

Session-Based Queueing Systems

Modelling, Simulation, and Approximation

Jeroen Horters

Supervisor VU: Sandjai Bhulai



Executive Summary

Companies often offer services that require multiple steps on the server side to complete. These services often experience times of high demand, leading to a high server load. If nothing is done to regulate this, this could result in services failing before full completion or, in the worst case, servers crashing. To prevent these events, some actions must be taken. In session-based queuing systems (SBQs), the amount of traffic on these systems is regulated by limiting the number of customers that are active on the entire system, rather than on a per-queue basis. This system has been implemented in several companies, without any scientific support.

The simulations show that adding sessions results in better performance for customers that manage to get into the system, but also results in a significant blocking probability. It is hard to determine whether this is an overall improvement of the system. The numerical approximation on Jackson networks shows very similar results, but performs only faster than the simulation on very small problems.

Contents

- Executive Summary 1
- 1. Introduction..... 3
- 2. Background..... 4
- 3. Approach 6
- 4. Model 7
 - 4.1. Simulation..... 7
 - 4.2. Approximation..... 9
- 5. Results 11
 - 5.1. Simulation..... 11
 - 5.2. Approximation..... 13
- 6. Conclusion 15
- 7. Literature..... 16
- 8. Appendix..... 17
 - A. Additional Results Simulation 17
 - B. Additional Results Approximation..... 21

1. Introduction

Every day, the ING bank processes thousands of online transactions. These transactions on a technical level consist of various steps. To prevent these transactions from failing halfway through the process due to an overload of the servers, ING needs to put a system in place to control the server load.

ING started using the Session-Based Queueing systems (SBQs) to solve the problem at hand. SBQs are an extension of more traditional queueing models that involve blocking, where a single queue has a limited number of positions in the queue. When all these spots are filled, additional customers are blocked from the queue. SBQs use this property for an entire system of queues, where a limited number of customers are allowed in the total system, more commonly referred to as the number of sessions.

There is currently no academic literature available that describes these queueing models. So even though they are used by some companies, not much is known about their performance. The purpose of this research is to answer the following main question:

What is the performance of session-based queueing systems?

This paper will outline two different approaches to answer this question by using simulation as well as by numerical approximation.

In Chapter 2, we take a more detailed look at the models that form the basis of the session-based queueing model, as well as some other types of models that will be used in the remainder of this research. Next, in Chapter 3 we formulate a general approach to answer the research question. In Chapter 4, we construct the models needed to do the simulation and the numerical approximation. Furthermore, Chapter 5 shows the results of these methods. Finally, Chapter 6 shows the conclusions of this research and discusses the answer to the research question.

2. Background

To understand the workings of SBQs, we will need to establish some basic knowledge about simpler queueing systems. The most generic queueing model is commonly known as the M/M/1 model. In this model, we assume that both the inter-arrival and handling times of the customers that enter the system follow an exponential distribution. This leads to the arrivals following a so-called Poisson Process (Koole, 2016, pp. 29-30). For the sake of not making this research any more complicated than it needs to be, we will assume Poisson arrivals and exponential handling times for all models described from this point forward.

The M/M/1 model is considered stable as long as the arrival rate is lower than the service rate, or in a more general sense, the following equation holds:

$$\frac{\lambda}{\mu} = \rho < 1$$

Here, λ denotes the arrival rate, μ the service rate and ρ the load on the system. As long as this equation holds, during simulation, the queue will never grow to a significant length and the queue is guaranteed to go empty over time (Kijima, 1997). When this equation does not hold, the system becomes unstable and the length of the queue will grow to infinity as time does. Also when arrival and service rates are very close to each other, the system will encounter very high occupancy rates, which is generally unwanted by service providers.

To prevent these server overloads from happening, we can limit the maximum queue length by introducing a limited queue. If we apply this to the M/M/1 queue, we get a model that is called the M/M/1/N system. This model works the same as the M/M/1 model with the exception that customers are blocked when the maximum queue length has been reached. Even though this does not seem like a complex extension of the basic model, there is no explicit solution to this system. We can, however, model this system as a birth-death process and calculate waiting times from there in a closed-form solution (Sharma & Gupta, 1982).

Since the SBQs are once again a more complicated extension to these M/M/1/N systems, we can expect that there is no closed-form solution for the SBQs either. Therefore, we need to resort to doing simulations. However, there is still a possibility that making a numerical approximation could be possible.

When trying to construct a numerical approximation for SBQs, it quickly became apparent that this would only be possible for systems that already have a closed-form solution when no sessions are in place. The candidate subset of models that allowed for the most complex queueing networks were the so-called Jackson networks.

A Jackson network is a collection of M/M/1 queues that not only have their arrivals from outside the system, but also allow for networks to connect to one another. For each queue in the network, there is a probability distribution r that describes where a customer is routed after service has ended in that queue. This means that with a certain possibility, this customer is either leaving the system or gets queued into another (or the same) queue within the network.

We can describe the stationary distribution of Jackson networks in the following way: Firstly, we define new parameters γ for each queue which denote the actual inflow of customers into each queue. This is simply the sum of the arrival rates plus the fractions of the inflows from other queues as shown in the equation below. Since we have one of these equations for every queue, we can solve this set of equations

$$\gamma_i = \lambda_i + \sum_{j=1}^V \gamma_j r_{ij}$$

When all inflow parameters are known, we can now calculate the long-term probability of each state of the system occurring. These probabilities are given by the following equations (KooLe, 2016, pp. 78-80):

$$P(N_1 = n_1, \dots, N_v = n_v) = \prod_{i=1}^V \pi_i(n_i)$$

$$\pi_i(n_i) = P(N_i = n_i) = \left(\sum_{n=0}^{\infty} \prod_{j=1}^n \frac{\gamma_i}{\mu_i(j)} \right)^{-1} \prod_{j=1}^{n_i} \frac{\gamma_i}{\mu_i(j)}$$

Here, $\mu_i(j)$ denotes the service rate at queue i when there are j customers present. In our models, this will be a constant rate. Because this is a probability distribution, the sum of all possible states is equal to one. The difficulty in doing these calculations comes from the many possible combinations of states for queues. However, because all queues are M/M/1, the calculations often boil down to infinite products, which often have known limits. Also, when queues get long enough, the probability of such a queue occurring gets very small and these states can be ignored when calculating average wait times.

Finally, for these calculations to be correct, all the server load ratios for each queue must be smaller than 1. In other words, each queue by itself must be stable for the system to be stable.

Now that we know what the session-based queueing models are derived from and we know exactly how we can use Jackson models, we can start constructing an approach to test the performance of SBQs.

3. Approach

In order to run a good simulation, a capable software package needed to be chosen. A few different possibilities were considered and ultimately Arena was chosen. Arena was primarily designed for queueing models and there were multiple options to include the sessions into the different models. Additionally, Arena provides the user with detailed reports on the statistics of the models after simulating them, which would be very useful for the analysis.

Furthermore, it seemed relatively simple to create more complex networks, such as Jackson networks in Arena. The only restriction seemed to be the maximum number of entities that Arena can handle at the same time. This would however not be a problem, since the highest number of sessions was lower than this number, guaranteeing that this limit would never be reached.

Because simulations usually take a long time to run, there was an incentive for a numerical approximation. In order to accomplish such an approximation, sessions needed to be included in the known numerical solution for Jackson networks. Afterward, this method had to be implemented in some programming language. Due to previous experience with MatLab, it was chosen as the programming language used for this part of the research.

4. Model

4.1. Simulation

After deciding that Arena would be the most efficient software solution to create and simulate the models in, some decisions regarding the design of the model had to be taken. For this particular research, most models that were to be simulated were very simple models. However, the goal of the actual modelling was to make the model as general as possible. The following properties are essential to ensure a general SBQ model:

- Any model can have sessions added to turn it into an SBQ model
- The SBQ can be a submodel
- The SBQ can be nested

In practice, this means that it should not matter what queueing model we apply sessions to. We should be able to apply sessions to only a part of a larger model or even apply sessions to a subset of queues that already belong to a session-based model. Most of these properties are insignificant to this specific paper, but they will make future research more efficient.

Since all queueing models use discrete-event simulation, we can observe the system at any moment and know exactly how many customers are in which queue. There are never any travel times and customers are never stuck between different elements of the system. Therefore, we can always count the total number of customers in each separate queue, which is denoted as Work In Progress (WIP) in Arena. The WIP is simply the sum of the queue length plus the customers that are being served.

As seen in Figure 2, we can always imagine a box that surrounds the queues to which the sessions are applied. Now we add a decision process anywhere where a line enters this box. In this decision process, we check if the sum of all WIPs of the queues within the box is smaller than the number of sessions. If this is true, we allow the customer into the box. Otherwise the customer is rejected. By consistently adding this decision to all our models we can add sessions in a very simple and intuitive way.

After being able to form all imaginable models into SBQs, a subset of models needed to be picked for simulation. There was one kind of model that certainly had to be tested, namely the system with multiple queues in series, which is what ING uses. This model can be seen in Figure 3. The parallel model from Figure 2 also seemed interesting. It can be interpreted as a shared waiting room for multiple general practitioners for example. There are only a limited number of seats before people can no longer take place in the waiting room. Very often a

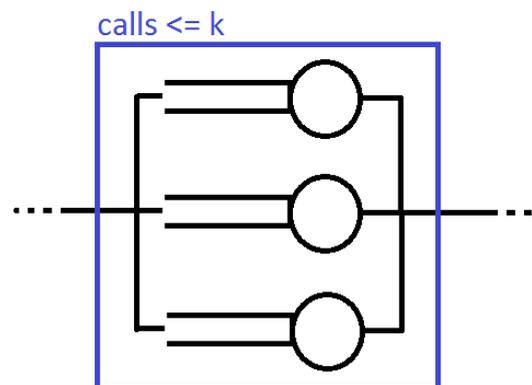


Figure 1: Example of a model with three parallel queues

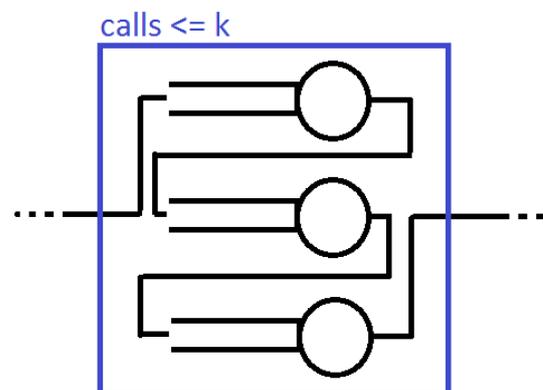


Figure 2: Example of a model with three queues in series.

practitioner’s office uses this notion of a shared waiting room, so it seemed interesting to model. For both models, a different number of queues were simulated to see if the number of queues would influence the results.

Lastly, a slightly more complicated Jackson network was constructed. This network has five queues, two different flows of customers into the network and some queues that use randomness to route the customers further into the system. Figure 4 shows the structure of this model. The transition probabilities and service rates can be seen in Table 3

	μ	Probability to transition to queue				
		1	2	3	4	5
1	3	0	0.3	0.4	0.3	0
2	4	0	0	0	0	0
3	4	0	0	0	0.5	0.5
4	3	0	0	0	0	0
5	3	0	1	0	0	0

Table 1: Service rates and transition probabilities for the Jackson model in Figure 4.

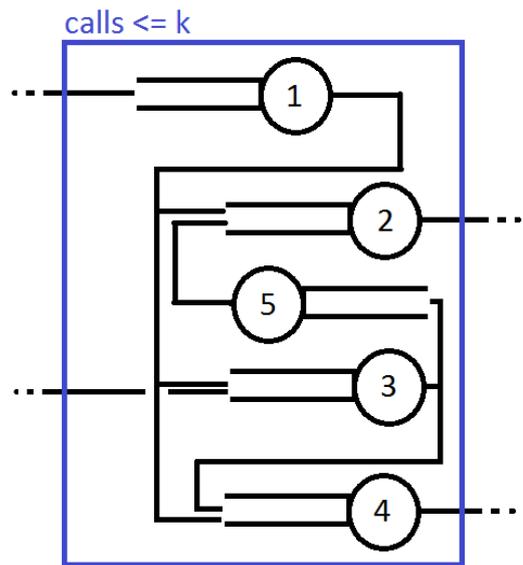


Figure 4: Example of a Jackson network.

After making a selection of models that were to be tested, there were more choices to be made before the simulation could be started. For each model, for each queue, arrival and service rates had to be chosen. As seen in Table 3, values for the Jackson network’s service rates had been randomly, but carefully chosen. For most other models, the initial values for λ and μ were set to 2 per hour and 3 per hour respectively. Using these values would ensure that there would be plenty of arrivals every simulation, and simultaneously the load on the queues would not be too high. The arrival rates were later varied between queues to look at the effect of higher loads and even overloaded systems, where one or more queues have a value of ρ that is larger than one.

For all models, the simulated period was set to 20 days with a warmup period of 24 hours. This warmup period has the purpose of removing the start of the simulation from the results. The statistics for the start of the simulation are generally beneficial, as the system starts empty, so the first customers will not encounter any waiting regardless of how unstable the system on average may be.

The last parameter that was yet to be chosen was the value of k , the number of sessions. For all models, the starting value for k was set very low, generally equal to the number of queues in the system and then gradually brought up until there were rarely any blocked customers, at which point the system will behave as if there were no sessions at all. It quickly became apparent that it would be too time-consuming to test all values of k for all models, so larger increments were used, as compared to when the value of k was higher. An example of the way different values for k were used can be seen in Appendix A.

4.2. Approximation

To get a numerical approximation for the steady-state probabilities of a Jackson network with sessions, we need to go through a number of steps. Firstly, we need to add the sessions to the model. Then, we need to change the probability calculations accordingly. Finally, we have to ensure that the probabilities still create a valid probability distribution.

Jackson networks are usually modelled as infinite Markov Chains. Each state in the state space denotes a specific combination of customers in each queue. The transition rates are then given by the arrival rates for each queue for transitions into states with more customers and a combination of the service rates and the probability table for the other transitions. We can then calculate the steady-state probabilities using the formulas described in Chapter 4.

Adding sessions to this model seems trivial initially. In each state, we know exactly how many customers are in each queue, so we know the total number of customers in the system for every state. We can then remove every state and its incoming and outgoing transitions from the state space where this number is larger than the number of allowed sessions. For a system with two queues, a part of the remaining state-space would look like Figure 5. There is, however, a problem with this solution.

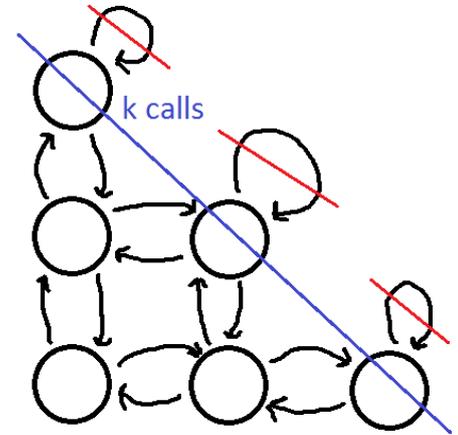


Figure 5: A simplified representation of the edge of the statespace of a Jackson network. The transitions that were removed are crossed out in red.

By removing all transitions belonging to the states that were removed, the model is no longer complete. Along the now existing border where the number of customers is equal to k , the only possible transitions are the transitions to a lower state. However, these are not the only events that can occur when the system is in this state. Arrivals will still occur, except the customers are now blocked from entering the system. This means that all transitions related to arriving customers are one and the same transition from that state to itself. If these transitions would not exist and the formulas for the full Jackson network would still hold, we would have a closed-form solution for the Jackson SBQs.

However, these transitions do exist. Due to these transitions, the probabilities are different and the formulas are no longer fully accurate. However, it would be impossible to add these transitions and still have simple formulas to calculate the steady-state distribution with. Additionally, in most cases, the probability density of these states is expected to be low, because they usually contain a high number of customers. When the density in the removed nodes is low, the impact of the missing transitions is also expected to be low. Taking all these statements in consideration, the decision was made to ignore the transitions and only use the nodes where the number of customers is not larger than the number of sessions.

If we apply this to the formulas for the steady-state distribution, we get the following equation for each state:

$$P(N_1 = n_1, \dots, N_v = n_v) = \begin{cases} \prod_{i=1}^v \pi_i(n_i) & \text{when } n_1 + n_2 + \dots + n_v \leq k \\ 0 & \text{otherwise} \end{cases}$$

Because we need the probabilities to form a distribution, we will need to add a final step to the calculation. As you can imagine, by removing states from the original infinite state-space, we also removed some of the original probability density, resulting in a total probability that is smaller than 1. To solve this problem, we simply calculate the sum of all probabilities after we calculate them and then divide each probability by that sum to get the actual distribution.

It is imperative to realise that the resulting model and steady-state distribution are only an approximation of the actual truncated Jackson model. The probabilities generated by this model will not be fully accurate, but the expectation is that they are reasonably close.

5. Results

5.1. Simulation

As mentioned in the chapter about modelling, a number of different SBQs were modelled and simulated. In this chapter, the results of the parallel system with three queues and the more complex Jackson network will be discussed in detail. Results from other systems can be found in Appendix A.

For most simulations, values for arrival and service rates were arbitrarily chosen, as long as the load on each of the individual queues is smaller than 1. After choosing all other variables, the value for k , the number of sessions was varied to observe the effect that sessions have on the system.

In Table 6 we see the results for the Jackson network. If we look at these results there are a number of observations that can be done. The most intuitive result is that the average number of customers in the system goes down as k goes down. This may not seem very remarkable by itself; however, the number of average customers as a percentage of k does not remain constant. Due to the stability of the system the average number of customers will converge to the value it would have if there were no sessions in place at all.

Next, we see that both the occupancy and the average sojourn time for the system decrease as k decreases. This was also according to expectation. When allowing fewer customers into the system, the probability of long queues occurring will go down and so will the strain on the servers.

Furthermore, the customers that do make it into the system will encounter shorter queues on average and will, therefore, have shorter sojourn times.

Lastly, adding the sessions to the queueing system will cause customers to get blocked from entering the system. When the number of sessions is still relatively high, the number of blocked customers is still very low, so is the impact on the sojourn time and occupancy. When the number of sessions gets small enough, both the blocking probability goes up significantly as the occupancy and sojourn time go down.

Sessions	S	Refused	Served	Total block %	Occupancy					Total Occupancy	Av customers in system
6	1.29	2185	7424	22.74%	52%	39%	55%	51%	36%	46.6%	3.9904
8	1.46	1288	8237	13.52%	59%	43%	60%	57%	41%	52.0%	5.010842
10	1.6	772	8635	8.21%	60%	46%	63%	59%	42%	54.0%	5.756667
12	1.7	430	8992	4.56%	62%	47%	66%	63%	44%	56.4%	6.369333
14	1.85	375	9204	3.91%	64%	48%	69%	64%	46%	58.2%	7.09475
16	1.92	185	9436	1.92%	67%	50%	70%	64%	47%	59.6%	7.5488
18	1.91	75	9420	0.79%	65%	50%	68%	68%	47%	59.6%	7.49675
20	1.97	61	9391	0.65%	66%	58%	69%	65%	46%	60.8%	7.708446
∞	2.19	0	9568	0.00%	67%	51%	70%	66%	47%	60.2%	8.7308

Table 6: Results of the simulation on the Jackson network as described in Chapter 4.

In Table 7 we see the results for the parallel system with three queues. For this model, we see the same trends as were described for the Jackson network. Also, when using different values for the arrival and service rates we still get the same trends.

Sessions	λ	μ	S	Refused			Served			Block %				Occupancy				ρ	av customers
				Q1	Q 2	Q3	Q1	Q 2	Q3	Q1	Q 2	Q3	Total	Q1	Q 2	Q3	Total		
3	2	3	0.45	291	312	328	632	673	641	31.53%	31.68%	33.85%	32.36%	40.0%	47.0%	43.0%	43.4%	0.666667	1.824375
4	2	3	0.53	266	238	244	674	770	730	28.30%	23.61%	25.05%	25.60%	45.0%	54.0%	50.0%	49.8%	0.666667	2.400458
5	2	3	0.58	171	191	173	807	789	799	17.48%	19.49%	17.80%	18.26%	54.0%	54.0%	56.0%	54.7%	0.666667	2.893958
6	2	3	0.64	150	114	129	841	829	825	15.14%	12.09%	13.52%	13.61%	56.0%	57.0%	55.0%	56.0%	0.666667	3.326667
7	2	3	0.68	102	101	113	907	852	828	10.11%	10.60%	12.01%	10.89%	61.0%	57.0%	57.0%	58.4%	0.666667	3.664917
8	2	3	0.77	101	91	100	878	898	897	10.32%	9.20%	10.03%	9.85%	63.0%	61.0%	61.0%	61.7%	0.666667	4.287938
10	2	3	0.89	47	54	71	902	925	924	4.95%	5.52%	7.14%	5.88%	63.0%	63.0%	62.0%	62.7%	0.666667	5.100813
15	2	3	0.87	8	14	14	977	938	977	0.81%	1.47%	1.41%	1.23%	65.0%	66.0%	68.0%	66.3%	0.666667	5.24175
20	2	3	0.92	7	8	5	953	1010	939	0.73%	0.79%	0.53%	0.68%	65.0%	67.0%	65.0%	65.7%	0.666667	5.562167
50	2	3	1.19	0	0	0	950	990	1018	0.00%	0.00%	0.00%	0.00%	67.0%	69.0%	68.0%	68.0%	0.666667	7.333375
3	2.5	3	0.47	513	520	499	705	688	699	42.12%	43.05%	41.65%	42.27%	48.0%	46.0%	47.0%	47.0%	0.833333	2.048417
4	2.5	3	0.54	405	417	414	795	805	790	33.75%	34.12%	34.39%	34.09%	55.0%	55.0%	53.0%	54.3%	0.833333	2.68875
5	2.5	3	0.61	335	330	330	899	857	859	27.15%	27.80%	27.75%	27.56%	63.0%	56.0%	59.0%	59.4%	0.833333	3.323229
6	2.5	3	0.69	294	304	285	893	913	950	24.77%	24.98%	23.08%	24.26%	61.0%	61.0%	68.0%	63.4%	0.833333	3.96175
7	2.5	3	0.76	208	258	250	951	987	982	17.95%	20.72%	20.29%	19.69%	67.0%	66.0%	68.0%	67.0%	0.833333	4.623333
8	2.5	3	0.83	201	192	233	1005	1032	985	16.67%	15.69%	19.13%	17.16%	70.0%	70.0%	68.0%	69.3%	0.833333	5.225542
10	2.5	3	0.95	120	147	154	1117	1051	1049	9.70%	12.27%	12.80%	11.57%	77.0%	73.0%	70.0%	73.4%	0.833333	6.366979
15	2.5	3	1.27	71	86	64	1141	1134	1149	5.86%	7.05%	5.28%	6.06%	79.0%	77.0%	79.0%	78.3%	0.833333	9.059333
20	2.5	3	1.38	36	30	37	1164	1182	1151	3.00%	2.48%	3.11%	2.86%	78.0%	80.0%	79.0%	79.0%	0.833333	10.05388
50	2.5	3	2.27	0	0	0	1256	1195	1234	0.00%	0.00%	0.00%	0.00%	89.0%	86.0%	80.0%	85.0%	0.833333	17.42698

Table 7: Results of the simulation on a system with three parallel queues. Arrival and service rates are equal for all queues.

5.2. Approximation

As for the simulations, for the results of the approximation we will mainly focus on the parallel model with three queues. Like with the simulation, we see that the occupancy and the average number of customers in the system increase when the number of sessions increases, while the blocking probability decreases.

Furthermore, if we compare the results from the approximation in Table 8 and the results from the simulation in Table 6, we can see that not only the trends, but also the values are very similar. For all of the values, the difference is only a few percent. This also holds for the more complicated Jackson network we described in the paper, as can be seen in Table 9. Once again, the values are very similar to the simulation. Additional results for the numerical approximation for Jackson networks can be found in Appendix B.

Even though we would like the results for both approaches to be equal, we see that there is still a small difference between the simulation and the approximation. There are a few obvious causes for this discrepancy. Firstly, the approximation is not perfect, as discussed earlier, due to the way the state space is truncated. Additionally, any simulation will always result in some error due to randomness. This error could be reduced by simulating for a longer period or taking the average over a larger number of runs. Lastly, it could be the case that the two approaches do not represent the same problem, even though they were constructed to model the same problem.

Sessions	lambda	mu	block%	occupancy	av customers
3	2	3	34.33%	43.78%	1.87
4	2	3	25.56%	49.63%	2.42
5	2	3	19.26%	53.83%	2.91
6	2	3	14.62%	56.92%	3.36
7	2	3	11.13%	59.24%	3.77
8	2	3	8.49%	61.01%	4.13
10	2	3	4.92%	63.34%	4.72
15	2	3	1.19%	65.87%	5.57
20	2	3	0.26%	66.49%	5.88
50	2	3	0.00%	66.67%	6
3	2.5	3	43.01%	47.49%	2.09
4	2.5	3	34.97%	54.19%	2.76
5	2.5	3	28.97%	59.19%	3.41
6	2.5	3	24.35%	63.04%	4.04
7	2.5	3	20.69%	66.09%	4.65
8	2.5	3	17.73%	68.56%	5.24
10	2.5	3	13.27	72.28%	6.37
15	2.5	3	6.84%	77.63%	8.84
20	2.5	3	3.66%	80.29%	10.79
50	2.5	3	0.06%	83.28%	14.82

Table 8: Results of the approximation for the network with three parallel queues.

Sessions	block	Occupancy					av customers
6	22.20%	51.89%	38.92%	54.48%	51.89%	36.32%	3.99
8	14.02%	57.32%	42.99%	61.09%	57.32%	40.12%	5
10	8.82%	60.79%	45.58%	63.83%	60.79%	42.55%	5.85
12	5.48%	63.01%	47.26%	66.16%	63.01%	44.11%	6.53
14	3.35%	64.43%	48.32%	67.65%	64.43%	45.10%	7.04
16	2.01%	65.33%	48.99%	68.59%	65.33%	45.73%	7.43
18	1.18%	65.88%	49.41%	69.17%	65.88%	46.11%	7.7
20	0.68%	66.21%	49.66%	69.52%	66.21%	46.35%	7.89

Table 9: Results of the approximation for the Jackson network as defines in Chapter 4.

Lastly, we need to discuss the speed and the efficiency of the algorithm for the numerical approximation. For the smaller models, the algorithm works extremely fast and it can calculate the statistics for the model in a matter of seconds. However, due to the need for the different partitions, the algorithm starts slowing down significantly when increasing both the number of queues and the number of sessions. For example, calculating a model with six queues and around fifty sessions already can take multiple minutes, depending on the size of the model.

Calculation times can be decreased for certain models by using clustering of similar queues and several other mathematical tricks. However, for more complicated or larger models, which are ultimately the models that companies such as ING would like to analyse, this numerical approximation will be significantly slower than running simulations or perhaps not even possible due to hardware restrictions.

6. Conclusion

Both the simulation and the numerical approximation of the SBQ models show that using a session-based blocking method for a queueing system reduces the load on the system. The occupancy of the agents goes down and customers that enter the system experience shorter sojourn times on average. However, reducing the number of sessions also causes customers to be blocked from the system at a significant rate. This means that the main research question cannot directly be answered and it is up to the owner of the system to decide whether a lower occupancy or a larger number of served customers hold a higher value to decide on the number of allowed sessions.

Moreover, when the different queues within the system are not very homogeneous and a subset of queues experiences a higher load than the rest of the queues, using an SBQ approach might cause the entire system to suffer from these higher load queues.

The numerical approximation gives very similar results to the simulation models and is significantly faster for small systems. However, due to the nature of the approximation using partitions causing exponential calculation times, it is not feasible to use this method for larger, more complex models.

Whether ING should continue using SBQs for their transaction servers depends on their relative cost between blocked customers and the improved performance. The percentage of blocked customers is not small enough to give a definitive answer to this problem.

7. Literature

Kijima, M. (1997). *Markov Processes for Stochastic Modeling*. Boston: Springer.

Koole, G. (2016). *Optimisation of Business Processes*. Amsterdam: MG Books.

Sharma, O. P., & Gupta, U. C. (1982, September). Transient Behaviour of an M/M/1/N Queue. *Stochastic Processes and their Applications*, pp. 327-331.

8. Appendix

A. Additional Results Simulation

Sessions	λ	μ	S	Refused			Served			Block %				Occupancy				ρ	av customers
				Q1	Q 2	Q3	Q1	Q 2	Q3	Q1	Q 2	Q3	Total	Q1	Q 2	Q3	Total		
3	3	3	0.49	762	694	736	728	701	730	51.14%	49.75%	50.20%	50.38%	50.0%	47.0%	51.0%	49.4%	1	2.203979
4	3	3	0.56	614	592	606	840	860	813	42.23%	40.77%	42.71%	41.90%	57.0%	58.0%	55.0%	56.7%	1	2.931833
5	3	3	0.65	540	540	515	911	913	930	37.22%	37.16%	35.64%	36.68%	61.0%	62.0%	65.0%	62.7%	1	3.729375
6	3	3	0.72	461	491	475	972	988	970	32.17%	33.20%	32.87%	32.75%	68.0%	67.0%	66.0%	67.0%	1	4.395
7	3	3	0.84	441	409	494	1011	997	1038	30.37%	29.09%	32.25%	30.62%	71.0%	72.0%	69.0%	70.6%	1	5.3305
8	3	3	0.97	455	447	467	1037	1018	1049	30.50%	30.51%	30.80%	30.61%	75.0%	74.0%	74.0%	74.3%	1	6.272667
10	3	3	1.03	318	324	302	1142	1135	1121	21.78%	22.21%	21.22%	21.74%	78.0%	79.0%	75.0%	77.4%	1	7.291542
15	3	3	1.39	211	190	192	1277	1241	1218	14.18%	13.28%	13.62%	13.70%	85.0%	86.0%	83.0%	84.7%	1	10.81883
20	3	3	1.97	214	224	222	1263	1284	1208	14.49%	14.85%	15.52%	14.95%	88.0%	87.0%	85.0%	86.7%	1	15.41115
50	3	3	4.13	67	65	75	1364	1374	1422	4.68%	4.52%	5.01%	4.74%	93.0%	99.0%	97.0%	96.3%	1	35.79333
3	4	3	0.53	1239	1142	1234	715	790	736	63.41%	59.11%	62.64%	61.73%	48.0%	57.0%	51.0%	52.0%	1.333333	2.474438
4	4	3	0.6	1018	1126	1066	871	858	904	53.89%	56.75%	54.11%	54.94%	59.0%	61.0%	65.0%	61.7%	1.333333	3.29125
5	4	3	0.68	0.91	1021	922	1000	950	956	0.09%	51.80%	49.09%	40.08%	66.0%	63.0%	69.0%	65.9%	1.333333	4.116833
6	4	3	0.79	903	882	968	997	1020	1028	47.53%	46.37%	48.50%	47.48%	71.0%	71.0%	70.0%	70.7%	1.333333	5.011563
7	4	3	0.87	895	846	799	1090	1092	1028	45.09%	43.65%	43.73%	44.17%	75.0%	75.0%	69.0%	73.1%	1.333333	5.818125
8	4	3	0.99	841	840	866	1090	1125	1071	43.55%	42.75%	44.71%	43.67%	75.0%	68.0%	75.0%	72.6%	1.333333	6.777375
10	4	3	1.22	805	840	785	1093	1167	1157	42.41%	41.85%	40.42%	41.56%	78.0%	84.0%	80.0%	80.7%	1.333333	8.684875
15	4	3	1.7	710	677	678	1285	1176	1311	35.59%	36.54%	34.09%	35.38%	90.0%	85.0%	89.0%	88.1%	1.333333	13.35917
20	4	3	2.29	660	664	645	1269	1244	1287	34.21%	34.80%	33.39%	34.13%	87.0%	87.0%	88.0%	87.3%	1.333333	18.12917
50	4	3	5.6	618	599	585	1392	1288	1350	30.75%	31.74%	30.23%	30.90%	100.0%	91.0%	93.0%	94.8%	1.333333	47.01667

Table 10: Results of the simulation for the system with three parallel queues

Sessions	Queues	lambda	mu	S	Refused	Served	Total block %	Occupancy		Total Occupancy	rho	av customers
3	2	2	3	0.94	208	728	22.22%	47.0%	47.0%	47.0%	0.666667	1.425667
4	2	2	3	1.14	151	833	15.35%	58.0%	52.0%	55.0%	0.666667	1.978375
5	2	2	3	1.24	90	880	9.28%	57.0%	59.0%	58.0%	0.666667	2.273333
6	2	2	3	1.36	71	909	7.24%	61.0%	59.0%	60.0%	0.666667	2.5755
7	2	2	3	1.55	54	952	5.37%	65.0%	65.0%	65.0%	0.666667	3.074167
8	2	2	3	1.51	27	942	2.79%	61.0%	64.0%	62.5%	0.666667	2.963375
10	2	2	3	1.59	10	956	1.04%	64.0%	62.0%	63.0%	0.666667	3.16675
15	2	2	3	1.81	0	974	0.00%	67.0%	63.0%	65.0%	0.666667	3.672792
20	2	2	3	1.81	0	974	0.00%	67.0%	63.0%	65.0%	0.666667	3.672792
50	2	2	3	1.81	0	974	0.00%	64.0%	65.0%	64.5%	0.666667	3.672792
3	2	2.5	3	1.25	306	684	30.91%	58.0%	51.0%	54.5%	0.833333	1.78125
4	2	2.5	3	1.37	219	749	22.62%	61.0%	57.0%	59.0%	0.833333	2.137771
5	2	2.5	3	1.59	157	818	16.10%	65.0%	64.0%	64.5%	0.833333	2.709625
6	2	2.5	3	1.88	149	844	15.01%	68.0%	67.0%	67.5%	0.833333	3.305667
7	2	2.5	3	1.95	94	872	9.73%	71.0%	67.0%	69.0%	0.833333	3.5425
8	2	2.5	3	1.99	73	887	7.60%	73.0%	65.0%	69.0%	0.833333	3.677354
10	2	2.5	3	2.43	50	941	5.05%	76.0%	75.0%	75.5%	0.833333	4.763813
15	2	2.5	3	2.61	18	939	1.88%	75.0%	73.0%	74.0%	0.833333	5.105813
20	2	2.5	3	2.96	9	942	0.95%	77.0%	70.0%	73.5%	0.833333	5.809
50	2	2.5	3	2.92	0	952	0.00%	75.0%	75.0%	75.0%	0.833333	5.791333

Table 11: Results of the simulation for the system with three queues in series.

Sessions	λ	μ				ρ				S	Refused	Served	Total block %	Occupancy				Total Occupancy	av Customers In System
6	2	3	3	3	3	0.7	0.7	0.7	0.7	2.47	1005	3778	21.01%	54.0%	54.0%	53.0%	52.0%	53.3%	3.888192
8	2	3	3	3	3	0.7	0.7	0.7	0.7	2.8	626	4090	13.27%	58.0%	57.0%	57.0%	57.0%	57.3%	4.771667
10	2	3	3	3	3	0.7	0.7	0.7	0.7	3.16	454	4331	9.49%	59.0%	61.0%	61.0%	62.0%	60.8%	5.702483
12	2	3	3	3	3	0.7	0.7	0.7	0.7	3.39	232	4479	4.92%	61.0%	63.0%	65.0%	62.0%	62.8%	6.326588
14	2	3	3	3	3	0.7	0.7	0.7	0.7	3.58	162	4647	3.37%	67.0%	65.0%	66.0%	64.0%	65.5%	6.931775
16	2	3	3	3	3	0.7	0.7	0.7	0.7	3.57	94	4587	2.01%	64.0%	64.0%	64.0%	64.0%	64.0%	6.823163
18	2	3	3	3	3	0.7	0.7	0.7	0.7	3.59	36	4602	0.78%	64.0%	64.0%	65.0%	64.0%	64.3%	6.883825
20	2	3	3	3	3	0.7	0.7	0.7	0.7	3.68	29	4613	0.62%	64.0%	64.0%	65.0%	64.0%	64.3%	7.073267
∞	2	3	3	3	3	0.7	0.7	0.7	0.7	3.87	0	4679	0.00%	65.0%	66.0%	65.0%	66.0%	65.5%	7.544888
6	2	1.5	3	3	3	1.3	0.7	0.7	0.7	3.6	1647	3060	34.99%	84.0%	42.0%	43.0%	43.0%	53.0%	4.59
8	2	1.5	3	3	3	1.3	0.7	0.7	0.7	4.67	1544	3197	32.57%	92.0%	45.0%	44.0%	44.0%	56.3%	6.220829
10	2	1.5	3	3	3	1.3	0.7	0.7	0.7	5.56	1352	3443	28.20%	95.0%	49.0%	47.0%	49.0%	60.0%	7.976283
12	2	1.5	3	3	3	1.3	0.7	0.7	0.7	6.64	1340	3481	27.80%	97.0%	50.0%	49.0%	49.0%	61.3%	9.630767
14	2	1.5	3	3	3	1.3	0.7	0.7	0.7	7.59	1119	3590	23.76%	98.0%	51.0%	51.0%	50.0%	62.5%	11.35338
16	2	1.5	3	3	3	1.3	0.7	0.7	0.7	8.02	1292	3575	26.55%	99.0%	51.0%	49.0%	52.0%	62.8%	11.94646
18	2	1.5	3	3	3	1.3	0.7	0.7	0.7	9.92	1056	3670	22.34%	100.0%	53.0%	51.0%	52.0%	64.0%	15.16933
20	2	1.5	3	3	3	1.3	0.7	0.7	0.7	11.68	1244	3536	26.03%	100.0%	50.0%	49.0%	50.0%	62.3%	17.20853
∞	2	1.5	3	3	3	1.3	0.7	0.7	0.7	∞				100.0%					
6	2	3	3	3	1.5	0.7	0.7	0.7	1.3	3.68	1756	3009	36.85%	43.0%	41.0%	42.0%	86.0%	53.0%	4.6138
8	2	3	3	3	1.5	0.7	0.7	0.7	1.3	4.58	1429	3230	30.67%	46.0%	43.0%	46.0%	91.0%	56.5%	6.163917
10	2	3	3	3	1.5	0.7	0.7	0.7	1.3	5.28	1225	3479	26.04%	49.0%	49.0%	50.0%	94.0%	60.5%	7.6538
12	2	3	3	3	1.5	0.7	0.7	0.7	1.3	6.9	1383	3427	28.75%	48.0%	48.0%	48.0%	98.0%	60.5%	9.852625
14	2	3	3	3	1.5	0.7	0.7	0.7	1.3	7.77	1187	3507	25.29%	50.0%	48.0%	49.0%	98.0%	61.3%	11.35391
16	2	3	3	3	1.5	0.7	0.7	0.7	1.3	8.99	1246	3560	25.93%	51.0%	50.0%	50.0%	99.0%	62.5%	13.33517
18	2	3	3	3	1.5	0.7	0.7	0.7	1.3	10.49	1261	3529	26.33%	49.0%	50.0%	50.0%	100.0%	62.3%	15.42467
20	2	3	3	3	1.5	0.7	0.7	0.7	1.3	11.83	1246	3450	26.53%	48.0%	47.0%	49.0%	100.0%	61.0%	17.00563
∞	2	3	3	3	1.5	0.7	0.7	0.7	1.3	∞							100.0%		

6	2	2.2	3	3	3	0.9	0.7	0.7	0.7	2.8	1253	3480	26.47%	68.0%	48.0%	49.0%	48.0%	53.3%	4.06
8	2	2.2	3	3	3	0.9	0.7	0.7	0.7	3.31	870	3908	18.21%	75.0%	54.0%	54.0%	56.0%	59.8%	5.389783
10	2	2.2	3	3	3	0.9	0.7	0.7	0.7	3.75	638	4128	13.39%	80.0%	57.0%	57.0%	59.0%	63.3%	6.45
12	2	2.2	3	3	3	0.9	0.7	0.7	0.7	4.24	554	4276	11.47%	82.0%	59.0%	60.0%	61.0%	65.5%	7.554267
14	2	2.2	3	3	3	0.9	0.7	0.7	0.7	4.48	317	4448	6.65%	84.0%	62.0%	62.0%	63.0%	67.8%	8.302933
16	2	2.2	3	3	3	0.9	0.7	0.7	0.7	4.83	292	4466	6.14%	84.0%	63.0%	62.0%	64.0%	68.3%	8.987825
18	2	2.2	3	3	3	0.9	0.7	0.7	0.7	5.25	203	4584	4.24%	85.0%	66.0%	64.0%	64.0%	69.8%	10.0275
20	2	2.2	3	3	3	0.9	0.7	0.7	0.7	5.17	117	4566	2.50%	85.0%	64.0%	64.0%	65.0%	69.5%	9.835925
∞	2	2.2	3	3	3	0.9	0.7	0.7	0.7	7.24	0	4727	0.00%	91.0%	65.0%	67.0%	67.0%	72.5%	14.25978

Table 12: Results of the simulation for the system with four queues in series.

Session s	λ	μ	ρ	S	Refused	Served	Total block %	Occupancy						Total Occupancy	Av customer s in system
10	2	3	0.67	4.08	666	3968	14.37%	56.0%	55.0%	54.0%	55.0%	57.0%	54.0%	55.2%	6.7456
13	2	3	0.67	4.71	475	4349	9.85%	62.0%	61.0%	61.0%	61.0%	60.0%	61.0%	61.0%	8.534913
16	2	3	0.67	5.15	278	4505	5.81%	62.0%	46.0%	63.0%	63.0%	63.0%	64.0%	60.2%	9.666979
19	2	3	0.67	5.25	110	4591	2.34%	64.0%	64.0%	64.0%	65.0%	64.0%	65.0%	64.3%	10.04281
22	2	3	0.67	5.68	109	4649	2.29%	66.0%	66.0%	65.0%	65.0%	65.0%	64.0%	65.2%	11.00263
25	2	3	0.67	6.13	70	4909	1.41%	69.0%	69.0%	69.0%	68.0%	68.0%	70.0%	68.8%	12.5384
28	2	3	0.67	5.89	34	4722	0.71%	66.0%	66.0%	66.0%	64.0%	68.0%	65.0%	65.8%	11.58858
31	2	3	0.67	6.08	8	4802	0.17%	68.0%	68.0%	66.0%	67.0%	67.0%	67.0%	67.2%	12.16507
∞	2	3	0.67	5.97	0	4711	0.00%	65.0%	67.0%	64.0%	66.0%	67.0%	66.0%	65.8%	11.71861

Table 13: Results of the simulation for the system with six queues in series.

B. Additional Results Approximation

Sessions	lambda	mu	block	occupancy	av customers
3	2	3	24.43%	50.38%	1.55
4	2	3	16.91%	55.39%	1.97
5	2	3	11.92%	58.72%	2.33
6	2	3	8.48%	61.01%	2.64
7	2	3	6.07%	62.62%	2.9
8	2	3	4.35%	63.76%	3.12
10	2	3	2.24%	65%	3.46
15	2	3	0.41%	66.39%	3.86
20	2	3	0.07%	66.66%	3.96
50	2	3	0.00%	66.67%	4
3	2.5	3	32.77%	56.03%	1.81
4	2.5	3	25.45%	62.13%	2.36
5	2.5	3	20.28%	66.43%	2.9
6	2.5	3	16.47%	69.61%	3.41
7	2.5	3	13.56%	72.03%	3.89
8	2.5	3	11.28%	73.93%	4.36
10	2.5	3	7.98%	76.69%	5.21
15	2.5	3	3.60%	80.33%	6.91
20	2.5	3	1.69%	81.93%	8.14
50	2.5	3	0.01%	83.32%	9.95

Table 14: Results of the numerical approximation for the system with three queues in series.

Sessions	lambda	mu	Block	Occupancy					av customers
6	3	3	20.66%	52.90%	52.90%	52.90%	52.90%	52.90%	3.86
8	3	3	13.10%	57.94%	57.94%	57.94%	57.94%	57.94%	4.85
10	3	3	8.29%	61.14%	61.14%	61.14%	61.14%	61.14%	5.68
12	3	3	5.19%	63.21%	63.21%	63.21%	63.21%	63.21%	6.33
14	3	3	3.20%	64.53%	64.53%	64.53%	64.53%	64.53%	6.84
16	3	3	1.94%	65.37%	65.37%	65.37%	65.37%	65.37%	7.22
18	3	3	1.15%	65.90%	65.90%	65.90%	65.90%	65.90%	7.49
20	3	3	0.67%	66.22%	66.22%	66.22%	66.22%	66.22%	7.67
∞	3	3	0.00%	66.66%	66.66%	66.66%	66.66%	66.66%	7.9
6	3	2.2	3	25.42%	67.80%	49.72%	49.72%	49.72%	4.1
8	3	2.2	3	18.07%	74.49%	54.62%	54.62%	54.62%	5.33
10	3	2.2	3	13.18%	78.92%	57.88%	57.88%	57.88%	6.44
12	3	2.2	3	9.81%	81.99%	60.12%	60.12%	60.12%	7.45
14	3	2.2	3	7.42%	84.16%	61.72%	61.72%	61.72%	8.37
16	3	2.2	3	5.69%	85.74%	62.87%	62.87%	62.87%	9.21
18	3	2.2	3	4.41%	86.90%	63.73%	63.73%	63.73%	9.97
20	3	2.2	3	3.45%	87.77%	64.37%	64.37%	64.37%	10.66
∞	3	2.2	3	25.42%	67.80%	49.72%	49.72%	49.72%	4.1

Table 15: Results of the numerical approximation for the system with four queues in series.

Sessions	λ	μ	block	Occupancy					av customers
10	2	3	15.77%	56.16%	56.16%	56.16%	56.16%	56.16%	6.95
13	2	3	9.32%	60.46%	60.46%	60.46%	60.46%	60.46%	8.46
16	2	3	5.35%	63.10%	63.10%	63.10%	63.10%	63.10%	9.64
19	2	3	2.96%	64.69%	64.69%	64.69%	64.69%	64.69%	10.51
22	2	3	1.57%	65.62%	65.62%	65.62%	65.62%	65.62%	11.12

Table 16: Results of the numerical approximation for the system with six queues in series.