	19.9	19.4	19.1	18.8	18.8	18.6	18.6	18.4	18.6	18.7	19.0	19.2
Expected passenger service time (s)	37.0	36.2	35.8	35.5	36.2	35.9	36.1	36.0	36.8	36.6	37.4	37.3	38.5	38.7	40.0	40.4

Table 14: Policy 2 for down-peak traffic with a low arrival rate and R~N (40. 5)

Arrival rate:	Policy 2 with λ=0,0463 (MEDIUM)															
T:	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Number of stops	427.7	423.9	418.8	412.4	405.1	399.2	392.9	386.2	379.7	373.7	366.8	360.2	354.2	348.7	342.2	336.7
Max number of passengers in the elevator	6.9	6.8	7.0	7.1	7.7	7.8	8.2	8.4	8.9	9.0	9.6	9.8	10.3	10.5	11.2	11.4
Energy consumption	2086.8	2080.4	2068.4	2038.3	1991.2	1973.6	1933.5	1898.7	1863.7	1833.3	1781.4	1742.4	1698.3	1665.4	1615.6	1584.3
Expected passenger riding time (s)	16.1	16.0	16.2	16.7	18.0	18.3	19.2	19.7	20.7	21.2	22.5	23.2	24.7	25.1	27.0	27.6
Expected passenger waiting time (s)	22.0	21.1	20.4	19.9	19.6	19.1	19.0	18.7	18.7	18.6	18.8	18.9	19.3	19.5	20.1	20.4
Expected passenger service time (s)	38.0	37.1	36.6	36.6	37.5	37.4	38.1	38.3	39.3	39.7	41.2	42.0	43.9	44.5	47.0	47.9

Table 15: Policy 2 for down-peak traffic with a medium arrival rate

Arrival rate:	Policy 2 with λ=0.1389 (HIGH)															
T:	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Number of stops	327.0	336.1	323.4	318.6	309.2	308.5	299.5	296.4	287.9	284.7	277.9	273.7	267.5	264.3	258.3	255.1
Max number of passengers in the elevator	13.9	13.7	14.8	15.5	19.3	19.2	22.2	22.5	26.3	26.4	30.1	30.5	34.8	34.8	39.4	39.4
Energy consumption	706.8	792.4	725.8	715.7	672.6	703.9	643.3	649.2	601.6	604.2	557.3	551.8	512.2	512.1	469.8	467.4
Expected passenger riding time (s)	19.2	17.6	19.5	20.5	24.7	24.1	28.5	28.6	34.4	34.3	40.9	41.0	48.7	48.3	57.5	57.1
Expected passenger waiting time (s)	25.1	22.6	23.1	22.7	23.3	22.3	23.4	23.1	24.4	24.5	25.9	26.6	28.3	28.9	31.1	32.0
Expected passenger service time (s)	44.3	40.2	42.6	43.2	48.1	46.4	51.9	51.7	58.7	58.8	66.8	67.5	77.1	77.2	88.6	89.1

Table 16: Policy 2 for down-peak traffic with a high arrival rate