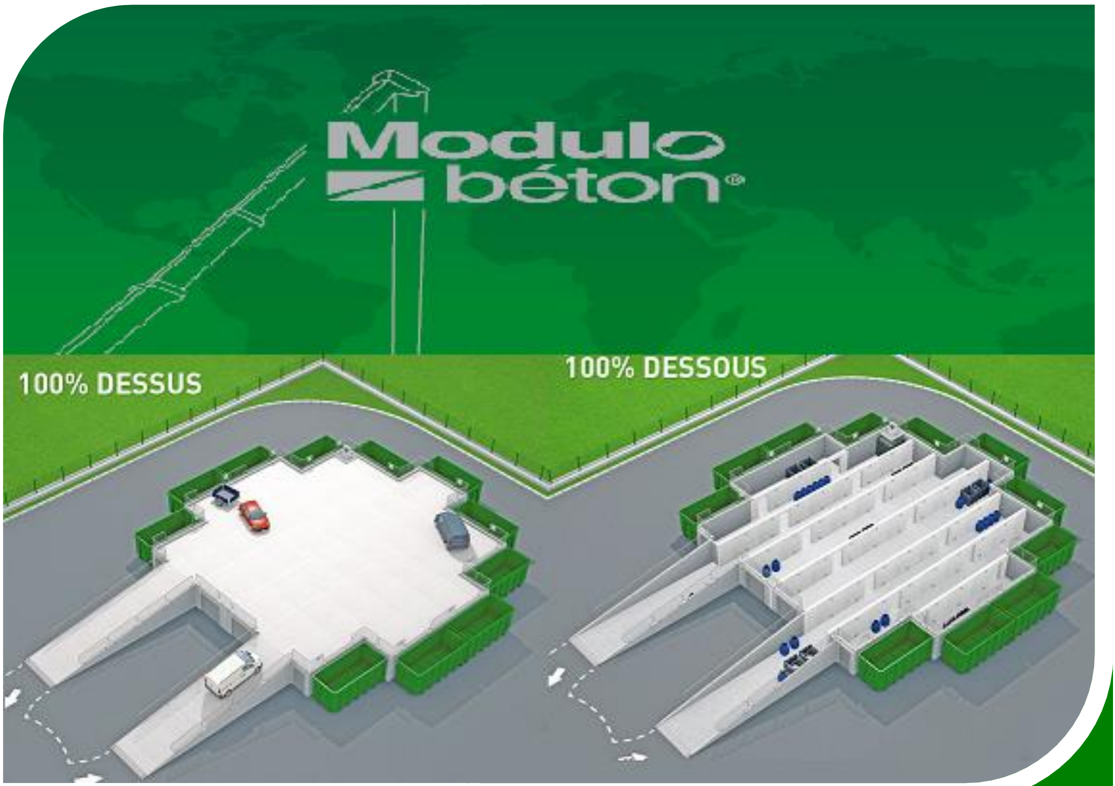
Analysing the effect of design decisions on the logistic performance of waste disposal stations



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10/5/2015

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Graduation Date

28-10-2015

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Acknowledgements

After years of studying, my time at the University of Twente is coming to an end. It has been a delight and privilege to have experienced life as a student in Enschede and in Cardiff during my semester abroad. It has been a very educational time filled with hardships and triumphs; and now, even though I feel like I will be learning and therefore a student my entire life, I am as ready as I will ever be to leave school behind and spread my wings in the real world. Of course I have not made it this far without the help, in some form or other, from several people.

First of all I want to thank my employer Ward Janssens. These last months have been filled with hard work. I have made some long days and I have had late nights. But I will most certainly not forget the great times I have had. The time I have spent in Canada, the week off and the time spent at the conferences of Whistler and Deerhurst, were truly amazing. For those experiences I am truly grateful to Ward and his colleague Rolf Philip. I have learned some valuable lessons there that I took home with me. They were lessons I could ponder over while I got back behind my laptop to shape a simulation model for evaluating designs based on logistic (queueing) performance.

When I had finally configured the framework for the model I planned to construct, the harder part of the job started. I had to program the model. This has proven to be a tremendous challenge and I am glad to say that, in a way, I have prevailed and programmed a good model. A model that will be valuable input for the construction of a commercial tool that Modulo Béton will use in their operations. During all the academic challenges I was at times in need of guidance and council. And in those moments I was glad that I could turn to my supervisors Leo van der Wegen and Martijn Mes. From the beginning they challenged me to channel my thoughts into words in such a way that they would be comprehensive for everybody. And whenever I was unsure about my progress and what to do next, Leo especially was there to give little nudges and hints to make me realise that I know more than I thought. I have learned that in those moments starting with (re-)structuring all that you do know and revisiting the final goal of the project help to provide clarity.

During my project I have had to seek collaboration with a lot of people in order to get access to resources. Mainly in the beginning of my project I was very busy networking to gain contacts at waste disposal companies that could provide me with valuable information and quite possibly also data later on. I would like to thank all the wonderful people I have met during those stages of the project. They were very helpful and accommodating in creating an opportunity to talk to me and show me around their waste disposal stations so I could learn about their job and waste disposal stations in general.

Special thanks also go out to my measurement team; my friends Chefiek, Cyrano, David, Jenny and Victor who helped me during data measurement sessions on some very hot Saturdays. I had a blast with you guys there clicking on stopwatches and registering times.

Finally last but not least I wish to thank all the family members and friends who have in some way, big or small, supported me this year. Whether they offered a listening ear, when I had had an off day, or whether they gave stimuli to help me progress I am grateful for their involvement. Especially during the tough programming days when I was slaving away during the holidays my roommate Eline was there for me with comforting words and a delicious apple pie.

After all these gratuitous words the only thing left for me is to wish you a pleasant and above all educational time reading this thesis.

Sarajan Graanoogst, Enschede, October 2015

Management Summary

Modulo Béton Canada Ltd. is the Canadian branch of Modulo Béton that holds a license to the Modulo design concept of waste disposal stations. They are just starting to sell more waste disposal stations in Canada but meet quite some resistance in selling their concept to municipalities. They feel that a computer model that can analyse the logistic (queueing) performance of a waste disposal station design will help them design better waste disposal stations and will offer them the means to convince clients of the performance of their concept. The main objective of this research project was therefore to **formulate a model that could be used in a design process to design better waste disposal stations from a logistic perspective.** This translated in the following main research question:

What model is an adequate way to calculate the waiting times and queue lengths at waste disposal stations?

After speaking with a lot of experts from the waste disposal industry, we have determined the main design decisions that are made to design a waste disposal station from a logistic perspective:

1. The layout (line-flow, O-flow, S-flow, etc.) – what should the physical layout look like? This is mostly based on client wishes (aesthetics) and requirements (waste diversion policy).
2. The capacity – how large must the site be to accommodate the expected number of visitors? This decision is based on demographic data of the municipalities the waste disposal station should ultimately serve.
3. The sizing – What should the capacity of the servers be? How many entrance/exit gates? How many containers are needed per waste stream? This decision will mostly be based on waste volumes brought, demographic data of the served municipality and service times for each waste stream.
4. The allocation – Where should the containers of each waste stream be located? This decision is mostly based on current practice. However, over time as more experience and know how is generated by using the model current practices will of course improve.

Based on this information, we started to look for viable modelling options in the literature. After discarding several analytical models we chose for utilising discrete event simulation for modelling a waste disposal station.

We proceeded to program this model in order to demonstrate the usefulness of such a model through several experiments. After our programming and data collection (to provide input parameters), we first verified the working of the model (did it operate the way we intended it to?) before we validated it (does the model measure the performance indicators realistically and accurately?). And after we verified and validated the working of our model we proceeded with two sets of experiments.

The first set of experiments was to demonstrate how the model could be used to improve an existing waste disposal station. This meant improving the site by making small changes in order to prevent large overhauls from rendering the site inoperable for an extended period of time. These small changes mostly involve increasing capacity for one waste stream while reducing capacity for another waste stream or swapping locations of waste streams.

The second set of experiments demonstrated how the model can be used in tandem with a set of guidelines to create a design from scratch. The first step in this process is to generate an initial design, a so called base case. Then through the iterative use of the simulation model, the performance

of this design and any potential improvements can be tested to improve the design step by step until a design yields the desired performance.

A lot of decisions can be tested using the model:

1. The sizing for each waste stream can be varied;
2. A limit can be placed on the number of visitors allowed on the site to simulate limited space;
3. The size of buffers can be varied;
4. The location of the containers of waste streams and substations can be varied;
5. A weighing scale can be included or not;
6. Road lengths can be varied.

To simulate different scenarios there is also a list of input parameters that can be varied. A user could change the frequencies of the waste stream to see what would happen if a certain waste stream was brought more often than anticipated. There is an input parameter that determines the distance visitors are allowed to walk, influencing the waste streams they can dump from a parking spot. This can be changed. Arrival rates, service rates and their distributions can also change. This, however, should only be done if research shows that another arrival-/service rate or distribution should be used.

Stuk over bevindingen fase 1 en stappenplan voor gebruik model

After performing the mentioned experiments we were able to generate some recommendations concerning the steps Modulo should take to benefit from the research done. The most important recommendations are:

1. Modulo needs a programmers to program a well-documented commercial version of the developed simulation model;
2. The input data used should be considered and if necessary adapted for each case. Input data should be updated over time and for the collection of input data enough people should be employed to ensure the collection yields a representative set of input data;
3. Several lessons were learned from the experiments done:
    a. Increasing the capacity (placing more containers) is a sound way of improving the performance;
    b. Making sure there is enough driving space between parts of a waste disposal station is also important (queueing space in front of gates and between gates);
    c. Performance increases when containers of one single waste stream are spread out instead of placed right next to each other.
4. While creating the commercial model several assumptions and simplifications made while creating the conceptual model should be reconsidered. The most important of these are:
    a. Travel time between containers within a substation can be ignored;
    b. Visitors visit the containers of the waste disposal station in a fixed order;
    c. Visitors will wait to dump the next waste stream on their ‘list’ until there is a parking space available from where that waste stream can be dumped.
5. Once a commercial tool is developed, a plan should be used to utilize the model effectively in a design project.

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Glossary

Bin – equivalent of a container, used for dumping waste

Design decisions –decisions made on various topics regarding the design of a waste disposal station

Design issues – The issues taken under consideration before making decisions regarding the design of a waste disposal station

Landfill – area for waste dumping that is buried for anaerobic digestion (in case the waste is garbage) in order to recover methane gases

Public drop off point – Location where the public (citizens of a certain area) may bring their waste/recyclables

Server – modelled part of a process

Station – The entire waste disposal station

Substation – part of the station where a selective group of waste streams is collected

System – model of the entire waste disposal station

Waste disposal station (WDS) – collection site for waste and recyclables provided by municipalities for public use

Waste drop off centres – same as waste disposal station

Waste separation facility – facility that separates several waste streams that have been brought in one collective stream

Waste stream – a category of waste like wood, metal, plastic, etc.

Waste transfer station – a place where waste is stored temporarily and collected in greater quantities for transport to either separation facilities or processing facilities

Chapter 1 Introduction

This chapter provides the reader with a general overview of how this study is conducted. In Section 1.1, some background information is provided about Municipal Solid Waste Management and Modulo Béton. In Section 1.2 the research motivation is given. What follows after is a clear description of the research problem in Section 1.3, an elaboration on the research objective in Section 1.4, and a clarification of the scope in Section 1.5 This chapter concludes with the research approach in Section 1.6, where the research questions give an outline of how this research is set up.

1.1 Context Description

This section starts off with a general outline of Municipal Solid Waste Management. The section then turns its focus to Modulo Béton and specifically on the branch in Canada for whom this research is conducted.

1.1.1 Introduction Municipal Solid Waste Management

Like every industry, the waste industry is also susceptible to changes. According to Contreras et al. (2010) these changes can be divided into four categories:
1. Legal drivers – these consist mostly of laws and regulations enforced by Governmental institutions.
2. Technology development and institutional drivers – new technologies that either made new waste management practices necessary (as they cause extra waste generation) or possible (new machines for cleaning and waste collection, and waste processing).
3. Regional and international drivers – Due to interaction between regional and international areas other drivers manifest. Trade in recycled materials e.g. has increased recently.
4. Socio economic drivers – the population growth and public awareness create the drive that emphasizes on dealing with increasing waste generation due to an increase in consumption. The focus is put on ensuring public health.

In dealing with waste, there are several practices that have been developed over time. As early as 1996 (Sakai, et al., 1996), the most preferable practices of waste management, according to most industrialised nations, that were identified (in order of preference) were *prevention* (reduction of use of materials and increasing consumer awareness), *reuse* (recycling), *biological treatment* of biological waste (composting and anaerobic digestion) and finally *incineration* (reducing volume of material for landfilling and sterilising it while recovering energy).

In 2012, a report from World Bank's Urban Development and Local Government Unit of the Sustainable Development Network (Hoornweg & Bhada-Tata, 2012) showed the same hierarchy. They, however, went into even greater detail. They made a classification of the waste management strategies. Two groups of strategies were identified:

1. Waste diversion – contains four strategies:
   a. Reduce – reduce quantity of waste generation
   b. Reuse – reusing products to reduce waste generation
   c. Recycle – use components and parts from deceased products
   d. Recover – recover raw materials from the waste streams
2. Waste disposal – contains the other strategies:
   a. Incineration – if done correctly energy can be recovered and pollution is minimised

b. Landfill – waste and residues of other strategies are sent to disposal sites.
c. Controlled dump – a less official and organised way of landfilling

All the preferable strategies require separation of the waste stream into its components in order to manage them. Modulo Béton has developed a product that enforces this separation process.

1.1.2 Modulo Béton and Modulo Béton Canada

The origins of Modulo Béton

In 2005, Modulo Béton's product, a modular design for Waste drop-off centres, was developed and patented in France by Michel Bosio and Jean Jaques Pegot. What once started as a venture with 3 sales agents, quickly grew to a company selling numerous sites in France and generating more than €7 million sales annually.

The strategy the company decided to follow was one of growth through international dispersion by means of licensing and royalties. Modulo has signed license agreements for the Netherlands, Germany, Belgium, the United Kingdom, Italy, Spain, Norway, Denmark, Sweden, Finland and Switzerland. Currently, the patent has been successfully gained in these European countries where ventures have started that are currently well developed.

Starting in Canada and the USA

In 2013, Modulo signed license agreements for Canada and the USA. A patent has been granted in the USA and for Canada one is underway. The markets that Modulo Béton Canada is targeting are Municipalities that buy recycling centres for public use, and the private sector. The private sector consists of companies in the waste industry. Depending on State and Provincial regulations and programs, Modulo's customers usually purchase transfer stations or drop off facilities. Modulo sells its concepts through shows, conferences and a network of independent sales representatives. Collaboration also occurs with consultants and engineers that are hired by Modulo's potential customers.

So far 2 sites have been sold and installed in Canada, but the company is expected to have a break through soon. In 2015, the sales are expected to be between six and nine sites in total for both Canada and the USA. To smoothen their process, however, they require something they did not have before. They would like to have a method, a model if you will, to estimate the customer satisfaction of their products through the waiting times before actual construction of the sites. They argue that shorter waiting times increase customer satisfaction. In the following section, this will be clarified.

1.2 Research Motivation

The waste management industry is changing. More and more governmental policies are pushing for waste diversion. In Europe, the focus is primarily on separation at the source, resulting in cleaner recyclable materials and easier, less costly waste processing. To facilitate separation at the source, there is an increase in residential waste drop-off centres. These facilitate small businesses and residents to drop off their recyclable waste. Since regulations regarding these facilities may be altered over time and the communities around these facilities are susceptible to change as well, these facilities should have a flexible design and construction. It would be desirable to have constructed sites that can be altered to deal with any changes that occur (see Section 1.1 for info thereon). These sites would not become obsolete under influence of a changing environment due to their fixed design but can be altered to meet the changing needs of the client. Modulo Béton has a modular design for (public) waste drop-off centres also known as “Recycling Centres”, or as “Waste Disposal Stations” or “Waste drop-off centres” that meets the need for flexibility. In 2013, Modulo Béton Canada began selling this concept in Canada and expansion into the USA is expected soon.

In North America, drop-off centres are different due to the larger scale of the waste disposal and the fact that landfilling is still the primary way of dealing with waste. Waste diversion is, however, becoming more important and drop-off centres are expected to become popular in North America as well. Modulo would like to seize the opportunities in this branch, but needs to develop the ability to advise clients thoroughly on size, traffic management, control, layout, etc. for these sites. Modulo Béton Canada wants to move towards resident friendly approaches (less queueing and waiting times) and they want to take this into account when approaching potential clients. The ability to show customers and partners the consequences of site planning for, e.g., queues is of crucial importance.

This is a different approach compared to the current way of thinking, which advocates making calculations about the traffic and then focusing on sizing the site up to facilitate the “unavoidable” queues. The final goal of Modulo Béton Canada is to deliver designs of waste disposal stations that are resident friendly. They want to provide designs that guarantee fewer queues and reduce the time residents spend at a station waiting in queue. In order to reach this ultimate goal they need a way to calculate the queueing time and length for concept designs.

1.3 Problem Description

Right now, Modulo Béton has no way of calculating or reliably estimating (pre-implementation) the impact that any of the design aspects have on the length of the queues that arise or the time residents spend at the “Waste disposal station”. Apart from the design decisions, there are of course undoubtedly also other factors that influence the flow of residents arriving at the drop-off centres.

The factors of influence can be divided into uncontrollable parameters (think about resident characteristics like types of waste they have come to drop off) and variables that can be influenced (among which are the design decisions). These factors need to be identified and the effect they have on the queues and the waiting times should be made clear.

Once the nature of the impact of these factors is known, a model could be made that calculates the performance of a potential “Waste disposal station” based on its design. Therefore the nature and extent of the impact of these factors should be researched. In summary the problem Modulo has is that they have no method to determine the performance of the design of a waste disposal station.

1.4 Research Objective

Making calculations concerning the performance of the “drop-off centres” requires knowledge of the relationship between the design decisions and the waiting time and queue length. These two measurements, the so-called queueing results, are of importance as the queueing length influences the space required and the queueing time influences customer satisfaction. Both are expected to influence the clients’ willingness to buy a drop-off station from Modulo Béton. The research objective of this study is therefore:

Provide a means to analyse waste disposal stations based on queueing results for residents as a result of design decisions.

To attain this goal, we need to first determine which design decisions can be characterised as "main design decisions" or design decisions that are the most influential.

1.5 Scope of the Research

There are undoubtedly also other factors that will eventually influence the length of queues or the time visitors spend at the drop-off centres. One of the factors that come to mind is the method used to change the containers. During the time that one container has been filled and needs to be replaced there is a moment when a 'server' is unavailable. Another container needs to be designated as a replacement or, if all containers are already in use, the full container needs to be replaced before the server can once again be called 'operational'.

Another factor is the number of employees present on the site to smooth the process by assisting visitors (by, e.g., giving directions on where to bring which waste streams). This effect is of less interest to Modulo and will be therefore not be taken into account. Since both features come into play after the "Waste drop-off centre" has been built it and it will already be operational they will not be taken into account as they are outside of Modulo's sphere of influence.

This study will only focus on variables that can be influenced before the waste disposal station is built, i.e., the design decisions. The study will research how these design decisions influence the queueing length and queueing times at a "Waste disposal station" in general.

1.6 Research Approach

From the research objective and the problem description, the main research question can be formulated as follows:

"What model is an adequate way to calculate the waiting times and queue lengths at waste disposal stations?"

The aim is therefore to learn about the impact of design decisions on waiting time, queue length at the different stations as well as at the entire site. Once this relation is known, smart design decisions can be made to minimize queueing times of customers at a waste disposal station. To answer this central research question, a few sub research questions should be answered first. In the remaining part of this section the sub research questions are presented along with the research method that is used to answer them.

The first step in this study is to determine which design decisions are of importance and have an effect on the performance of waste disposal stations. The first sub research question that is answered in Chapter 2 is therefore:

"Which factors are taken into account when designing a waste disposal station?"

To answer this question, a literature study will be conducted. To get a holistic view the opinion of experts will be sought through interviews with managers of waste disposal stations and experts within Modulo Béton. Both types of sources will be used to answer the question in Chapter 2.

The next step is to find a way to model a waste disposal station design in such a way that the object of study is represented and that it can be studied using different techniques. Using applicable techniques, performance can be measured in order to assess the effect of the design decisions on the performance. So at first information on the design issues from Chapter 2 are used to decide on the form the conceptual model will have. In Chapter 3 this issue is addressed. Both mathematical (analytical) models and simulation are taken under consideration. Thus the second research question that will be answered there is the following:

"Which quantitative model(s) can be used to model a waste disposal facility realistically and how should they be employed?"

After determining the characteristics a waste disposal station, it turned out to be of such complexity that we had a hard time finding a mathematical model suitable to analyse the waste disposal station realistically. The model that was found was complex and arduous in its use. Therefore, we decided to employ simulation to analyse waste disposal stations.

In Chapter 4 a conceptual model is formulated as a basis for the simulation study. The simulation will require the use of a software tool that needs certain data input. The question that needs answering is therefore:

"What data input is needed for the simulation model and how may this data be collected?"

The necessary data was collected at a waste disposal station in the Netherlands containing information on arrival and departure times of individuals dropping off waste. Since the data is collected in the Netherlands, it may be that visitor details (arrival and service patterns) are different than those in North America. Since the laws concerning waste streams and communities differ within North America and the Netherlands other input values will most likely vary as well. But since the aim of this thesis is to formulate a generic model to analyse waste disposal stations regarding queuing, and not a study to analyse and give advice on waste disposal stations in Canada, data from the Netherlands will suffice. A sensitivity analysis to assess whether different input values will have a large impact can demonstrate the robustness of the model.

Once the first four research questions have been answered, we can start with the next phase of the research, the simulation study. During the simulation study we test the conceptual model we made after the first four sub-questions were answered. For this purpose we formulate a sound experimental design in Chapter 5. Then, after the experiments have been conducted, the results are summarized in Chapter 6. In Chapter 7, the conclusions and recommendations are provided based on the experimental results. The final chapter will contain a guideline on the use of a simulation tool in a waste disposal design process.

Chapter 2 Design of a Waste Disposal Station

Chapter 2 gives insight into how the process for designing a waste disposal station takes place. More importantly it gives an overview of the design decisions that are taken into consideration whilst making a design.

In the first section of this chapter, the design process is elaborated upon. In Section 2.2, we describe a typical waste disposal station based on observations made at several waste disposal stations in the Netherlands and two from Canada. This section illustrates what design issues were taken into account at several waste disposal stations from conventional design (in the Netherlands) and from Modulo's design (in the Netherlands and Canada). The third section in this chapter provides a final list of design issues that are of importance. In Section 2.4, these design issues are elaborated upon in greater detail and a selection is made regarding which to take into account for modelling later on.

2.1 The Design Process

Getting insight into the design process is the first step taken to identify the design decisions that influence the queueing at the waste disposal stations later on. After speaking with experts from Witteveen Bos, a consulting company for construction projects like waste disposal stations, and Modulo Bèton Nederland B.V., several insights were gained. According to Witteveen Bos a lot depends on the municipality to whom the waste disposal station is sold. They provide input concerning what the station should be able to facilitate. The input that is given by municipalities usually encompasses the following:

1. Policies concerning waste management – this influences the waste streams that should be collected and indirectly influences the different collection stations required at the waste disposal station.
2. Policy concerning the visitors of the waste disposal station – This influences road and space parameters. The roads should facilitate vehicles of a certain size.
3. Required capacity – The waste disposal station will be expected to deal with certain volumes per waste stream.
4. Policies concerning entry – Will visitors have to pay or not? This will influence the process of entry at the gate of the waste disposal station.
5. Location size –Occasionally the site location is known before a request for proposal is produced.

After taking this information into account an iterative process starts of designing, assessing the implications for queueing, and making adjustments until a final design is realized.

Modulo Bèton Nederland B.V. follows a slightly different process. They strive to create a partnership with a client and an engineer to collectively assess the client's needs and the design possibilities.

The design process from Modulo Bèton Canada roughly follows the following steps:

1. Preliminary meeting – after initial contact has been established with clients through shows and conferences a formal meeting can be set;
2. Inventarisation – assessing the client's needs and preferences. This often happens in collaboration with a consultant hired by the client;

3. Making two to three design sketches – In collaboration during a design process a few design options are developed and upon completion presented;
4. Discuss the designs with the client – after discussion draft proposals are asked and prepared;
5. When these are reviewed two different steps ensue based on the type of client (private company or municipality)
    a. In case of municipality there is an official pre-qualification notification. Then a tender or request for proposal (an invitation for an official offer) is made by the government;
    b. In case of a private organisation an official bid and an official decision is reached;
6. Forming contractual agreements and upon agreement signing the legal documents
7. Develop engineering proposal – translating the design of contract to technical building plans;
8. Proposal approach for arranging permits – during this step a code review is done to ensure the building plans are conform the local laws and regulations. During the review the building plans are finalized and they are submitted to the client and local officials so a permit can be obtained;
9. Building the waste disposal station - The moulds are brought to a chosen facility for production of the necessary blocks. The necessary other parts are produced as well. After production construction commences;
10. Maintaining the delivered product – After the site has been installed and inspected maintenance manuals are provided and optionally maintenance contracts are signed.
11. The site is formally delivered to the client who signs for delivery and then the site is ready for usage.

Still, depending on the client, each design process is different. In each project though, a certain set of qualifications needs to become clear in the design stage before manufacturing and building starts. Some influencing factors have been distilled from this list.

1. Categories & sub-categories of waste that are collected;
2. Volumes per waste type collected on an annual basis (per month could be useful and insightful);
3. Proposed layout;
4. Proposed routing;
5. Number of visitors per day in a week;
6. Storage requirements – may influence the area used for construction, thereby influencing the required capacity of the terrain.

After combining this list with the information gained from Witteveen & Bos we can form a more complete list. Since most of these factors are beyond the influence of waste station operators they may be classified as high-level decisions/sources of influence that give direction to the design of a waste disposal station. We can divide the influencing factors in demographic and municipality influences.

Demographic influences:
1. Size of community;
2. Visitor numbers;
3. Waste volumes generated by the community (daily/weekly/monthly/yearly);
4. Area of waste disposal station (Rural, Urban, Suburban);
5. Size of the location chosen for the waste disposal station (only an issue if a site has already been bought and paid for).

Municipality influences:
1. Purpose for the waste disposal station (dump site for civilians, for companies, or mainly a transfer station for temporary storage before transport to large processing facilities)
2. Waste streams collected as stated by law
3. Traffic laws (left/right, congestion issues)
4. Safety regulations (labour agreements among others)
5. Construction regulations

2.2 Design (decisions) of Waste Disposal Stations

Waste disposal stations in the Netherlands can be divided into roughly two groups when it comes to design:
1. Waste disposal stations of conventional design, e.g., the waste disposal stations in Eindhoven, Hengelo and Velsen;
2. Waste disposal stations of Modulo's design, e.g., the waste disposal stations in Lelystad, Molletjesveer and Woerden.

Both have been observed to get a holistic view of the designs that are currently in use and to see the design characteristics of both. To be able to model a general waste disposal station that would be applicable in Canada, two sites (one at Waterloo and one at Cambridge) and two conferences were visited in Canada to learn more about waste (disposal) management and "Waste drop-off stations" in Canada. At both the annual RCBC zero waste conference in Whistler (British Columbia) and the Municipal Waste association Spring Workshop in Huntsville (Ontario) valuable insights were gained about waste disposal management in Canada. Both occasions provided a unique experience and opportunity to talk to people from Canada from various acting groups in the waste management scene from Canada. There were representatives from both the demand side (municipalities) and the supply side (manufacturing, construction and consulting companies) present. All these people were together in one room, where the somewhat informal atmosphere led to easy conversation and people were incredibly open to questions.

2.2.1 Waste disposal stations in the Netherlands

In the Netherlands, several conventional waste disposal stations have been visited or studied like the station at the Lodewijkstraat in Eindhoven and the station in Velsen. Both of these stations have been built according to a similar principle. There is an entrance to the site where visitors declare their waste and are permitted entry upon showing their citizenship pass. Once past this first server, the visitors enter the terrain where the collected waste streams are usually divided into two or three groups. One of the groups is located at a platform. One of the other groups is usually built up around the place where chemical waste like paint, acidic and base products is collected. Another group of containers is placed around a platform that has been made with solid concrete or other methods that would render the sites inflexible for changes.

The waste disposal stations of modulo's design are, when it comes to collectables (waste streams) and interior (grouping of waste streams at several different locations), virtually the same when it comes to the grouping of the containers. The only difference is the fact that the platform is built from blocks that can be moved to alter the design if necessary. Another feature of the blocks is that they are of such a design that space becomes available underneath the platform. This space, in the form of hallways and rooms, can facilitate several uses of which the most common is storage of chemical waste. That is the reason that at least one of the groups of the containers is located at the foot of the platform.

From various interviews and viewings of sites, we identified the design decisions that influence the queueing at these waste disposal stations:

1. The layout (form) of the waste disposal station as it influences walking distances;
2. The amount of containers placed;
3. The size of the parking areas for the substations;
4. The amount of gates at the entrance;
5. The route that all cars must follow to traverse the waste disposal station;
6. The locations of the containers (which waste stream is collected where);
7. The amount of waste streams that are facilitated by the waste station;
8. Capacity restriction on the site.

2.2.2 Waste disposal stations in Canada

Waste disposal stations and waste management in Canada overall are still in most ways less developed than waste management in Europe. Due to a different political system in Canada, different policies are enforced in different provinces. There are, however, some similarities. Waste is collected curb side in most of the provinces although this is mostly classified as garbage, i.e., a mixture of plastic cans, food waste, paper, carton, etc.

On separation, the policies vary widely. Some municipalities only employ landfilling. However, in some provinces, municipalities have started to develop recycling. In these provinces a waste management site usually contains a landfill site, a waste separation facility, a garbage dump, a public drop-off point and sometimes also a composting area. At the landfill, waste of several types is dumped. When the site is deemed filled to capacity, the top is covered and over a certain period of time methane gasses are drawn from the site. Over time the site is usually turned into a recreational facility like a park, although the place is determined to be unsuitable for building houses. At the separation facility, plastic, cans and paper are separated. The composting area contains machines that process garden waste into compost.

The public drop-off point is comparable to a waste disposal station in the Netherlands with a few exceptions. First of all the area employed is much bigger while the same number of caretakers is employed (in Waterloo and Cambridge). Also, the platform is arranged differently. It is usually arranged in a way that the cars drive on ground level on a road, but the containers have been placed a level lower (comparable to a basement). Since the area is a lot bigger the containers are placed much further away from each other. Depending on the province where the station is built more or less waste streams are separated. For example in British Columbia currently seventeen waste streams are collected whereas in Ontario this number is significantly less (nine). The way of collection differs as well. E.g., in the Netherlands, all sights visited so far collect electronic waste at ground level containers. At Waterloo (in Ontario) a throw down bin is employed. This way of working risks the release of dangerous components of, e.g., television screens when these break upon impact with other electronic objects in the container or the container itself. The observed sites in Canada, especially the one near Waterloo, seemed to be less organized and controlled. This is only logical, since they employ about as many people for the control of their sites as the waste disposal stations in the Netherlands. However, since their sites cover a much bigger area, the control is not as good as it is in the Netherlands. The basic working of the public drop off point, however, is the same as in the Netherlands. The drop off point serves the community of a municipality (or several) and allows visitors to drop off several waste streams based on local policies. For these reasons we may argue that the same design issues hold for Canada as for the Netherlands.

2.3 Waste Disposal Station Design Issues

In this section the design issues are elaborated upon. Upon reviewing the interviews with several operators at waste disposal stations and reflecting on these we can identify influencing factors on several levels. First there are the higher level influences. They are described in Section 2.2.1. Some of these lead to design decisions that are fixed for the long term (years), which are therefore considered to be strategic decisions. But some can be dealt with monthly and changed over time based on changes in the sphere of influencers. These are therefore considered to be tactical design issues. And then there are the policies made on a tactical level that are enforced on an operational level. These often influence the design process and design decisions as well.

In summary, and taking Section 2.2 into account, there are several design decisions influencing the waiting times and queue length. They can be divided into several categories.

1. Layout – The form of the waste disposal station and platform (e.g., line-flow, circular or O-flow, U-flow) is a high level decision. The outcome is based on clients' wishes (aesthetics) the area available for the waste disposal station and the expected number of visitors for the disposal station. This is one of the decisions that is usually made for the entire life of use of the waste disposal station and is therefore a strategic design decision.
2. Sizing – The number of containers per waste stream is a strategic decision as it is directly based on the waste volumes that are expected to flow to the waste disposal station. These waste volumes do not change much over the years as a growing population is usually the only thing influencing them.
3. Capacity – The space allotted to the waste disposal station and its substations is also a strategic decision that is made based on calculations and estimations of the expected number of visitors of the waste disposal station and is usually fixed for a period of years.
4. Allocation – Where to place the containers (in what order?) is a tactical decision that is based on past practices as well as on observations made while the waste disposal station is in operation. Usually for a medium length of time the placement of containers is fixed after considering previously mentioned issues (past practices and observations). During operation, the allocation might change as outside changes force management to operate their waste disposal station in a different manner.

Once a waste disposal station has been placed, there are several operational actions that influence the waiting times and queue lengths (like maintaining a capacity limit at the site to prevent blocking or dealing with container replacement). These stem from tactical decisions made, concerning how the waste disposal station is to be managed, that influence operators' actions on a daily and therefore operational level. As some may influence the design as well, it makes sense to give advice on these as well. The most important among these are policy influences based on the operational issue of blocking. When the utilization increases of the station personnel may have policies to deal with this problem in order to prevent blocking:

1. In Lelystad, the length of the driveway before the stations is increased to accommodate more cars at once;
2. In Woerden, they close off the entrance and admit only upon exit of a visitor though the possibility exists that they close until the number of cars has dropped below a certain level.

2.4 Modelling Issues

The design issues mentioned in the previous section provide guidance on phenomena that will need to be taken into account whilst building a model. These have therefore been selected and elaborated upon in further detail. In these deliberations, the possible influence they may have is discussed and assessed. Ultimately a selection is made of the design issues in order to determine which of them will be included in the conceptual model that will be the basis for the simulation study.

The first category of influence is the layout. This may influence the characteristics of the model that is used eventually, which influences visitor flow and behaviour. So far three different flow layouts have been observed. These are the line-flow, the U-flow and the O-flow. Due to the layout all types have different utilisation of space and distances between containers differ for the options.

The number of containers per waste stream (per type) is connected to the waste volumes generated and the size of the community the waste disposal station is supposed to service.

The location of containers might be observed from current practices at waste disposal stations although this may be influenced by the area where the waste disposal station is built, by the purpose the municipality has for the station and traffic laws, safety regulations and other regulations the municipality enforces.

Layout

Among others aesthetics and size of construction site seems to mostly influence the layout of the design. The most obvious effect the layout may have on the queueing, is the effect the layout has on the position of the containers with respect to each other. This may influence the parking spaces available at each container, and it may influence the walking distance to other containers visitors need to visit. For example, once parked, visitors usually go to all containers within a certain perimeter of their parked vehicle given the weight of the load. For each layout option, the number of containers in this perimeter will differ, effectively causing a difference in service times and transfer (transport) times between servers.

<u>Examples of the line flow:</u>

A complete line-flow hardly occurs, as this layout forces every visitor to drive past every substation. A line-flow does, however, occur within a substation, namely the platform e.g. in Lelystad. Enough space is arranged to allow visitors to drive past containers they do not need to visit.

<u>Examples of the U flow:</u>

In Woerden the U-flow can be observed. That particular waste disposal station was placed on a relative small patch of land. In this case the U-shape enforced a U-turn on the platform whilst still providing space for the various waste streams to be collected. Once again there was ample space for visitors to allow driving past substations that they did not need to visit.

<u>Examples of the O-flow:</u>

The substations are usually placed in a circular or triangular layout that enables visitors to solely drive past the substations they need to visit which improves the flow. In Enschede the platform is also created in a circular layout.

Sizing

Depending on the waste volumes, a number of containers of a certain size are deemed necessary to collect without the need for a short container emptying cycle. However, seasonality may influence waste volumes. Usually an approximation is made for how many containers are needed although a (mathematical) model may calculate what exact number yields the best results.
Another consideration of influence is the speed with which waste of certain streams is dumped. If dumping takes long, having another container where visitors can dump the same type of waste has a positive influence on the flow.

According to a study done in 2006 (DHV B.V., 2006), to determine the cost price of a waste disposal station, there are 20 waste streams that are collected in different containers. The quantities in which they usually occur at a waste disposal station were also important for the calculation of the cost price. This information, however, is also useful for this study. In the overview, however, no container reservation can be observed for plastics. Since every waste disposal station visited for this thesis had one for hard plastics and one for soft plastics they have been added to the list (see Table 1). The provided numbers are averages calculated from data collected from more than 100 waste disposal stations in a survey performed by the Royal Dutch NVRD. Large waste disposal stations for larger communities (more visitors) may need more containers. However, factors like area (rural areas produce more garden waste, while urban areas produce more construction and demolition waste) will influence sizing too.

Waste streams	# containers	Type of container
Crude garden waste (p)	2	High container without lid 30m^3
Glass bottles	2	Bottle containers 4m^3 each
Glass plates	1	Low container without lid 12m^3
Paper and carton (p)	1	High container without lid 30m^3
Textile	1	Closed textile containers 3m^3
Goods destined for thrift shops	1	High storage container 30m^3
Small chemical waste		Small chemical waste depot
Gas discharge lamps	2	Small container 1,4m^3
Electronic devices	1	High storage container 30m^3
A- and B-grade wood (p)	2	High container without lid 30m^3
C-grade wood (p)	1	High container without lid 30m^3
Old metals (p)	1	High container without lid 30m^3
Car tires	1	Low container without lid 12m^3
Gas cylinders	1	Gas cylinders container 2m^3
Crude waste (p)	2	High container without lid 30m^3
Asbestos	1	Closed asbestos-container 30m^3
Debris	2	Low container without lid 12m^3
Construction and demolition waste (p)	1	High container with lid 30m^3
Soil waste	1	Low container without lid 12m^3
Roofing waste	1	Low container without lid 12m^3
Hard plastics (p)	1	High container without lid 30m^3
Soft plastics (p)	1	High container without lid 30m^3

Table 1 Overview of waste streams collected and the average number of containers present at each site (DHV B.V., 2006); extended with plastic

Allocation

At all locations visited, observations showed that there usually is a platform at a waste disposal station and that there are some waste streams that are collected at a location placed either before or after the platform. The allocation seems to differ between waste disposal stations. However, some waste streams have been observed to be placed at the platform at every waste disposal station whilst some streams almost never were.

The waste streams that have been observed to be collected at the platform usually are soft and hard plastics, metals, crude waste, A- (pallets) and B grade wood (wood from inside, like furniture), roofing waste, building waste, plaster, C-grade wood (from garden furniture, fences, etc.), crude garden waste (clipping waste), and paper and carton. The waste streams that are usually collected before or after the platform are chemical waste, glass plates (like mirrors or glass shutters), glass bottles, electronic devices, matrasses, soil waste, asbestos, demolition waste, textile, Styrofoam, (cfl) light bulbs, tl lamps, tires (with or without rims), frying fat and fryers filled with solidified fat, and products that go to thrift shops. Some waste disposal stations have been observed to have a different policy, but in the norm the division mentioned above is followed. Additionally Table 1 under "Sizing" gives an overview of the waste streams collected and the method (container type) used for collection. As a basic rule of thumb usually the waste streams collected in high containers are placed at the platform.

This division of waste streams in a group collected at the platform and other groups away from the platform is final. Therefore the impact of the allocation mostly concerns the question of how to position the containers within each group.

2.5 Summary

With regard to the layout, all waste disposal stations follow the same premise that visitors first undergo an intake process. At this stage visitors are registered in the system and checked to see whether they are indeed allowed to bring waste to the disposal station. Furthermore they need to declare what they brought so that they can be given directions on where to bring what. After this process they can visit the containers they need to visit to dump their waste after which they can leave the site.

Since, in theory, the capacity and the location of the containers affect the queuing model the most, as the containers are the servers of the model, and no other clear effects were observed while visiting the waste disposal station, we can conclude that the different layout options do not cause sufficient distinction in the effect they have on the waiting times to be included as decision in the 'conceptual model'. We may argue that there is a difference in distances that visitors need to cover and therefore the time they need to dump waste. However, it is not wise to try to analyse and improve a system through a model based on the strategic, tactical and operational level at the same time. It is cumbersome to analyse the effects of all strategic, tactical and operational decisions in one study. Since our time is limited, we have decided to analyse the effect of tactical decisions on the operational level (on queues and waiting times) for a fixed strategic decision. So the layout or the shape the substations make and have, is considered to be a model input and of a fixed nature.

Based on this consideration and the aforementioned information we have decided to make a model where the high level influences are not variables to vary in this study. Instead the conceptual model will be built around a certain layout. The effects of the different layout options have been discussed earlier and these can be easily incorporated once a commercial tool is built.

Tactical decisions like sizing and capacity are influenced by target community characteristics and current practices. These culminate in the waste volumes, visitor numbers and tactical considerations. The latter consist of the popularity of the waste streams (which part of the community brings waste of that particular type?) and the dump speed of the waste stream (how long does it take a visitor on average to dump his waste of that type?). The model will make calculations based on sizing and capacity as decision variables. Queuing theory dictates that the position of servers in a system has an impact on waiting times, sojourn times and queue length as well. Therefore the allocation of containers is also of importance in the model and is also considered to be a decision variable.

Tactical decisions regarding policies to be enforced on an operational level regarding, e.g., the maximum capacity that is maintained to prevent blocking and how to deal with blocking in general have an impact as well. These are a result of past experience at waste disposal stations in the Netherlands and of new experiences once the waste disposal station has been taken into use. The effect of these decisions can be observed. A capacity variable can be added to the model.

The model that should be the result has the potential to provide two types of output. First, the model is required to calculate the sojourn times, waiting times and queue lengths based on the tactical decisions: the decision variables. Afterwards, it may prove interesting to study a few possible interventions based on policies to be able to formulate rules of thumb that have a positive impact on the flow; i.e. reduce waiting time and queue length. Specifically we may analyse how to deal with an extremely busy Saturday. Figure 1 shows a graphical overview of the concepts just described.

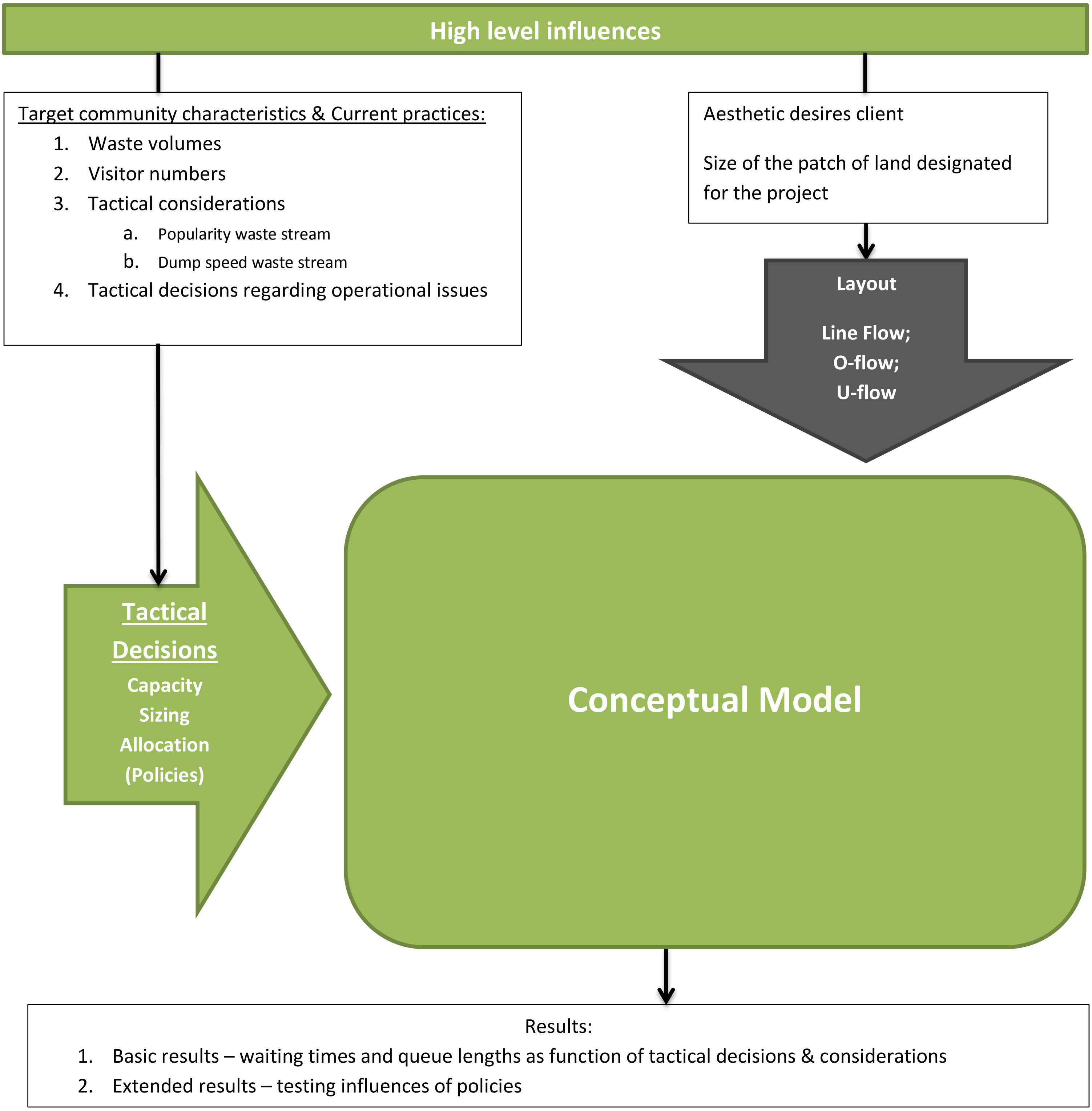

Figure 1 Graphical overview of design decisions for the model and the expected outcomes

Chapter 3 Reviewing and Selecting a Modelling Technique

As stated in Section 1.5, the final goal of this project is to develop a model that can analyse designs of waste disposal stations with respect to waiting times and queue lengths, based on design decisions. We are considering two options for developing such a model. An analytical model could be used or perhaps adapted to suit our needs. We could also develop a simulation model. To make a firm decision, regarding which of these options to use, we review several models from literature and weigh both options.

In the following sections analytical models and their ins and outs are described first before simulation studies are given attention. At the end of this chapter a decision is made regarding which modelling technique to use.

3.1 Analytical Models

When viewing a waste disposal station, one can identify several 'servers' where visitors can come and, following the method of self-service, bring waste of several types. For modelling purposes, intuition therefore points in the direction of queuing theory. In Winston (2004) two large groups of queuing networks are observed. Open networks of queues and closed networks are different in the aspect of the number of jobs that are present in the system at any point in time. In closed networks, the number of jobs in the system is constant whereas in open networks the number of jobs in the system can fluctuate constantly. Clearly the waste disposal station in its pure form (every visitor arriving between opening hours is allowed in the system) is like an open network than a closed network in configuration.

There is a wide range of phenomena that may be modelled using a (open) network of servers. To get a better idea of whether there is an analytical model that is applicable to our case, several options were given attention. These options were first studied generally by analysing what types of phenomena they are usually used for and what assumptions are made to justify said use. If our case can be seen as one of the phenomena and the assumptions are not too stringent we will analyse the analytical model in greater detail. Dallery and Gershwin (1992) have quite extensively described how queueing may be used to analyse manufacturing flow lines. Even though (in retrospect) a waste disposal station does not share the characteristics of a flow line, this paper was quite useful in providing insightful information regarding queueing theory applied to practical cases. Therefore the work of Dallery and Gershwin is briefly described in Section 3.1.1. After reviewing "An open queueing network for lead time analysis" (Vandaele, Boeck de, & Callewier, 2002) it became apparent that our case, a waste disposal station, is more comparable to a job shop. Therefore Section 3.1.2 is devoted entirely to that topic.

3.1.1 Queueing theory applied to manufacturing flow lines

Manufacturing flow lines describe linear (manufacturing) systems where every job follows the same routing and flows from the front to the end of the system. Add the fact that the system usually processes only one type of job and it becomes quite clear that this type of systems hardly suits our case. In our case every visitor (job) is unique and can potentially follow a different route through the system. Despite seeing this large and seemingly unassailable difference we might still learn something from the different types and adaptations that Dallery and Gershwin describe. There are quite a few different types Dallery and Gershwin describe. A few of them are:

1. Asynchronous vs synchronous flow lines – In asynchronous systems machines have different instants. This means that they can have different operators, failures occur in a different fashion and operating times can vary as well and may be nondeterministic. These systems cannot be operated in events. Synchronous flow lines in comparison operate according to fixed deterministic operating times and can be operated in events. This means that system changes can be ‘scheduled’ by events (e.g. machine becomes available, start processing, processing is finished, etc.)
2. Saturated vs non-saturated – In saturated flow lines the assumption is made that the first machine is never starved (always has enough jobs fed to it to never be idle). In addition the last machine is never blocked so delivery to clients is guaranteed. Non-saturated lines deal with random input processes and departures.
3. Blocking and starvation – If disruption occurs then machines upstream from the disruption may operate until the buffers before the disruption are filled. At that moment a blocking occurs. The machines downstream from the disruption may operate until the buffers after the disruption have been emptied. When that happens starvation occurs.
4. Reliable vs unreliable machines – In systems with reliable machines, the machines will not fail. Unreliable machines may fail.

In a waste disposal station we have observed asynchronous behaviour (different non-deterministic operating times). Furthermore the system is non-saturated (the arrivals and departures are random). In waste disposal stations only blocking is an issue. When utilization is high it may happen that driveways become blocked with visitors waiting for space to open up at a specific container. The last topic might be relevant to operators of waste disposal stations but falls outside our scope.

A very interesting topic that Dallery and Gershwin raised was the difference between exact methods for analysis and approximate methods. Exact methods have, according to them, a set of very strong advantages:
1. Exact solutions are more valuable when the model fits reality;
2. Exact solutions may provide qualitative insights as well;
3. Exact solutions can be solved rapidly.

The first advantage is of importance to us. Exact solutions are more useful, however, if the model does not fit reality the solutions can be quite useless. This was the main reason for looking for a more suitable model type than the one for the manufacturing flow lines.

If exact solutions cannot be obtained due to constraining factors (limited computation power, time or other resources) one of the options left is trying to approximate the real system by adapting the exact models. Most of the approximation methods are based upon decomposition. The idea is to decompose larger exact systems into smaller subsystem that may be analysed more easily. The trade-off made is based upon complexity versus accuracy. For complex systems it is difficult to find an exact solution even though it will be of a better quality. This is certainly something to keep in mind while developing our model. For each smaller subsystem a set of steps needs to be followed to complete an analysis:
1. Identifying subsystems that can yield exact solutions;
2. Deriving a set of equations to find the value of unknown parameters of each subsystem;
3. Developing a means to solve the set of equations previously mentioned.

The final topic of interest to us that Dallery and Gershwin focussed on was the issue of variance. All methods that they have studied and described in their paper are focused on dealing with steady state averages concerning production rates and average buffer levels. However, for every production system its variance is very important. A standard deviation of ten percent of the mean can result in an occasional productivity that can be 50 percent of the norm. This could lead to costly situations. Therefore it is desirable to use a dataset that is extensive enough to provide statistics like probability distributions on for example production rates.

Taking this information with us, we continue with the next section. In this section a model, for a system more closely resembling our waste disposal stations, is described thoroughly and its usefulness is assessed.

3.1.2 Modelling job shops using open queueing networks

Job shops are different from flow lines in more than one important aspect. First of all job shops are (manufacturing) systems that produce (or process) different products (or jobs). Second, all products (jobs) arrive according to their own arrival pattern. Furthermore all products (jobs) require a different series of processing; leading to different sets of machines (machining or processing centres) they need to visit. Additionally the time spent at each station is different for each type of product. Finally, each product (type) has a unique route that they follow through the system.

From this description of job shops by Vandaele et al. (2002) it becomes quite apparent that a waste disposal is more akin a job shop than a flow line. For one, each visitor at a waste disposal station is unique as it brings different types of waste in different quantities. This automatically leads to unique routes they take through the waste disposal station while in the process of dumping their waste at the substations they need to visit. The difference in amount of time spent at each location is also a clear result from the heterogeneity of the visitors. The only aspect of the description given by Vandaele et al. that is not that clearly represented is that concerning a different arrival pattern for each product type. As far as has been observed there is no distinct pattern for the different customer types nor is there any reason to assume this would be so.

Going a little bit further back in time, Buzacott and Shantikumar (1985) provide us with more insight into job shops. They describe a class of job shops with a dispatch area. The behaviour of such a job shop is determined by the following three characteristics:

1. The job routing
2. The job arrival (all at once or as a continuous process)
3. Dispatch and scheduling policies

According to their classification our case would be modelled as a *pure dynamic job shop* where each arriving job is dispatched immediately and processing occurs in order of arrival (First Come First Served). They state that these types of models may be solved using exact methods if they are similar to the so-called Jackson Networks (1963). This would require the arrivals to occur according to a Poisson process, the service times to be exponentially distributed and the buffers to have infinite space. As in our case it turns out that the service-times are sometimes distributed differently (see Section 4.3) and we need finite space buffers to resemble the limited space available on the waste disposal station, it was worthwhile to also look into approximate methods for calculating Queueing measures.

Both Buzacott and Shantikumar (1985) and Bitran and Dasu (1992) state that there are four approximate methods to analyse non-Jacksonian queueing networks. Of these four they both select the decomposition method that interestingly enough was also reviewed by Dallery and Gershwin for analysing their flow line networks. According to this method each queue is analysed separately. The output of one queue would, however, influence the input of subsequent queues. And as the input should be independent and identically distributed (i.e. renewal), this method leans heavily on the assumption of renewal input and output of all the queues of the system. Still, this decomposition method can be used for job shops with any number of service centres, any probability routing matrix and any service time distribution (as long as their squared coefficient of variation is less than or equal to one). The method can also be extended to deal with cases of multiple machines at the service centres and more than one type of job.

In order to assess the usefulness of their method, the complete set of assumptions that Buzacott and Shantikumar (1985) made, was checked and two assumptions were found to be a problem (for a complete overview of the list of assumptions from Buzacott and Shantikumar see appendix A). The second job assumption states that all jobs are statistically independent. This may not be the case as there are arguably outside influences on all visitors that influence the types of waste they bring, how much they bring and when they bring it (garden waste is a strong example of a waste type influenced strongly by the season). One of the machine assumptions seems to be more problematic though. They state that each machine center (in our case substation) consists of only one machine. This is in direct conflict with reality as more than one waste stream is usually collected at a substation. We may conclude that the decomposition method to analyse the waste disposal stations seems like a viable option. However, the specific decomposition Buzacott and Shantikumar (1985) used is for us not applicable.

Bitran and Dasu (1992) state that, while using decomposition, three basic steps need to be taken for every decomposed queue:

1. Characterization arrival process: based on the streams arriving from other stations the arrival process is (approximately) determined;
2. Analysis of the queue: Based on the arrival process determined in Step 1 the queue is analysed. Waiting time, sojourn or lead time and queue length can be determined among other performance measures;
3. Determination departure process: The departure process of the station currently under consideration is determined. Note that the departing streams of some stations are input to others.

Bitran and Dasu explain that variants on the decomposition method can be developed as long as these steps are in some way incorporated. A very popular approach is the Parametric Decomposition Approach (PDA). This approach assumes that apart from stochastic independence of the stations, the flow between stations is approximated by renewal processes. Furthermore two parameters of the arrival and service time are of importance. With the mean and the variance the performance measures can be calculated at each stage.

Vandaele et al. (2002) use decomposition as well. Their approach closely resembles the PDA and potentially offers a way to calculate the performance measures Modulo Bèton is interested in. Before explaining the formulae used in this method in great detail we provide an overview of all the variables used in said calculations and their symbols (see Table 2).

Two key input parameters of any queueing model are the arrival and processing rate. These parameters, among others, are used to enable the calculation of the expected waiting time ($E(Wq_m)$) at any machine (machining station).

F1:

$$E(Wq_m) = \frac{\rho_m * \left(S^2{}_{Y_m} + S^2{}_{X_m}\right) * X_m}{2(1-\rho_m)} * exp\left\{\frac{-2(1-\rho_m)\left(1-S^2{}_{Y_m}\right)^2}{3\rho_m * \left(S^2{}_{Y_m} + S^2{}_{X_m}\right)}\right\}, if\ S^2{}_{Y_m} \leq 1$$

$$E(Wq_m) = \frac{\rho_m * \left(S^2{}_{Y_m} + S^2{}_{X_m}\right) * X_m}{2(1-\rho_m)}, if\ S^2{}_{Y_m} > 1$$

As can be observed in F 1, some other parameters need to be measured before the waiting time can be calculated. Of great importance among these are the squared coefficients of variation of the aggregate processing time at machine m and the aggregate inter-arrival time at machine m. The following set of formulae is used for this purpose. By calculating other variables needed to calculate the previously mentioned parameters.

F2: $$\rho_m = \frac{\lambda_m}{\mu_m}$$

F3: $$\lambda_m = \sum_{p=1}^{P} \sum_{o=1}^{Op} \lambda_p * \delta_{opm}$$

F4: $$\acute{\lambda}_m = \sum_{p=1}^{P} \lambda_p * \delta_{1pm}$$

F5: $$X_m = \sum_{p=1}^{P} \sum_{o=1}^{Op} \frac{\lambda_p * \delta_{opm}}{\lambda_m} * X_{po}$$

F6: $$w_{pom} = \frac{\lambda_p * \delta_{opm}}{\lambda_m}$$

By substituting F5 in the general formula for the aggregate service rate of machine m (See Table 2) and using that expression for μ_m and expression F3 in F2 the utilization on machine can be obtained which is also needed for the calculation of the waiting time. The following expression is derived.

F7: $$\rho_m = \sum_{p=1}^{P} \sum_{o=1}^{Op} \lambda_p * \delta_{opm} * X_{po}$$

We can now successfully calculate the squared coefficient of variation of the aggregate processing time at machine m with formula 8 (F8).

F8: $$S^2{}_{X_m} = \frac{\sum_{p=1}^{P} \sum_{o=1}^{Op} w_{pom} * X^2{}_{po} - \left[\sum_{p=1}^{P} \sum_{o=1}^{Op} w_{pom} * X_{po}\right]^2}{\left[\sum_{p=1}^{P} \sum_{o=1}^{Op} w_{pom} * X_{po}\right]^2} + \sum_{p=1}^{P} \sum_{o=1}^{Op} w_{pom} * X^2{}_{po}$$

To derive the expression for the squared coefficient of variation for the aggregate inter-arrival time at machine m, the squared coefficient of variation of departure times at previous machines should be analysed as well. Using an equation from Hopp and Spearman (Hopp & Spearman, 2008) which holds for single servers an approximation can be gained.

F9: $$S^2{}_{d_n} \approx (1-\rho_n^2) * S^2{}_{Y_n} + \rho_n^2 * S^2{}_{X_n}$$

Symbol	Explanation
Indices $\begin{cases} p = 1 \dots P \\ m = 1 \dots M \\ o = 1 \dots Op \end{cases}$	Product index (in our case the visitors would be the odd jobs) Machine index (in our case the machines would be the substations) Operation index (in our case the operations are the various waste types to dump) with Op being the number of operations done on product p
$\delta_{opm} = \begin{cases} 1 \\ 0 \end{cases}$	Bin variable, equals one when operation o is performed on product p on machine m; otherwise equal to zero.
$\lambda_p = \frac{1}{Y_p}$	The average arrival rate of product p
Y_p	The average inter-arrival time
$C^2{}_{Y_p}$	Variance of the inter-arrival time of product p
$S^2{}_{Y_p}$	Squared coefficient of variation of the inter-arrival time of product p
$\mu_{po} = \frac{1}{X_{po}}$	The average processing (or service) rate of operation o on product p
X_{po}	The average processing (or service) time of operation o on product p
$C^2{}_{X_{po}}$	The variance of the processing time of operation of on product p
$S^2{}_{X_{po}}$	Squared coefficient of variation of the processing time of operation o on product p
ρ_m , ρ_n	The utilization rate on machine m, or previous machine n
λ_m , λ_n	The aggregate arrival rate of products (jobs) at machine m , or previous machine n
$\acute{\lambda}_m$	The external aggregate arrival rate at machine m
X_m	The aggregate processing time at machine m
$\mu_m = \frac{1}{X_m}$	The aggregate service rate at machine m
w_{pom}	Weight of each product/operation combination in total arrival rate at machine m
$S^2{}_{X_m}$, $S^2{}_{X_n}$	Squared coefficient of variation of aggregate processing time at machine m, or previous machine n
$S^2{}_{d_n}$	Squared coefficient of variation of departure time at a preceding machine n
$S^2{}_{Y_{nm}}$	Squared coefficient of variation of inter-arrival time at machine m of products coming from machine n
t_{nm}	Proportion of products leaving machine n and going to machine m
$S^2{}_{Y_m}$, $S^2{}_{Y_n}$	Squared coefficient of variation of aggregate inter-arrival time at machine m
$\acute{S}^2{}_{Y_m}$	Squared coefficient of variation of aggregate external inter-arrival times at machine m
$E(Wq_m)$	Expected waiting time at machine m
$Var(Wq_m)$	Variance of the waiting time at machine m
$E(LT_p)$	Expected Lead time of product p
$Var(LT_p)$	Expected variance of the lead time of product p
$S^2{}_{Wq_m}$	Squared coefficient of variation of the waiting time at machine m
σ_{q_m}	Probability of delay ($P(Wq_m>0)$)
$S^2{}_{Dq_m}$	Squared coefficient of variation of the conditional waiting time (i.e. the waiting time given the that the server is busy)
$d^3{}_{s_m}$	$E[X^3]/\bar{X}^3$

Table 2 Complete list of symbols used in the queueing model developed by Vandaele et al. (2002)

In order to progress further we need to first calculate squared coefficient of variation of inter-arrival time at machine m of products coming from machine n, ${S^2}_{Y_{nm}}$, and the squared coefficient of variation of aggregate external inter-arrival times at machine m. The following set of equations takes care of that (F10-F13)

F10: $${S^2}_{Y_{nm}} = t_{nm} * {S^2}_{d_n} + (1 - t_{nm})$$

F11: $$t_{nm} = \frac{1}{\lambda_n} * \sum_{p=1}^{P} \sum_{o=1}^{Op} \lambda_p * \delta_{opn} * \delta_{o+1pm}$$

F12: $$\lambda_m = \sum_{n=1}^{M} \lambda_n * t_{nm} + \acute{\lambda}_m$$ [1]

F13: $${\acute{S}^2}_{Y_m} \approx \frac{1}{3} + \frac{2}{3} * \sum_{p=1}^{P} \frac{\lambda_p * \delta_{1pm} * {S^2}_{Y_p}}{\acute{\lambda}_m} , if \ \sum_{p=1}^{P} \delta_{1pm} \geq 2$$

or $${\acute{S}^2}_{Y_m} = {S^2}_{Y_p} , if \ \sum_{p=1}^{P} \delta_{1pm} = 1$$

Intuitively an approximation for the squared coefficient of variation for the aggregate inter-arrival time at machine m can be developed (F14).

F14: $${S^2}_{Y_m} \approx \sum_{n=1}^{M} \left(\frac{\lambda_n}{\lambda_m} t_{nm}\right) * {S^2}_{Y_{nm}} + \frac{\acute{\lambda}_m}{\lambda_m} * {\acute{S}^2}_{Y_m}$$

Using the approximation (F14), equations F9, F10 and F12 a set of linear equations can be determined (for each machine m one), that can be used to determine the squared coefficient of variation for the aggregate inter-arrival time at machine m.

F15: $$-\sum_{n=1}^{M} \lambda_n t_{nm}^2 (1 - \rho_n^2) {S^2}_{Y_n} + \lambda_m {S^2}_{Y_m} = \sum_{n=1}^{M} \lambda_n t_{nm}^2 \left(t_{nm} \rho_n^2 {S^2}_{X_n} + 1 - t_{nm}\right) + \acute{\lambda}_m {\acute{S}^2}_{Y_m}$$

Once the squared coefficients of variation of the aggregate processing time at machine m and the aggregate inter-arrival time at machine m have been determined along with the utilization rate on machine m and the aggregate processing time on machine m the waiting times can be calculated.

Using these and another set of equations can be used to determine the average product lead time (in our case the average staying time of a visitor in a waste disposal station) and the variance thereof. The average lead time can be calculated already using formula F16. To use formula F17 to calculate the variance another set of equations needs to be solved first (F18-) as the variance of the waiting time, which is unknown, is needed.

F16: $$E(LT_p) = \sum_{o=1}^{Op} \sum_{m=1}^{M} E(Wq_m) \delta_{opm} + \sum_{o=1}^{Op} X_{po}$$

F17: $$\mathrm{Var}(LT_p) = \sum_{o=1}^{Op} \sum_{m=1}^{M} Var(Wq_m) \delta_{opm} + \sum_{o=1}^{Op} {C^2}_{X_{po}}$$

F18: $$Var(Wq_m) = [(Wq_m)]^2 * {S^2}_{Wq_m}$$

F19: $${S^2}_{Wq_m} = \frac{{S^2}_{Dq_m} + 1 - \sigma_{q_m}}{\sigma_{q_m}}$$

[1] Not to be confused with the symbol for aggregate arrival rate at the first machine visited by product p (F3)

F20: $\sigma_{q_m} = \rho_m + ({S^2}_{Y_m} - 1)\rho_m(1-\rho_m)h(\rho_m, {S^2}_{Y_m}, {S^2}_{X_m})$

F21: $h(\rho_m, {S^2}_{Y_m}, {S^2}_{X_m}) = \begin{cases} \frac{1+{S^2}_{Y_m}+\rho_m {S^2}_{X_m}}{1+\rho_m({S^2}_{X_m}-1)+\rho_m^2(4{S^2}_{Y_m}+{S^2}_{X_m})} & {S^2}_{Y_m} \leq 1 \\ \frac{4\rho_m}{{S^2}_{Y_m}+\rho_m^2(4{S^2}_{Y_m}+{S^2}_{X_m})} & {S^2}_{Y_m} \geq 1 \end{cases}$

F22: ${S^2}_{Dq_m} = 2\rho_m - 1 + \frac{4(1-\rho_m){d^3}_{s_m}}{3({S^2}_{X_m}+1)^2}$

F23: ${d^3}_{s_m} = \begin{cases} \frac{3}{4}\left[\frac{1}{q_m^2} + \frac{1}{(1-q_m)^2}\right] & {S^2}_{X_m} \geq 1 \\ (2 * {S^2}_{X_m} + 1)({S^2}_{X_m} + 1) & {S^2}_{X_m} < 1 \end{cases}$

F24: $q_m = \frac{1}{2} + \sqrt{\frac{{S^2}_{X_m}+1}{{S^2}_{X_m}-1}}$

When, using these equations, the average and variance of the lead time per product have been determined, one could postulate a probability distribution for the product lead time and use this to assess the service level. One could also determine the lead time guaranteeing a target service level. Vandaele et al. (2002) do assume that there is deterministic routing between machines. For an approximation this seems like a reasonable assumption in our case, even though in reality the routing is rarely deterministic.

In all the models reviewed it seemed one of the most distinct characteristics of the waste disposal station is not taken into account. The fact that there is shared capacity for several queues at each substation is not covered by any of these models. The fact that visitors of a waste disposal can park in a parking spot and visit several queues from there, dumping waste in several containers while standing still in one spot is something unheard of in the methodologies studied. However, the last model could be used. If we model the substations of the waste disposal station as the machining centres (machines) that can perform several operations and if we model the visitors to be the products (jobs) processed there, then the model as described by Vandaele et al. (2002) could be used. However, one of the assumptions of the model seems to be a problem. Vandaele et al. assume there is a buffer of infinite space in front of each service element which is of course not the case for a waste disposal station as the terrain has limited space available for visiting cars.

As this model is somewhat complicated in its use and as creating a routing probability matrix requires a larger workforce for measurements than was available, it seemed prudent to look into a different method for modelling waste disposal stations. We decided to determine whether a simulation model would be a better way of representing a waste disposal station as realistically as possible.

3.2 Simulation Models

Simulation studies are often utilised to analyse how systems react to interventions (actions initiated on purpose as a means of improving the system's performance) or outside influences (often called scenarios). As it may be too costly or time consuming (or both) to try and test these effects in reality, a simulation study is done. Usually a simulation model takes the form of a computer program. Literature describes several types of simulation and reasons for simulating. The view of Robinson

(2004) is provided in Subsection 3.2.1 The Subsection afterwards describes the process of conducting a simulation study. For that purpose Law (2006) is used.

3.2.1 An introduction to simulation studies

The first question we need to ask ourselves when starting to review various options for simulation is “what is simulation?”. Quite simply put a simulation is an imitation of a phenomenon (in the field of production and logistics usually something like a production system) that can be observed in reality. Robinson (2004) states that there are several types of systems:

1. Natural systems: these all originate from the universe;
2. Designed physical systems: physical systems that are designed and built by humans (these are tangible);
3. Designed abstract systems: systems that are designed by humans (theories, math and literature, none of which is tangible);
4. Human activity system: These usually concern social behaviour.

Obviously a waste disposal station is a designed physical system.

The next question that is of importance is “why should one use simulation?”. Robinson mentions three major reasons for using simulation. First on his list is variability. Many operation systems are subject to a form of variability. Popular sources for variability are the arrivals of jobs to the system, the processing times, or the nature of the jobs arriving at the system. Another reason for using a simulation model to analyse a system is the uncertainty surrounding the effect interconnectedness of various parts of the system has on the system. Since this is difficult to model analytically, the best next thing is to simulate the events to observe what those effects might realistically be. The last issue Robinson (2004) brings forward is the complexity of systems. Some systems are too complex to analyse analytically. This statement brings forth another issue. “How do you determine what the complexity of the system is?” Robinson remarks that there are many ways to define complexity yet by employing combinatorial and dynamic complexity one can get a very good indication of complexity. Combinatorial complexity relates to the number of components in a system that leads to different system combinations. In job shops the combination of operations that a job can follow in the system can be made up from a great many number of operations. Job shops are therefore an example of combinatorial complexity.

A waste disposal station displays examples of variability (in arrival process, service process and the variability in jobs), interconnectedness (the business of stations affecting the behaviour of the process for other visitors) and combinatorial complexity. Since there are many decision variables in the process of designing a waste disposal station and therefore many combinations of settings that are possible it seems prudent to state that the combinatorial complexity of a waste disposal design is indeed high.

A third question that needs answering is “when should a simulation study be conducted?”. Robinson sees this question differently from the why-question. He states that in general terms simulation studies (of the discrete event variant) are performed for modelling systems that can be modelled as queueing systems. Conveniently enough that is just the type of system our waste disposal station is (and DES is the type of simulation under consideration). A simulation study is therefore a good option for modelling in our case.

So, how do we go about creating a simulation model for this system? First of all, we need to determine what kind of simulation to perform with the model. There are several forms of simulation according to Law (2006):

1. Discrete Event Simulation: This type of simulation models a system as it changes over time. These changes occur at discrete time intervals during so-called *events*;
2. Continuous Simulation: This simulation modelling type concerns a system in which the variables dictating the state of the system change continuously;
3. Combined Discrete-Continuous Simulation: Some systems evolve under influence of both discrete and continuous influences. For these cases the use of a combined discrete-continuous simulation is fitting.
4. Monte Carlo Simulation: This is a modelling method that uses random numbers to solve stochastic or deterministic problems;
5. Spreadsheet Simulation: If the system under study is not too complex a discrete event simulation or a Monte Carlo simulation could be done in a spreadsheet.

For our case, a discrete event simulation seems the most fitting choice as the state of the waste disposal station is determined by the number of visitors at certain locations within the system. These states change according to events like arrivals of new visitors or visitors starting to dump at a certain container or leaving said container upon finishing the dumping process.

Now, a simulation study always occurs according to a structured process. We have dedicated an entire subsection to the description of this process. Law has a thorough description and Mes (2012) adapted this list of steps for a simulation study to give more guidance concerning the grouping of the activities done in a simulation study and the phases of a project in which they should occur. The entire process is described in Section 3.2.2.

3.2.2 Conducting a simulation study

Law (2006) lists ten steps that need to be taken in a simulation study. The adapted list by Mes (2012) (see Figure 2 below), gives a clear overview of all the steps taken in the execution of a good simulation study.

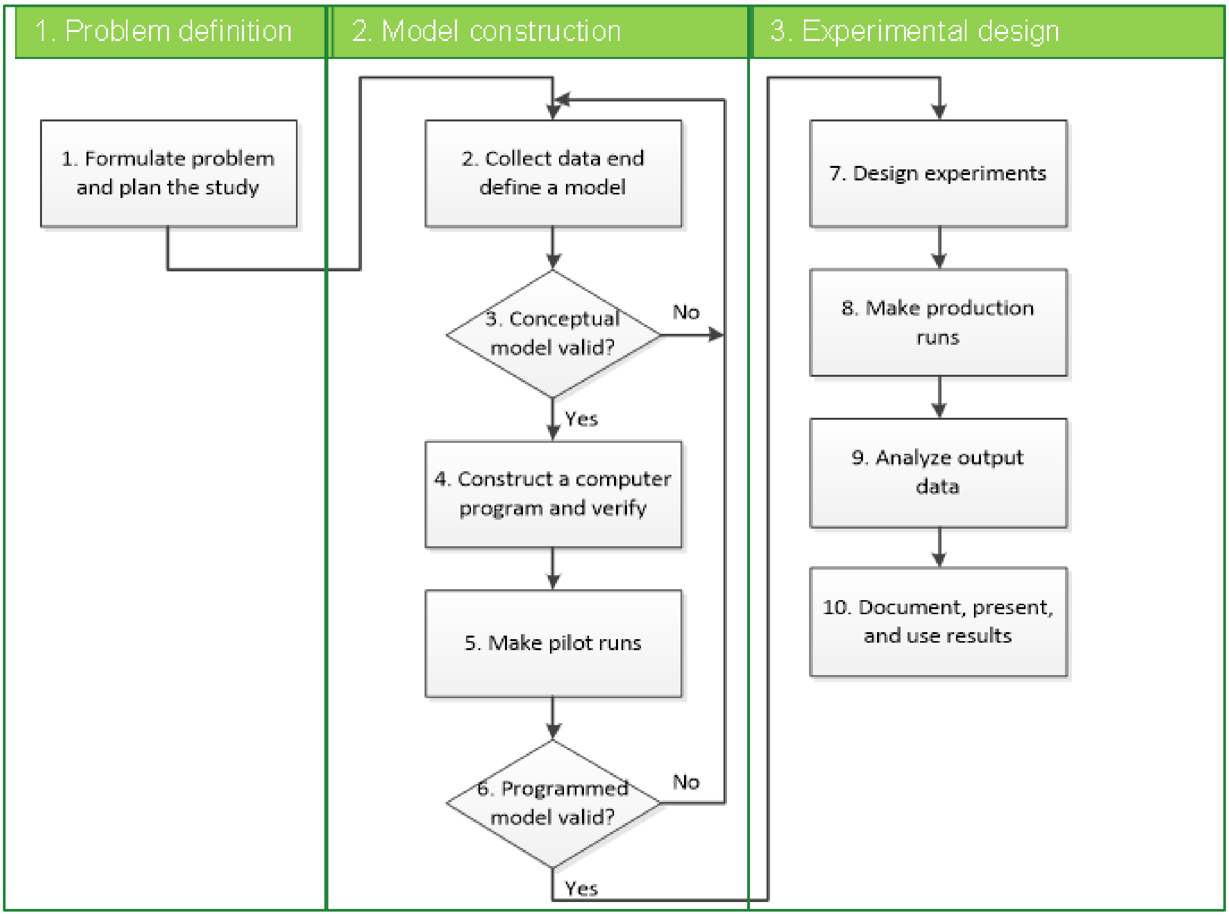

Figure 2 The 10 steps of any simulation study (Mes, 2012)

1. Problem definition

This first stage is not just a necessity for simulation studies. Defining the problem involves translating the problem description as provided by the client or employer into a problem that is indeed active, needs attention and provides an opportunity to act on. This translation is not always necessary, but it may happen after some preliminary research that the problem as stated is just a symptom of the real problem. In the final problem description the performance measures used to evaluate the system are decided upon. The scope of the model and the system configurations to be modelled are determined as well along with the time frame available for the study.

2. Model construction

In this stage the model is first defined in a conceptual (paper) model carefully describing the workings of the model, the input and output, the logic and the assumptions and simplifications made while constructing the model. During this stage data collection occurs as well. This data contains both data needed to estimate input parameters and data that can be used later on to assess the model's validity. When agreement is reached about the conceptual model the computer program is constructed. Test runs determine in this case whether the programmed model indeed operates according to the logic of the conceptual model. Once the model has been validated we can move on to the next stage, namely the experimental design.

3. Experimental design

In the final stage the experiments to be conducted are designed in such a way that the goal of the simulation study is reached in a timely and cost efficient manner. After the design for the experiments has been completed the experiments are run and the results are analysed. Once analysed, the results are carefully documented, reported and the results are used.

3.3 Choosing a Model Type

For making a right and well informed decision regarding whether to use an analytical model or a simulation model for the purpose of creating a model for Modulo Bèton that they can use in their processes the advantages and drawbacks of both options have been considered.

According to Buzacott and Shantikumar (Buzacott & Shantikumar, 1993) there are six important aspects to take into account when deciding upon a means to model a (discrete manufacturing) system.

1. Complexity vs simplicity – Based on how much detail is needed to realistically model the system a level of complexity is required. While considering this aspect one should keep in mind that the more detailed the model is the more difficult it is to develop the model. Still an oversimplified model is more likely to produce inaccurate results.
2. Flexibility – Systems are bound to change over time. If a model is flexible it may be able to handle these changes making it unnecessary to develop an entirely new model.
3. Data requirements – as the complexity of the model increases the amount of data, required to provide the necessary input data needed to run the model, increases.
4. Transparency – The model should be clear and comprehensible to the user. This means careful and detailed documentation are needed.
5. Efficiency – If the model is programmed in a computer programme certain storage requirements and running time are required to make timely decisions based on the model calculations.
6. User interface – Especially for more complicated models a good user interface is essential to guide the user in making correct use of the model. This means generating results and interpreting these results correctly.

Analytical models and simulation models perform differently for each of these considerations. In Table 3 a comparison is made between the two.

	Analytical models	Simulation models
1	Computational complexity increases exponentially as model complexity increases. Approximations may handle more complexity but developing and testing is difficult.	Can handle complexity fairly well.
2	Structure changes usually require a new model to be programmed. Parameter changing is usually easy.	If well designed, simulation models provide quite some flexibility. This does require a listing of aspects on which the model requires flexibility and guidelines on how to change the model so the user can do this independently.
3	Data requirements are *usually* less as the model is a fairly simple description of the reality. Still requirements may increase as the complexity of the model increases.	Simulation models usually require quite some data input. Once again though this is dependent upon the level of detailed used in the model.
4	Analytical models usually require a certain level of mathematical skills that are not typically found in most end users.	Simulation models require a good description of the logic to make the model transparent to the user.
5	Analytical models are unpredictable in development time yet once programmed it needs less time to get results, especially if programmed in a computer algorithm.	If the programming group is experienced, assessing the development time is usually reliable. Using the model to assess changes in a collection of variables can take some time though.
6	Analytical models should be incorporated in a decision support system. This system requires a guide for proper use in order to be of value to the end user.	Simulation models require a good user interface with visual and interaction features to facilitate ease in use by the end user. A good guide in how to use the model is needed here as well.

Table 3 Comparing Analytical and Simulation models based on six criteria (Buzacott & Shantikumar, 1993)

In the end the most important consideration is what type of model would be of more use to Modulo Bèton. As they plan to use the developed model for commercial purposes the advantages of the simulation model outweigh the advantages of an analytical model and the drawbacks of a simulation model. First of all the level of complexity and flexibility desired is of such a level that simulation is the better option. Analytical models may require less data and usually require less running time. However, the fact that the transparency is a lot lower for analytical models, while simulation models can become quite transparent to the end user if a good documentation of the model is included, pleads for the use of simulation. Simulation models may require more data and running time, but these are an unavoidable evil if reliable results for decision making are to be gained. Furthermore, selecting the right experiments may be tricky to get results that are useful for decision making, but with a good guide this can be achieved.

Apart from these considerations there are other issues involved with using an analytical model:

1. Each model assumed there were infinite buffer spaces in front of every service station;
2. Information needed to formulate a transition matrix for the transitions between the substations is lacking.

Therefore, taking all of the considerations and these two issues into account, the decision has been made to develop a simulation model.

3.4 Summary

After a thorough literature study we are able to partially answer our third research question. “Which quantitative model(s) can be used to model a waste disposal station and how should they be employed?” We have looked at several analytical models and found one that could be used to model a waste disposal station. We have also looked at the option of using a simulation model. Upon comparing both options, using the six aspects of evaluating a means to model a discrete manufacturing system from Buzacott and Shantikumar (Buzacott & Shantikumar, 1993), we found out that for our case it would be best to use a simulation model. However, we will still need to determine a way to translate our case into a simulation model. In other words we still need to make a conceptual model. And in order to create and use a program of a simulation model we need to collect data as well. These steps are taken in the next chapter.

Chapter 4 Modelling a Waste Disposal Station

Working towards a conceptual model

In this chapter the theory and necessary steps used to model a Waste Disposal Station are discussed. According to Robinson (2004) and Law (2006) several steps are necessary to develop a sound conceptual model which is paramount in creating a computer (simulation) model of a system. The first few steps, developing an understanding of the problem situation and determining the modelling objectives, have been taken care of in Chapter 2 and Chapter 1 respectively. The main objective to achieve with the model is having a tool that can evaluate the performance of a waste disposal station based on its design when it comes to queueing. The third step (Robinson) involves deciding upon and describing the inputs and outputs of the model. This is done in Section 4.1. Also the characteristics of a Waste Disposal Station are translated to the concept of an “Open Queueing System”. The focus of this project was to develop a general model that could be adapted to meet a high number of different configurations of waste disposal stations. In order to validate the created model though, we need to test it on a real life situation. After collaboration with waste disposal companies in the Netherlands was established, we have selected a waste disposal station for our study. In Section 4.2 this waste disposal station is described. In Section 4.3 the procedure used to collect the necessary input data is described. Furthermore the collected data is analysed. This analysis is necessary to derive important information regarding the input to the model. This analysis may also yield valuable information regarding issues concerning the experimental design which will be explained in Chapter 5. The final step from Robinson’s framework concerns the content of the conceptual model. This content is described thoroughly in Section 4.4. These characteristics are used in a simulation study to analyse the influence of these on the queueing results.

4.1 Modelling Waste Disposal Station using Queuing Theory

When viewing a Waste Disposal Station as an (open) queueing network model, the first decision to take is how to model the different servers in the system. Once that has been achieved, arrivals and service times are considered. Since the goal of this project was to construct a model for calculating queuing results at waste disposal stations the decision was made to make a generic model. This has been done in Section 4.1.1. If formulated carefully, it should be possible for users to delineate all possible designs to such a generic form. This means that the generic model we set out to develop is the basis on which models can be made of other designs. After delineation has occurred, specific situations can be analysed for clients by making calculations regarding queuing results as a result of the waste disposal station design.

Since there are, however, also other factors that influence queuing at waste disposal stations that have less to do with the basic design layout but more with policies concerning management of the system, some of these are highlighted for research in Section 4.1.2.

4.1.1 A generic model of a waste disposal station

A waste disposal station can be divided into parts (see Figure 3). First of all, the terrain is usually divided into four to five parts. The first is the entrance. At some sites in the Netherlands these have weighing scales, but at each entrance there is an intake process. During the intake all visitors are checked to see whether they may indeed use the facilities of the waste disposal station. Usually a pass is scanned or the postcode of the visitor is asked. The visitors must declare their waste and they receive instructions about which containers to visit.

Then there are the substations. Each substation on its own can be seen as a network of servers. The containers of the different waste stream collected are modelled as a server with the number of parking spots available for visitors at the container(s) determining the capacity of the server. However, in reality several waste streams are usually visited from one location. In other words there is shared capacity for several waste streams.

Finally there is the exit. In some municipalities in the Netherlands public dumping is free and no weighing scales are utilized. In others there are weighing scales present in order to track the amounts of waste citizens bring. Tracking this data may be important as in some municipalities citizens are allowed to bring a certain amount (in weight) of waste for free. These municipalities need scales. Municipalities that demand payment based on the weight of waste need scales as well. As tracking waste data is also important to analyse developments in waste traffic, we decided to include a weighing process in our model.

As such, the entire system can be viewed as an open network of servers (entrance and exit) and other (sub-) networks of servers (containers). There is a platform with several containers placed next to it for collection. And apart from the platform there usually is at least one other substation where waste streams are collected. The allocation of the waste streams that are collected to the platform and other substations has been mentioned in Section 2.4 and will not be contemplated upon any further.

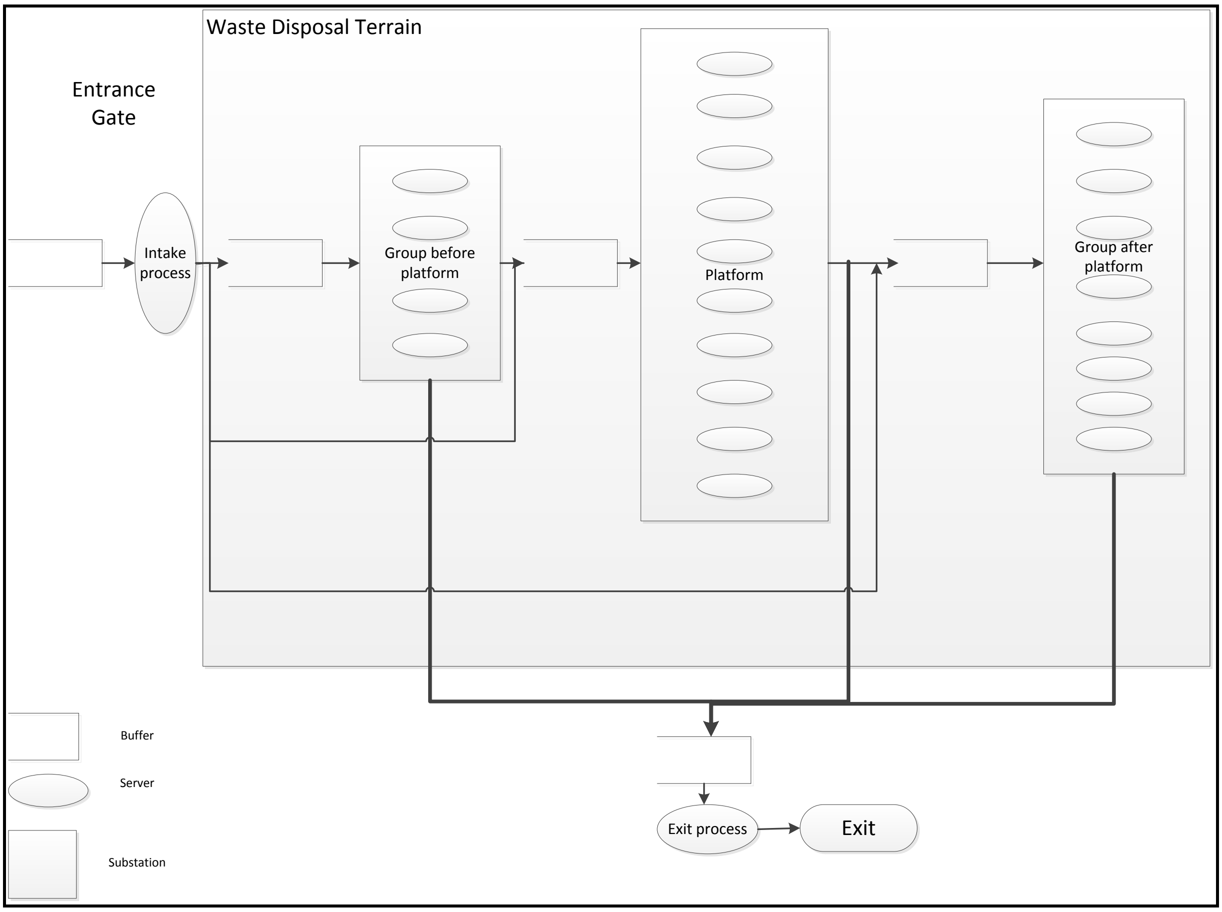

Figure 3 Schematic overview of a general design for a waste disposal station from a queueing perspective

Based on the above it makes sense to create a generic model that calculates the waiting times based on tactical decisions (sizing, capacity and allocation).

4.1.1.1 Influencing factors; variables

There are five groups of variables that are under scrutiny to analyse configurations of waste disposal stations using the general model. These are:

1. Number of gates at the entrance of the waste disposal station;
2. Number of containers per waste stream;
3. Number of parking spots per substation (or waste stream);
4. Total capacity of the site, substations and the buffer spaces (max # cars allowed in the system and at each substation);
5. Allocation of containers to a spot.

The number of containers is mostly determined based on the size of the community and considerations regarding the outbound logistics (how often do managers want a pickup of the containers). A number, determined by taking the size of the community and the average numbers into account (see Section 2.4), can be chosen for the amount of containers per waste stream. Simulation can find the best number of containers given a specific situation. Since averages give a fairly good estimate on the number of containers needed, the simulation can be limited to a range around those averages.

The number of containers has a slight influence on the number of parking spots as well as most waste disposal stations in the Netherlands are known to have space for 2 cars (without trailers) for each container.

The total capacity of the site will dictate how many cars are allowed on the terrain before the visitors will need to wait at the entrance of the site.

The allocation of the containers will influence the flow of visitors and therefore influences the waiting times in the system. Several interventions will be analysed to be able to make recommendations on this topic.

4.1.1.2 Input data

We distinguish three main groups of input data:

1. The layout of the waste disposal station;
2. Arrival rate and visitor profiles (type of vehicle, waste streams delivered, paid or free waste streams);
3. Service times at the front desk, weighing scale, the containers of the waste streams, and at the exit and their distributions.

The first part of important data input is the data concerning customers. How many customers arrive within a period of time? What types of waste do they bring? Are the waste types brought waste types for which payments are demanded? This is important as it will determine the interactions within the queuing model. Another important piece of information is the size of the vehicle the visitors arrive in as not the number of parking places but the amount of space they represent influences the number of visitors that can be present in the system at any moment. This information is obtained from data provided by two waste disposal companies in the Netherlands. The capacity of the waste disposal station and its substations limits the amount of cars that may enter the site. The service times are of paramount importance as well. Measurements have been done and the results of analysis of collected data are discussed in Section 4.3.

4.1.1.3 Model output

Three main groups of output are important for the model:

1. Average waiting times and queue length at substations;
2. Average waiting times and queue length at the entrance;
3. Total waiting time and sojourn time in the entire system.

4.1.2 Considering operational influences

As mentioned before, there are several operational decisions that are believed to have a strong impact on the waiting times as well. Some have an impact as they influence the way the design is made as well. I.e., there is a tactical decision made beforehand. The two main issues of attention are:

1. Impact of isolating certain waste streams (popular; time intensive)
2. Entrance policy in case of congestion issues:
    a. Closing gate and reopening it when the number of visitors on terrain (or platform) has dropped below a certain number;
    b. Closing the gate and allowing new visitors to enter upon the departure of another visitor;
    c. Not closing the gate.

These operational influences were chosen as they influence the physical layout of the site. Since the choice to close a gate means that a gate should be in place to facilitate this option, any decision made regarding the second issue also influences the layout of the site. Through simulation the impact of these possibilities can be assessed.

Ad1. Isolating certain waste streams

By isolating popular waste streams, through logic reasoning, one could ensure that there is ample capacity for that specific waste stream and visits to other stations are not hampered by the business of the waste containers for the popular waste streams.

Isolating time intensive waste streams would ensure that blocking cannot occur if the container for the time intensive waste stream is busy. Visitors that do not need to visit that server should be able to avoid the server, and thus not queue in front of it, to visit the servers they do need to visit.

Ad.2 Entrance policy in congestion cases

If congestion occurs on the terrain, i.e., the number of cars on the terrain has increased to the point where manoeuvring has become difficult and the traffic flow inside the system has slowed down, it seems sensible to allow for a lockdown of the system.

To allow for that action the site would need to employ some means, like an electronic gate that tracks the number of visitors on site and locks down when a certain threshold is reached. Since that is a design issue, this seems like a viable feature to research as well.

By keeping visitors in a queue in front of the gate until the site is less occupied, one could in the long run ensure that the waiting times overall are less than when the system allows visitors to keep entering even though it would increase the possibility of blockages.

4.2 Detailed Study of a Waste Disposal Station in the Netherlands

The waste disposal station studied in detail is managed by a company that partners with several municipalities to manage waste disposal sites and collect waste there, curb side and otherwise. After connection was established with aforementioned companies and certain agreements were made we were allowed to collect data at a site. Before this moment a preliminary visit was conducted at the site to thoroughly prepare the data collection moments. On this day the site was viewed thoroughly. The collected waste streams were listed and for each of them the location and capacity were recorded.

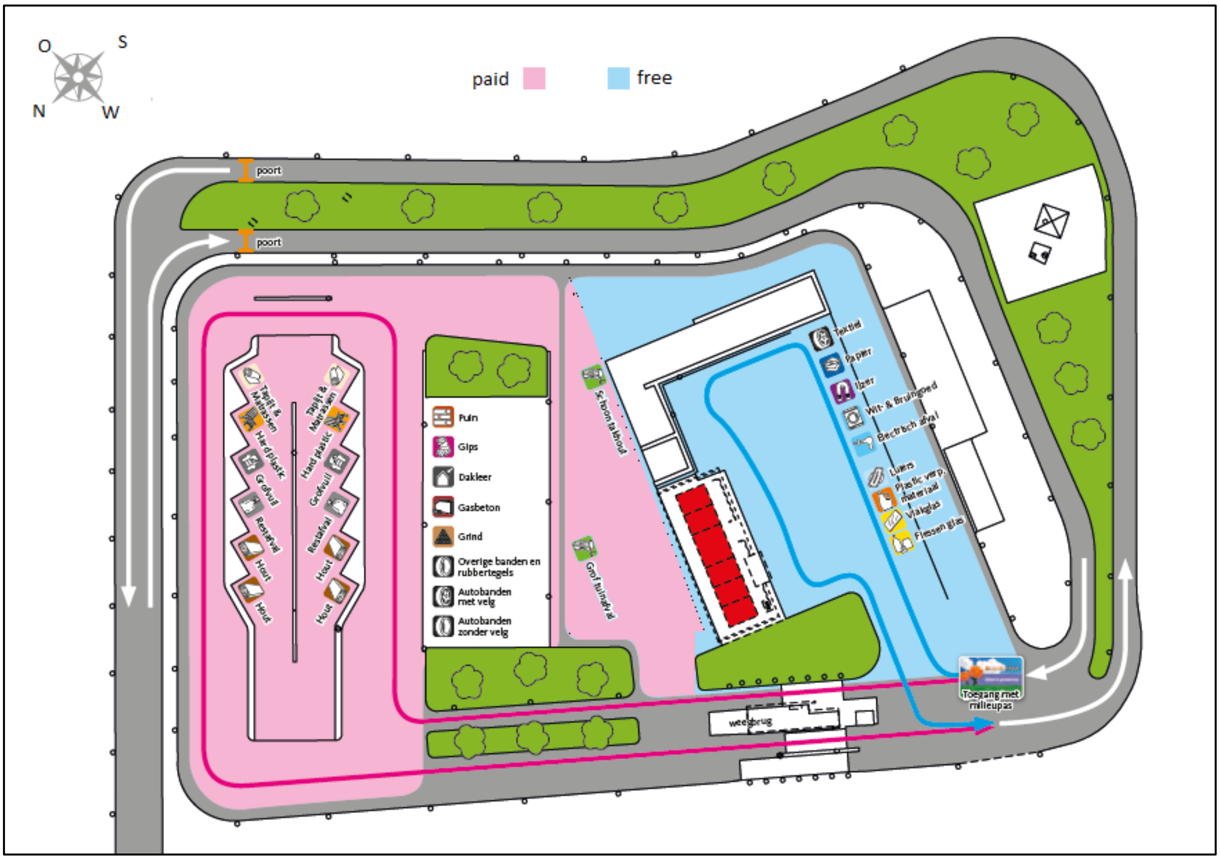

Figure 4 Detailed schematic of an existing waste disposal station in the Netherlands (2011)

In Figure 4, a representation can be seen of the waste disposal station. In the area that has been highlighted with a blue colour the so-called "free waste streams" are collected. In the pink area the "paid waste streams" are collected. This area is divided into two different sections. In one place only crude garden waste is collected whereas the other area holds all the other containers of the paid waste streams. In table 4 an overview can be seen of all the waste streams collected at the waste disposal, the area of collection and the number of containers present for collection.

Waste Stream	Area of collection	Capacity
A and B grade wood	Paid area	3 (A-1,B-2)
Asbestos	Free area	1
C grade wood	Paid area	1
Car tires	Paid area	2
Chemical waste	Free area	1
Crude home waste	Paid area	2
Crude waste	Paid area	2
Debris	Paid area	1
E-waste	Free area	1
Garden waste	Paid area	3
Gas concrete	Paid area	1
Glass bottles	Free area	2
Glass plate	Free area	1
Gravel	Paid area	1
Hard Plastic	Paid area	1
Mattresses	Paid area	1
Old metal	Free area	1
Paper and carton	Free area	2
Plaster	Paid area	1
Roofing waste	Paid area	1
Soft plastic	Free area	2
Styrofoam	Free area	1
Textile	Free area	2

Table 4 overview of all waste streams collected, the area of collection and the current capacity at the studied site

For a visitor of the site the flow through the system is as follows. He enters the site on the north side of the complex. From thereon there is a fairly large driveway (created to ensure that no congestion issues would develop on the public road) that leads to the first gate. There he needs to scan his citizenship pass, which allows him access to the dumping area. When he is past the first gate he can, based on the waste streams he has with him, visit the free and paid area in that order. If the visitor has only free waste streams with him, he proceeds to the free area located in front of the Small Chemical Depot. Afterwards he departs the waste disposal station via the same driveway on the return lane. If the visitor has only paid waste he goes to a second gate where he passes a weighing scale and needs to declare his waste. Afterwards he proceeds to the paid area where he dumps his waste in the respective containers. When he is done dumping waste, he returns to the weighing post, on a return lane, weighs out and leaves the system. Visitors that have both free and paid waste generally first visit the free area and then the paid area. Still, it does occur that visitors visit the places in random order.

4.3 Collection and Analysis of Input Data

As described in Section 4.1 the input data necessary for the model are:

1. The layout of the waste disposal station;
2. Arrival rate and visitor profiles (type of vehicle, waste streams delivered, paid or free waste streams);
3. Service times at the front desk, weighing scale, the containers of the waste streams, and at the exit and their distributions.

The layout will be determined for each client by Modulo Bèton in collaboration with the client and engineering bureaus (see previous section). The arrival rate and visitor profiles may be estimated by collecting data from a waste disposal station in operation and change them logically to suit the situation. It may be assumed that the time needed to dump waste at containers will not deviate much between waste disposal stations. The only room for deviation is due to the positioning of containers at substations where these are positioned around a central parking space as this influences walking distances. The differences that may occur when it comes to walking distances have not been taken into account in the development of the general model.

Section 4.3.1 describes the data collection methodology used for the necessary input data. Some of the data was provided by personnel from Company 1. That data was readily available in the database where they store data for measurements. These are used for their analyses and some of that data is also useful for this study. However, most of the data (lower level data) had to be collected by performing measurements. We have decided to model the busiest day of the week as the waste disposal station should be fitted to handle the busiest moment of the week throughout the year. Personnel of the waste disposal company helping us out with data assured us that the busiest day was the Saturday. Analysis of the data they provided showed us that on average the Saturday is indeed the busiest day, although the Friday had one peak for city 2 where the number of visitors was higher than the peak day of the Saturdays (see Figures 5 to 8 and appendix B for all the other graphs). These were collected on a few Saturdays in order to get data from the busiest day of the week.

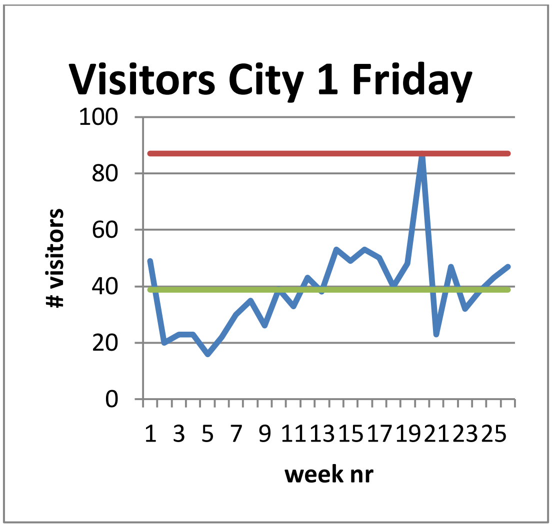

Figure 5 Visitor numbers from city 1 on Friday (blue) with maximum (red) and average (green) number

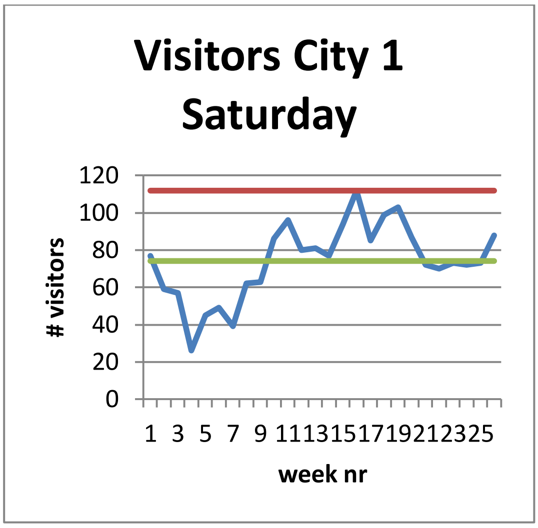

Figure 6 Visitor numbers from city 1 on Saturday (blue) with maximum (red) and average (green) number

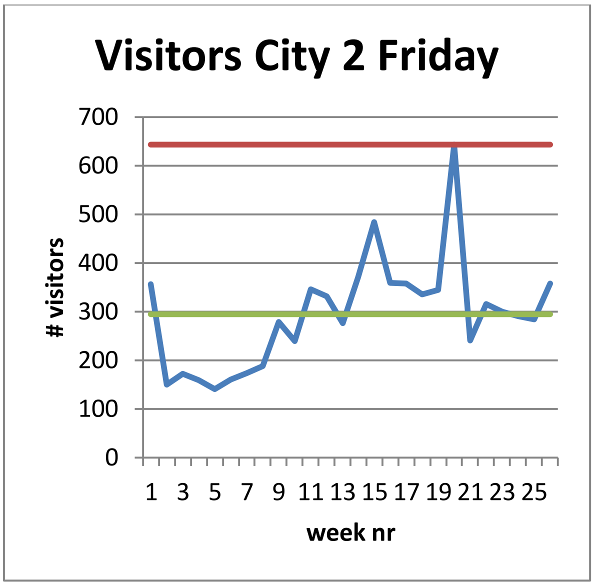

Figure 7 Visitor numbers from city 2 on Friday (blue) with maximum (red) and average (green) number

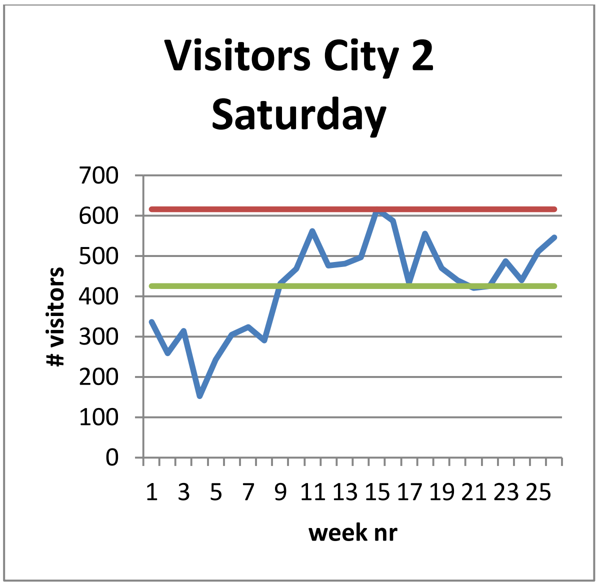

Figure 8 Visitor numbers from city 2 on Saturday (blue) with maximum (red) and average (green) number

Section 4.3.2 thoroughly describes all the analyses that have been done on the collected data in order to get parameter settings (like the arrival rates and inter arrival times, etc.) for the simulation model later. The first part focusses on the data required for the experimental design. The second part focusses more on the detailed information needed to determine the settings of the input data of the model.

4.3.1 Data collection method

The following data was collected at a waste disposal station in the Netherlands:

1. The arrival times of visitors needed to assess the arrival rate of visitors at the main entrance;
2. The service times at the main entrance and the different waste streams present on the waste disposal station.

3. The arrival times of the visitors at the weighing gate which can be used to assess the fraction of visitors that bring only waste of the paid waste streams.
4. The departure times of visitors, which can be used to estimate the sojourn time of visitors visiting only the paid area and both the paid and the free area. This data can be used later on to validate the model.
5. For all visitors whose service times were measured, the data collection team also registered whether they came in a normal car or whether they came in a large vehicle (a truck or a car with a trailer attached).

The times that were recorded, the service times at the entrance and at the various waste streams visited by visitors of the waste disposal station, were measured using one method. The time that passed between a visitor getting out of his vehicle and said visitor leaving again were recorded as the service time for the waste stream visited. It occurred, however, that visitors dumped various waste streams at the same time. For example a visitor would start dumping carton and would then switch to dumping plastic only to return to carton later on. In these cases the separate measurements of each waste stream were recorded and added together per waste stream. Another complication that arose during measurement was visitors arriving in couples (more than one person in the same car). This resulted in several dumping processes starting at the same time (parallel processing). This of course reduces the time passed before the visitors leave a spot. In these cases a data collector measured the time as best as he could by tracking some of these visitors with a stopwatch (until the measurer in question ran out of stopwatches) and others by simply counting. We realize this is not a very reliable or scientific method, but we had to measure with the limited tools that were available to us at that moment in time.

At the primary entrance there was a complication as well. Since at times blocking occurred, visitors that were present at the primary gate did not bother to scan their pass at that time as they would be unable to pass under the raised gate anyway. In these cases the measurer had to observe carefully to see when the scanning process would initiate in order to reliably measure the service time at the primary gate.

While recording data on the data collection days, some observations were made that deserve mentioning:

1. The temperature of the day seems to influence the speed at which the people dump their waste.
2. Sometimes visitors meet acquaintances and spend some time chatting. We decided not to erase observations where we observed this from the list of observations as it seemed representative.
3. The service times at the entrance and weighing scale seem to vary little. There were some outliers, but these were mostly caused by people who still had to search their citizenship pass upon arrival, or who seemed to have problems scanning their pass due to inconvenient parking.
4. At times, blocking occurs on the intersection with the primary gate and the weighing centre on opposing sides and the free dumping area and the exit on opposing sides. When visitors drove on to approach the weighing centre while there were already two visitors awaiting their turn the intersection would get blocked. Visitors from the primary gate just arriving could not get through, even if they only needed to visit the free dumping area. Visitors coming from the free paid area that were attempting to leave the site couldn’t leave either.

4.3.2 Analysis of the collected data

Extracting input data

All the data described in the previous section had to be processed in order to extract input data for the simulation model. The data can be grouped into several different categories:

1. The arrival rate of the visitors to the waste disposal station;
2. The service times of the visitors at the various locations of the waste disposal station (front desk, weighing scales and the containers of the several waste streams);
3. The visitor information.

4.3.2.1 Arrival rate

To determine the arrival rate and the inter-arrival-times, the data received from the waste disposal company has been used. As it contained the arrival times of visitors at the front desk it was quite easy to determine the arrival rates and inter-arrival times per hour block (in order to assess the arrival details for the different hour blocks). We decided to divide the opening hours of the waste disposal station into several blocks as the operators of the waste disposal station mentioned that the business clearly varied throughout the day.

Since all our data measurement sessions were in the months May and June and we model only the busiest day (being the Saturday), only Saturdays from the months in May and June were selected to determine the arrival rate. Table 5 shows the number of visitors that visited the waste disposal station in 2014 on the Saturdays of May and June.

	Arrival rates / hour (in case of hour 7 half an hour)									
operation hour	**May 3rd**	**May 10th**	**May 17th**	**May 24th**	**May 31st**	**June 7th**	**June 14th**	**June 21st**	**June 28th**	**Avg**
1	104	23	109	121	122	124	80	98	113	100
2	124	67	108	121	126	136	120	122	113	116
3	127	101	145	131	137	118	122	114	143	127
4	147	88	121	131	121	112	106	100	117	116
5	111	87	138	137	125	91	113	136	107	117
6	139	79	128	109	108	95	123	120	131	115
7	96	26	72	84	60	50	74	80	96	71

Table 5 Arrival rates per hour for all Saturdays in May and June 2014

After subtracting subsequent visits from each other, the inter-arrival times were analysed. Histograms of the time blocks all showed the same shape suggesting that the distribution of the inter-arrival times is the same for all the time blocks (see figures 9 and 10 for the inter-arrival times of time blocks one and three; appendix C contains all the histograms). Fitting tests were performed for the exponential distribution and the Gamma distributions (the histograms indicated this distribution might be a good fit) after estimating their parameters. The procedure used was to test if an exponential distribution properly fits the inter-arrival times. If this proved inconclusive, an attempt was made to fit a Gamma distribution (as the exponential distribution is merely a special case of the Gamma distribution (Larsen & Marx, 2012)). If the shape looked more like that of a Gamma distribution, then that distribution was tested immediately. The Chi-square test at 95 percent confidence level showed that these distributions were not a good fit (hour 1: 472.25 >> 18.31; hour 3: 6509.41 >> 18.31). However, there are strong arguments for using an exponential distribution nonetheless:

1. First of all is the consideration that subsequent arrivals of visitors are in real life independent from each other. This means that often enough a Poisson distribution can be used to model the arrivals. In the data used for determining the arrival characteristics subsequent visits are dependent as the data represents the moments visitors scan their pass at the entrance. And since this means that visitors often enough wait, until the visitors in front of them have scanned their pass and entered the waste disposal station, before they can enter the waste disposal station, their arrival is influenced by the visitors before them. This is simultaneously also the main reason for the Chi square test to fail as the inter-arrival times approaching zero seconds will never occur as if these occur in real life the registered data will always show a delay for reasons explained above. Using an exponential distribution would bring independence back again.
2. Upon generating a QQ-plot (see Figures 11 and 12 for the QQ plots of the inter-arrival times of hours one and three) of the data one could observe that, save for a few outlying observations the data follows a trend line with a slope of 45 degrees. This signifies that the theoretical distribution is a good fit for the empirical data.

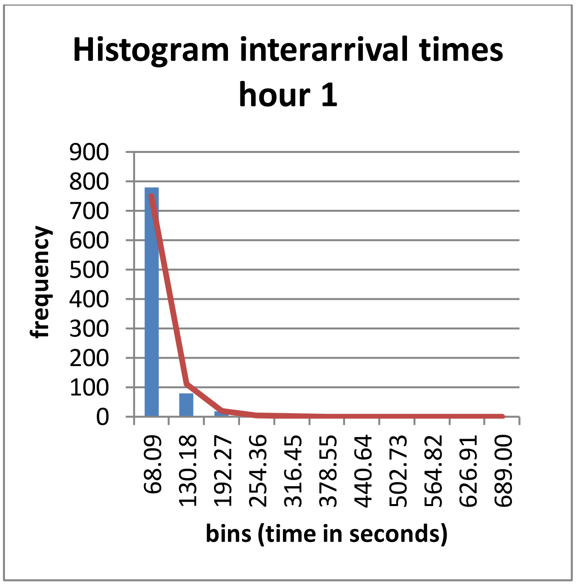

Figure 9 Fitting a distribution on inter-arrival time hour 1

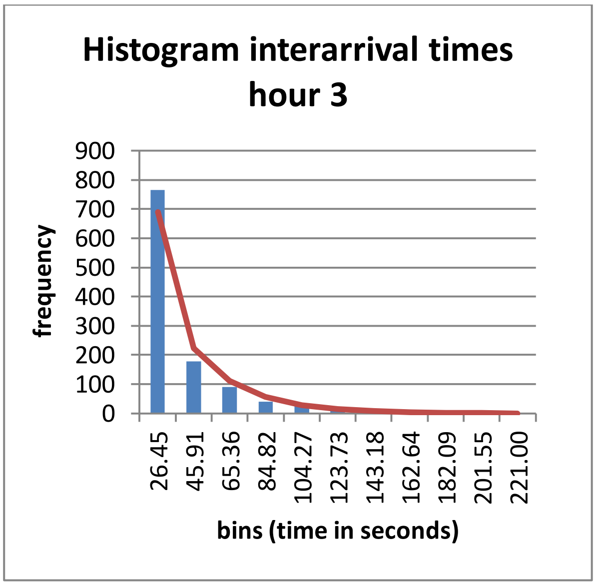

Figure 10 Fitting a distribution on inter-arrival time hour 3

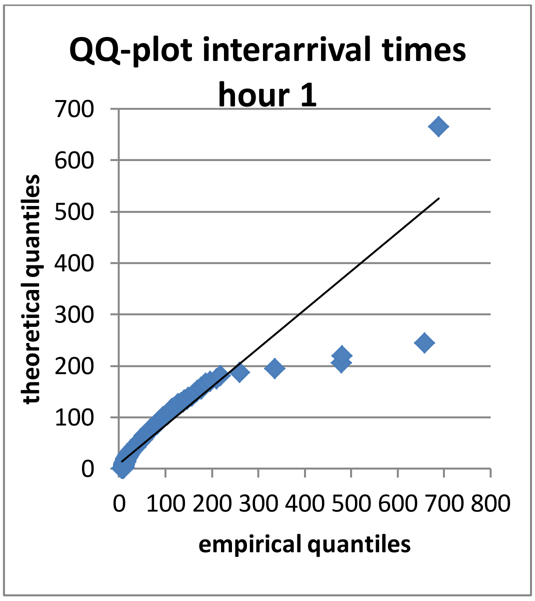

Figure 11 Quantiles plot of the first hour

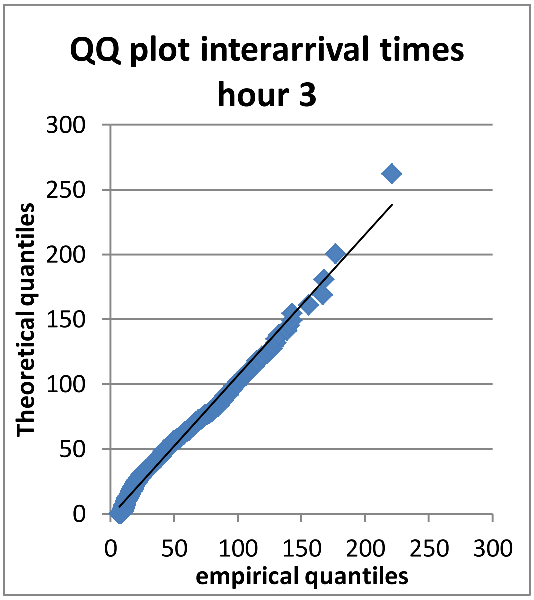

Figure 12 Quantiles plot of the third hour

4.3.2.2 Service times

The service times and their distributions were determined after analysing the measured data from the waste disposal station we studied. The first set of service times under scrutiny were the service times at the front desk and the weighing scale.

Once again the histograms (see figures 13 and 14) showed service times that were similarly distributed (when it comes to shape). Both the exponential and Gamma distributions were tested using a Chi-square test at 95 percent confidence level. Both were in both cases not significant (entrance: exponential (0.1011) $\chi^2 = 317.74$, gamma (0.8471, 0.0857) $\chi^2 = 193.18$; Weighing: exponential (0.0768) $\chi^2 = 434.34$, gamma (1.8679, 0.1435) $\chi^2 = 465$; $\chi^2_{0.95,\,9} = 15.51$). This means that we had to resort to using an empirical distribution for the service times of the entrance and the weighing process.

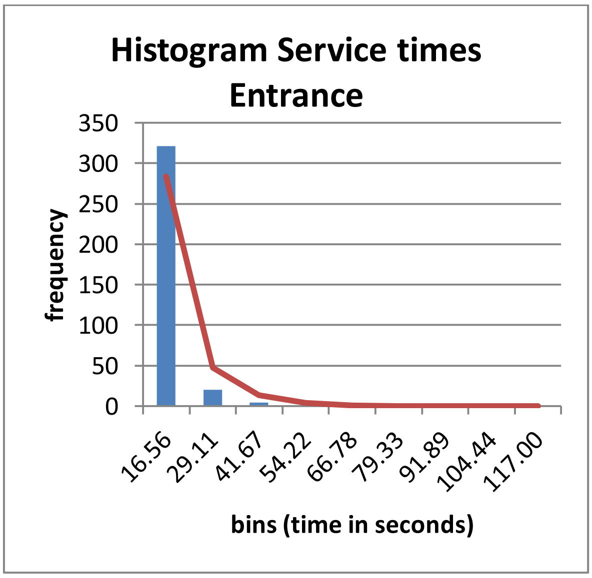

Figure 13 Fitting a distribution for the service time at the entrance

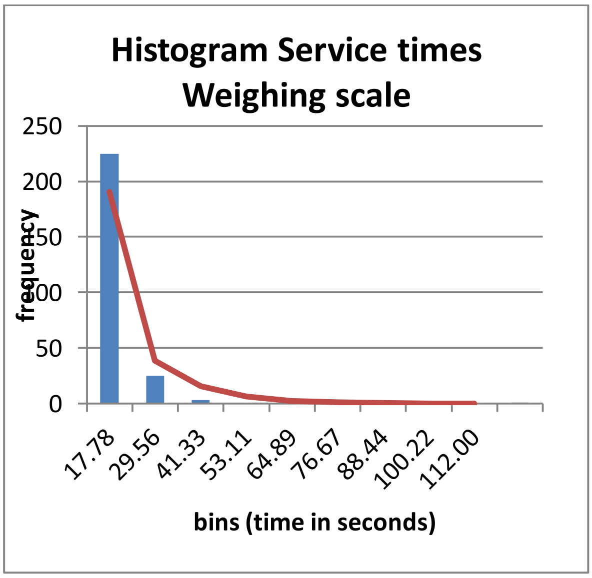

Figure 14 Fitting a distribution for the service time at the weighing scale

Mostly the same method described in Section 4.3.2.1 was used to fit distributions to the waste streams; with a few additions. First of all we decided to do make histograms using both Sturges' rule (# bins = Ceil($\log_2$(# observations)+1)) and the square root rule (# bins = Ceil(sqrt(# observations))) to determine the amount of bins. The bin rule that provided the most recognizable shape was eventually used to do the fitting test. For some waste streams we did not have many observations and these gave us a hard time deciding upon a suitable distribution. In the end we decided to base their distribution on those of other waste streams displaying a similar shape in histogram and a mean service time and variance in service time, or those that seemed to be very similar waste streams based on their nature, or both. For an initial analysis (number of observations, mean, minimum, maximum and variance) of the waste streams see Table 6 for the result of data collected at the wste disposal station. Some of the distributions can be observed in Figures 15 to18 . The remainder of the distributions can be seen in Appendix D.

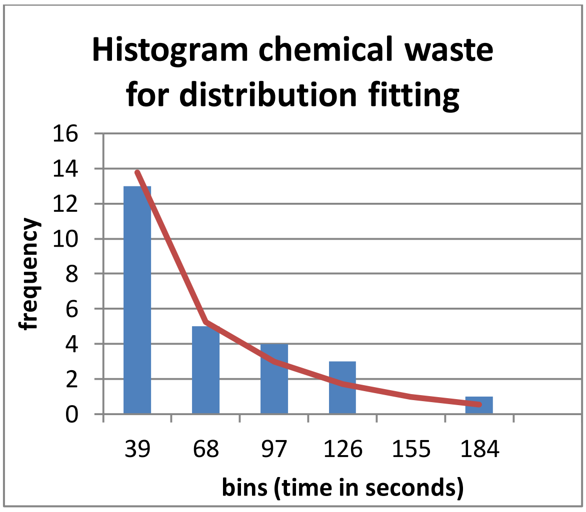

Figure 15 Fitting a distribution for the service time of chemical waste

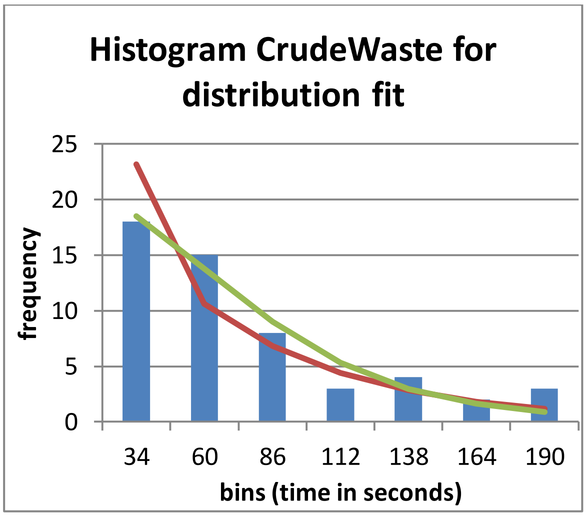

Figure 16 Fitting a distribution for service time Crude Waste; exponential (red) and gamma (green) distributions

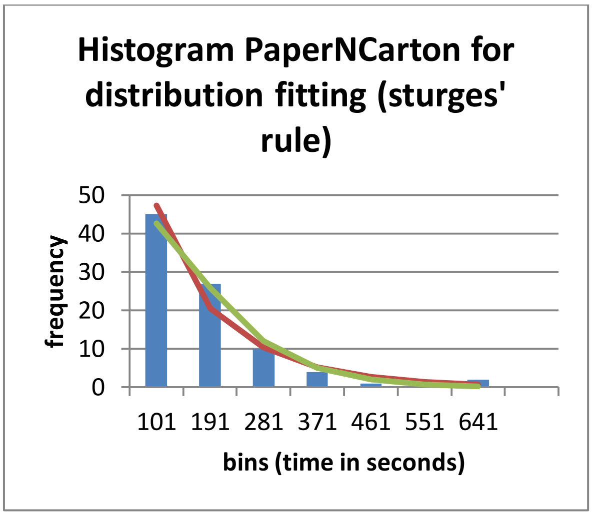

Figure 17 Fitting a distribution for service time Paper and Carton; exponential (red) and gamma (green) distributions

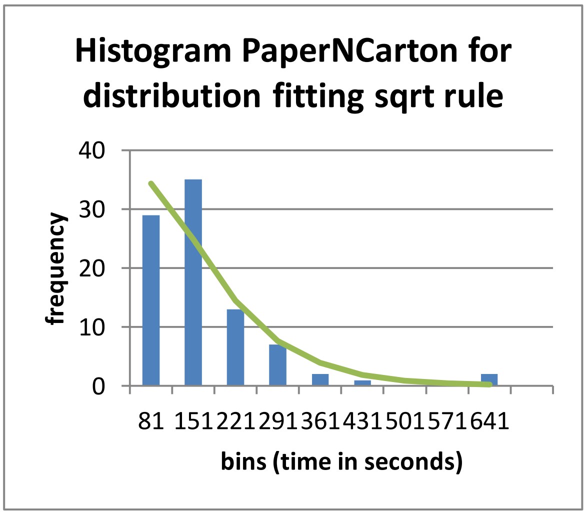

Figure 18 Fitting a distribution for service time Crude Waste; gamma (green) distribution

	Chemical waste	Glass plates	Glass Bottles	Asbestos	Paper	Soft Plastic
Count	26	6	24	0	89	72
Probability	0.082	0.019	0.076	0.000	0.282	0.228
Mean (sec)	52	77	91	0	133	91
Min (sec)	10	30	25	0	11	19
Max (sec)	180	160	210	0	640	458
Var (sec^2)	1504.81	2715.37	2248.80	NA	11586.61	5756.58
	Old metal	**E-Waste**	**Textile**	**Styrofoam**	**Crude Garden Waste**	**Plaster**
Count	42	33	17	16	79	4
Probability	0.133	0.104	0.054	0.051	0.250	0.013
Mean (sec)	103	96	101	84	257	255
Min (sec)	10	5	26	19	25	28
Max (sec)	496	590	425	194	1142	676
Var (sec^2)	14209.69	12108.22	10023.68	2214.87	39327.08	90149.67
	CarTires (with and without rim)	**Roofing waste**	**Gravel**	**Gas concrete**	**Debris**	**A and B grade wood**
Count	3	4	0	4	22	72
Probability	0.009	0.013	0.000	0.013	0.070	0.228
Mean (sec)	43	170	0	211	118	140
Min (sec)	30	106	0	58	10	10
Max (sec)	58	270	0	636	537	687
Var (sec^2)	197.3333	4945	NA	80391.58	14781.79	15139.06
	C grade wood	**Hard Plastics**	**Crude home waste**	**Crude waste**	**Mattresses**	
Count	8	30	84	53	23	
Probability	0.025	0.095	0.266	0.168	0.073	
Mean (sec)	181	97	91	59	89	
Min (sec)	25	10	3	8	21	
Max (sec)	578	300	360	189	393	
Var (sec^2)	40874.29	6590.976	4552.301	2133.525	9713.905	

Table 6 Basic statistical summary on service times of the waste streams

Small Chemical Waste

For Small Chemical Waste the histogram seemed to resemble the shape of an exponential distribution (See figure 15). After performing a Chi-square test with 95 % confidence we could accept the fact that indeed the data was exponentially distributed. The test value, equaling 6.77 was significantly lower than the critical value of 11.07. Therefore we may use an exponential distribution with lambda equal to one divided by the mean ($1/\mu = 0.0194$). All other waste streams were tested in this way to determine the distributions.

Glass plate

Since we did not have enough observations for this waste stream (only 6) we have decided to base its distribution on that for glass bottles.

Glass bottles

The histogram for glass bottles (using the square root rule) hinted at a Gamma distribution. Using the Chi square test (once again at 95% confidence level) we have ascertained this. We fitted a Gamma distribution with $\alpha = 3.86$ and $\beta = 0.04$.

Asbestos

For Asbestos we did not have enough observations (sadly enough zero). So we based its distribution and shape on that for chemical waste. In other words we will use an exponential distribution with lambda 0.0194.

Paper and Carton

The tests for paper and carton turned out to fail for both the exponential and the gamma distribution. So for this waste stream we decided to use an empirical distribution.

Soft Plastics

For soft plastics the tests failed as well and we will therefore use an empirical distribution for soft plastics as well.

Old Metal

Old metal was a significant fit for the exponential distribution with lambda equaling 0.0097.

E-Waste

E-waste was a significant fit for the exponential distribution with lambda equaling 0.0104.

Textile

Textile did not have that many observations (seventeen), but since the shape of its histogram quite clearly resembles that of old metal we have decided to use the exponential distribution again, but with lambda equal to 0.0099.

Styrofoam

Styrofoam did not have enough observations (sixteen) but its shape was similar to that of Glass Bottles. So we have decided to once again use the exponential distribution with lambda equal to 0.0119.

Crude Garden Waste

The service times for garden waste fitted significantly with an exponentially distribution with lambda 0.0038.

Plaster

For Plaster we did not have enough observations (only four) but based on the mean variance and the nature of plaster waste we decided to base the distribution on that of A and B grade wood. This means that an exponential distribution will be used with an estimated lambda of 0.0039.

Cartires

For car tires the number of observations was also lacking. In this particular case it was difficult to find a waste stream with a similar nature or mean and variance. In the end we have decided to use an exponential distribution with lambda equal to one divided by the mean service time which turned out to be 0.0231.

Roofing waste

For roofing waste (only four observations) we decided to base the distribution on that of crude garden waste for the following reason. First of all in both cases if a visitor brings waste of that type he brings a lot. The mean and variance may not be in accordance, but we assume that this fact can be attributed to the fact that there are so few observations. The result is a selection of the exponential distribution with a lambda of 0.0059.

Gravel

For gravel we once again have zero observations. Based on its nature though we have assumed that the service time for dumping gravel is similar to debris. This ultimately means that we use the exponential distribution with the same lambda 0.0085.

Gas Concrete

For gas concrete we have four observations. Based on its nature (similar to debris), we have decided upon using an exponential distribution with lambda equal to 0.0047.

Debris

For debris we have significantly fitted the exponential distribution with lambda equal to 0.0085.

A and B grade wood

The data for the service time of A and B grade wood turned out to be exponentially distributed as well. The estimated lambda was 0.0073.

C grade wood

For C grade wood we did not have enough observations, but given the nature of the waste type and its mean and variance we have to base its distribution on that of A and B grade wood. The lambda is equal to 0.0055.

Hard plastics

Hard plastic turned out to be exponentially distributed as well. The lambda estimated is 0.0103.

Crude home waste

Using the number of bins determined by the square root rule we have fitted a Gamma distribution to the service times for crude home waste. The estimated value for the shape parameter, α, is 1.8473 and the value of the scale parameter, β, is 0.0203.

Crude waste

For crude waste we have fitted a Gamma distribution, with α equal to 1.6757 and β equal to 0.0283.

Mattresses

For mattresses we have fit a Gamma distribution as well, with an α equal to 0.8567 and β equal to 0.0096.

4.3.2.3 Visitor information

There are several pieces of information about the visitors that have an impact on the model described in Section 4.1.

The fraction of visitors arriving in a small vehicle (a personal car) versus the fraction of those arriving in a larger vehicle (minivan or car with trailer) was determined by keeping count on the same day we measured the service times for the several waste streams. Table 7 shows the number of observations for both cases. This fraction is relevant as there is space for two normal cars, but only one large car in front of each container.

Vehicle type	frequency
normal	362
large	119

Table 7 Visiting ratio of normal and large vehicles

Another set of fractions we are interested in consists of the fractions of visitors bringing only free waste, only paid waste (for some waste streams people pay a weight fee) and both types. These fractions were calculated from data provided by the waste disposal company. The number of people registered at the front gate is the total number of visitors. The visitors that are only registered at the front gate are those that only visited the free waste streams. The visitors that are registered at the front gate and the weighing scale with less than two minutes in between are considered to have only visited the paid waste streams. The rest obviously is considered to have visited both waste streams. This two minute margin was chosen due to a measurement we have done at the waste disposal station. By analysing the sojourn times at the free side of the waste disposal station we quickly saw that with a mode of 180 seconds most observations were bound to lie above the two minute margin. After further analysis we observed that 8.66 percent of all cases spent two minutes between the front gate and the weighing centre. The percentage of visitors that visited the paid and free waste streams and spent less than two minutes at the free area was 69.78 percent of these cases (so only 6.06 percent of all cases visited both the paid and the free area whilst spending less than two minutes at the free area). Using the rules as stated above the fractions were determined (see Table 8).

	Frequencies	fraction
paid	3179	0.48773
free	1663	0.25514
both	1676	0.25713
total	5132	1

Table 8 Ratios of paid-, free- and both waste bringing visitors

Also important for our model is the amount of different waste streams the visitors bring. After measuring the service times of visitors at the waste disposal stations for two whole Saturdays, we could count for each waste stream how many visitors visited a container of that waste stream. In other words we could observe how many of the visitors had brought a certain number of different waste streams (see Table 9).

# waste streams	*Frequency*	*Probability*
1	147	0.465
2	66	0.209
3	46	0.146
4	26	0.082
5	13	0.041
6	9	0.028
7	5	0.016
8	1	0.003
9	2	0.006
10	1	0.003

Table 9 Frequency of number of different waste streams brought by visitors

Having measured the service times mentioned earlier we are also able to count how many visitors brought a certain waste stream. Using these numbers we can estimate the probability of a waste stream being brought by a visitor. These can be observed in Table 10.

Waste Stream	Frequency	Probability
A and B grade wood	72	0.1013
Asbestos	0[2]	0.0000
C grade wood	8	0.0113
Car tires	3	0.0042
Chemical waste	26	0.0366
Crude home waste	84	0.1181
Crude waste	53	0.0745
Debris	22	0.0309
E-waste	33	0.0464
Garden waste	79	0.1111
Gas concrete	4	0.0056
Glass bottles	24	0.0338
Glass plate	6	0.0084
Gravel	0	0.0000
Hard Plastic	30	0.0422
Mattresses	23	0.0323
Old metal	42	0.0591
Paper and carton	89	0.1252
Plaster	4	0.0056
Roofing waste	4	0.0056
Soft plastic	72	0.1013
Styrofoam	16	0.0225
Textile	17	0.0239

Table 10 Probability of a waste stream being brought by a visitor

After analysing both the frequencies of occurrence of the different waste streams and the service times we thought that there might be a relation between the number of waste streams brought and the time spent dumping those waste streams. It seemed logical that someone who brought only one or two different waste streams brought more of those specific waste streams. Consequentially he would spend more time dumping said waste streams than someone who brought seven to eight different waste streams. Since the space in the car is limited one can reason that if the same space has to be shared by more waste streams then one should bring less of those waste streams to make it fit. In order to study this relationship we analysed the correlation of the number of waste streams brought by visitors and the dump time of those waste streams. We could not discern a correlation of any kind (see Figures 19 to 22 for a scatterplot of soft plastic, crude garden waste, A and B grade wood and crude

[2] We decided to give the waste streams with zero observations (asbestos and gravel) a frequency of 0.1/day. This means that on average ten days could pass until a visitor comes by with said waste stream. If we assume that arrivals are exponentially distributed the probability of observing a visitor with either asbestos or gravel would be 25.92 percent. If we take the fact into account that we were unable to monitor every visitor coming to the waste disposal station we think this is a suitable solution.

home waste; the rest can be observed in Appendix E). Therefore we assume that the number of waste streams brought and the service times are independent.

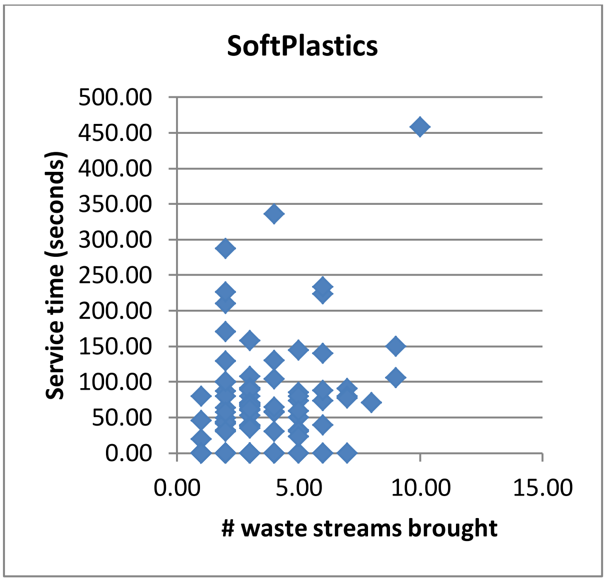

Figure 19 Correlation # waste streams brought and service time of soft plastic

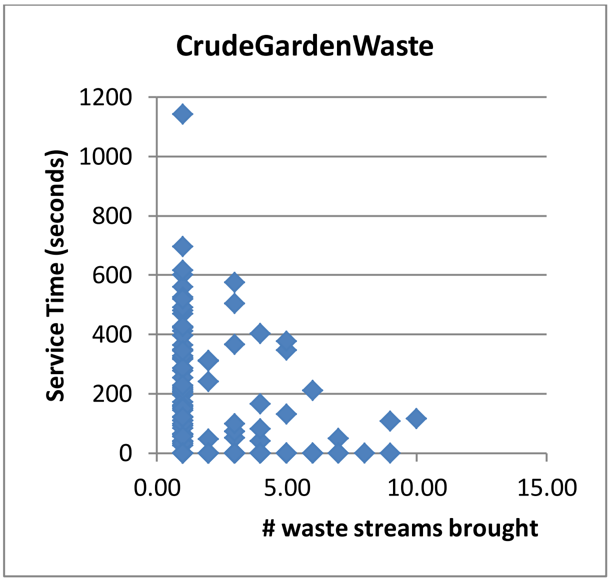

Figure 20 Correlation # waste streams brought and service time of Crude Garden Waste

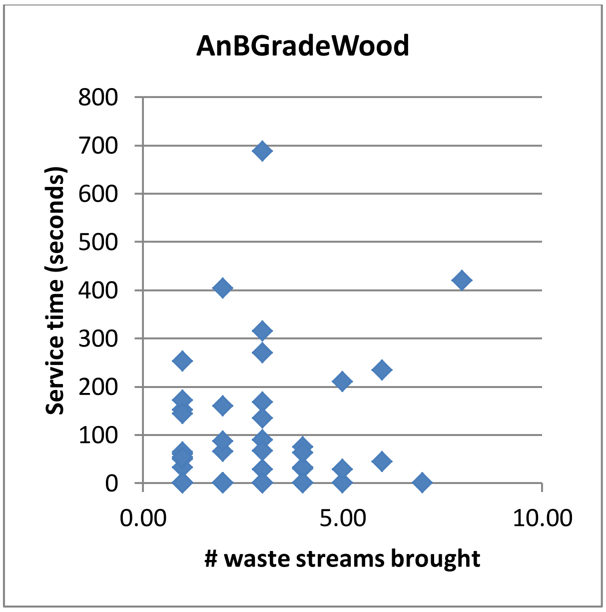

Figure 21 Correlation # waste streams brought and service time of A and B Grade Wood

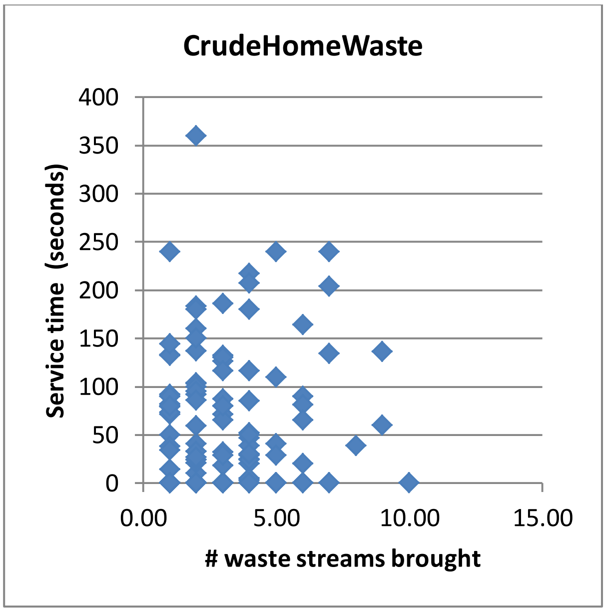

Figure 22 Correlation # waste streams brought and service time of Crude Home Waste

4.4 Content of the Conceptual model

In Section 4.1 a start was made with a conceptual model of a waste disposal station. It described the necessary input (variables and data) to generate the desired output. The waste disposal station was described in terms of queuing theory. This model, however, lacks the detail needed in order to assess the model's validity and credibility. The validity is determined by the modeller's views on the model's potential to lead to a sound simulation model that is accurate enough for its intended purpose. The model's credibility though is determined by the client's perspective. If he is convinced that the model will lead to an accurate enough computer model for its purpose, then the credibility is high. It is difficult to assess whether the model will lead to a computer model which is accurate enough to meet the model's objectives. Therefore this section focusses on the thorough description of the waste disposal station through the content of the conceptual model.

Section 4.4.1 describes the several parts of the generic model in greater detail. It contains a description of the several processes that take place at different parts of the waste disposal station. For that purpose, the flow of a visitor through the waste disposal station is described using logic flow diagrams. Section 4.4.2 describes the different servers that the model contains. Special attention is given to service times and the distributions thereof. Section 4.4.3 encompasses a description of the visitor profiles. Among other information the vehicle type and waste brought by visitors are provided through characteristics of the visitors. The arrival rate of the visitors is also briefly discussed. Section 4.4.4 contains a full list of all the assumptions and simplifications made and the rationale behind each of them.

4.4.1 The process flow in the conceptual model

Looking back at the generic model created in Section 4.3, there are 2 levels of the model. There is the level of the entrance and exit servers and the substations. And then there is the level within the substations. We will first follow the process of a visitor on the highest level and will go into greater detail within the substations thereafter.

4.4.1.1 The waste disposal at highest level; the process flow

Upon arriving at the waste disposal station, a visitor first enters a queue at the entrance of the station. As soon as there are no visitors before him, he can enter the intake process at the entrance. As described earlier in Chapter 4, visitors are weighed on a scale at the entrance and they declare the waste they have brought so the caretaker at the entrance can give directions on where to go to dump the waste the visitor brought with him. If the site is split in an area where certain waste streams may be dumped for free and an area where one must pay to dump then the weighing occurs at a so-called weighing centre then the weighing occurs separately from the intake process.

Once the visitors are done at the gate, they can join the queue at the first substation they need to visit and if the substation is not busy (there is space available for the visitor) the visitor can drive on to the area where the first waste stream he needs to visit is located. Once the visitor is done at that substation, he can visit the subsequent substations he needs to visit. When the visitor has brought all the waste to the designated containers, he may proceed to the queue for the exit.

At the exit, the process may depend on whether the municipality incorporates payments, however, we model the basic scenario where there is a weighing process for tracking data about the waste streams collected for future planning. This means that after a weighing on a scale, the visitors may exit the waste disposal station.

This entire process can be observed in a flow diagram in Figure 23.

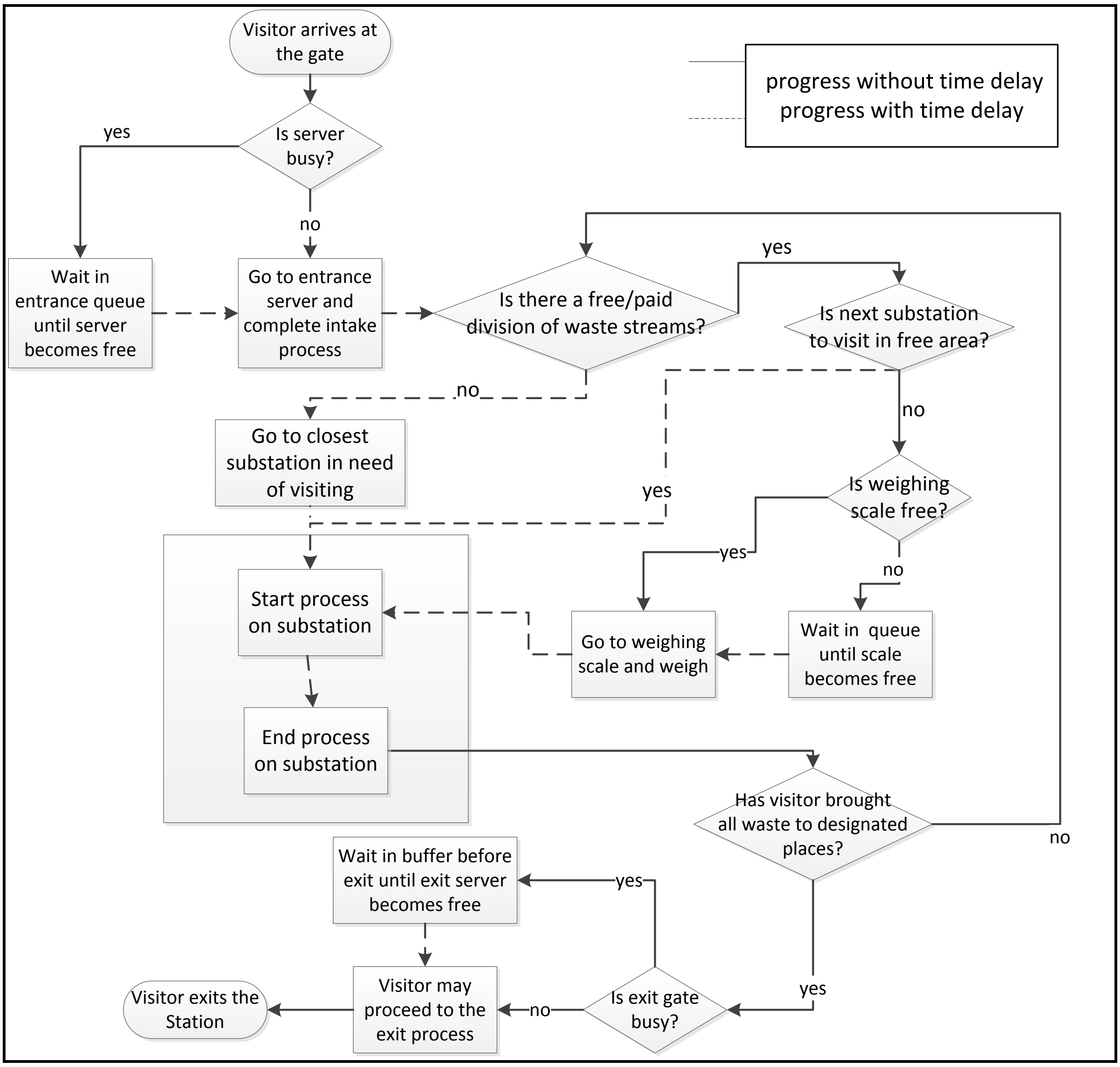

Figure 23 Visitor process at a waste disposal station on a higher level

4.4.1.2 Process flow at a substation

At every substation the process is basically the same. Figure 24 gives a graphical of the process. Once a visitor observes that there is enough space at the substation he wishes to visit, he drives to the first parking space available that is nearest to the first waste stream he brought with him. A limit is used to designate the distance visitors are willing or even allowed to cross from their parking spot to the containers of choice. If there is no spot available then the visitor waits until there is a spot available. Once a visitor is done at a container he may visit the next container. For simplicity we assume that the visitor does not drive back. Driving is not necessary as long as the container to visit is within a certain radius of his car. This means that a visitor may park, dump waste at several locations near his car and then drive off to the next spot near a container he needs to visit but had not visited yet. Once a visitor is done at the substation, he may drive on to the next or to the exit if he has dumped all the waste he came to bring to the waste disposal station.

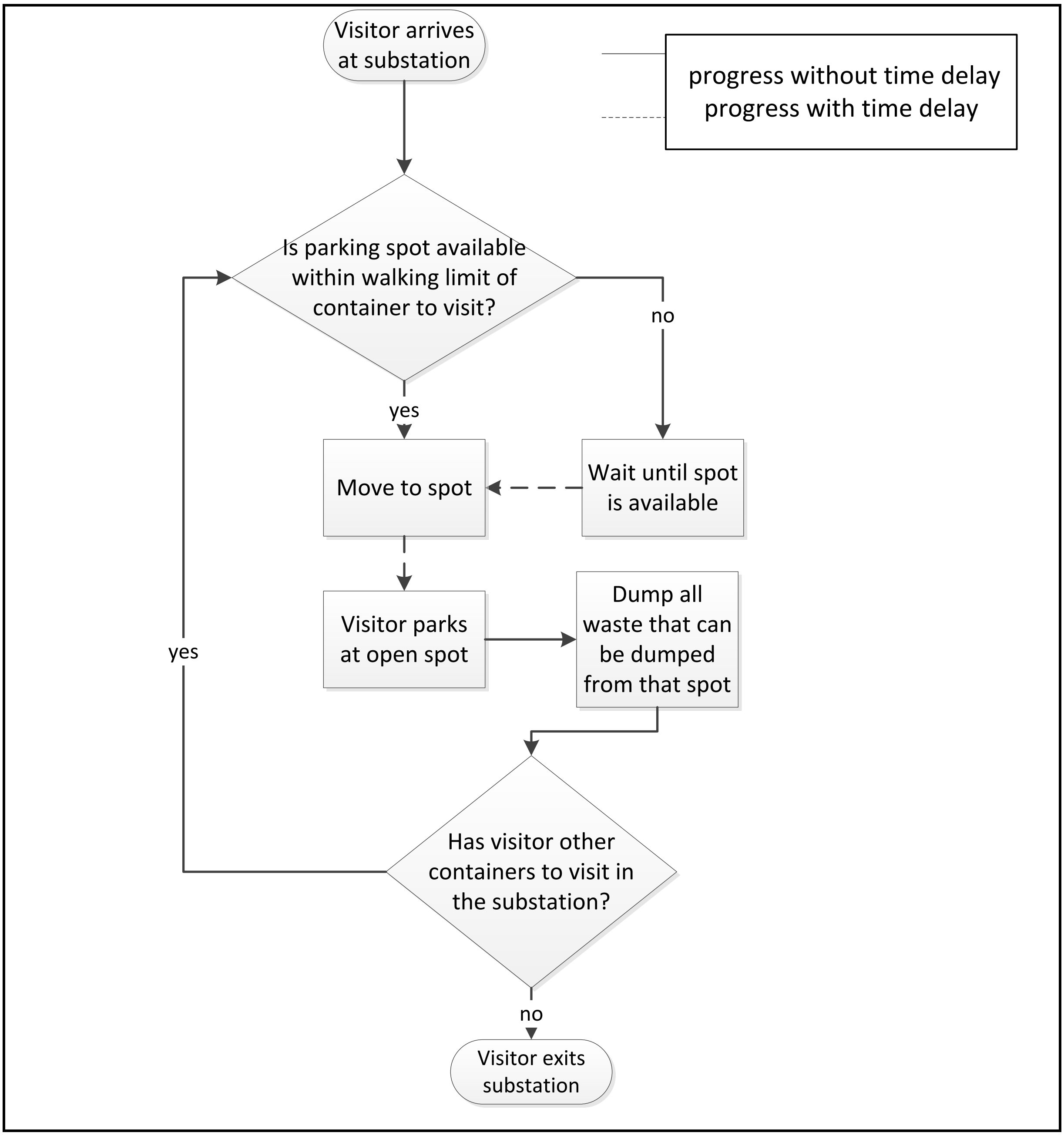

Figure 24 Visitor process at substation

4.4.1.3 What happens on a lower level of detail?

At each of the servers (entrance, substations and exit) there are processes going on at a lower level that are important to clarify in order to model them correctly. These are so-called logic flows. To start, an overview is given of the process at the entrance of the waste disposal station. Figure 25 gives a clear overview of the actions performed sequentially before the visitor actually enters the waste disposal station and moves on including the data registration moments needed to calculate the performance measures later on.

Upon arrival at the entrance, the arrival time at the site is registered and if the visitor is next in line for processing then he proceeds to the front desk. Otherwise he will have to join the queue at the entrance. At the entrance the arrival time at the front desk is recorded. Afterwards the visitor's waste content is determined and in our programmed model this is also a convenient moment to assign processing times (these are drawn from the determined distribution functions) for each waste stream the visitor brought. After this process is finished the visitor prepares to leave the front desk. At that moment his next destination on the waste disposal station is determined. Simultaneously his departure time at the front desk is recorded to calculate the sojourn time and waiting time at the front desk and the waste content of the visitor is updated. Depending on whether there is space on the waste disposal station (no blocked entrance) and the substation that is the visitor's next destination, the visitor will have to wait at the front desk or is allowed to move on to the next destination.

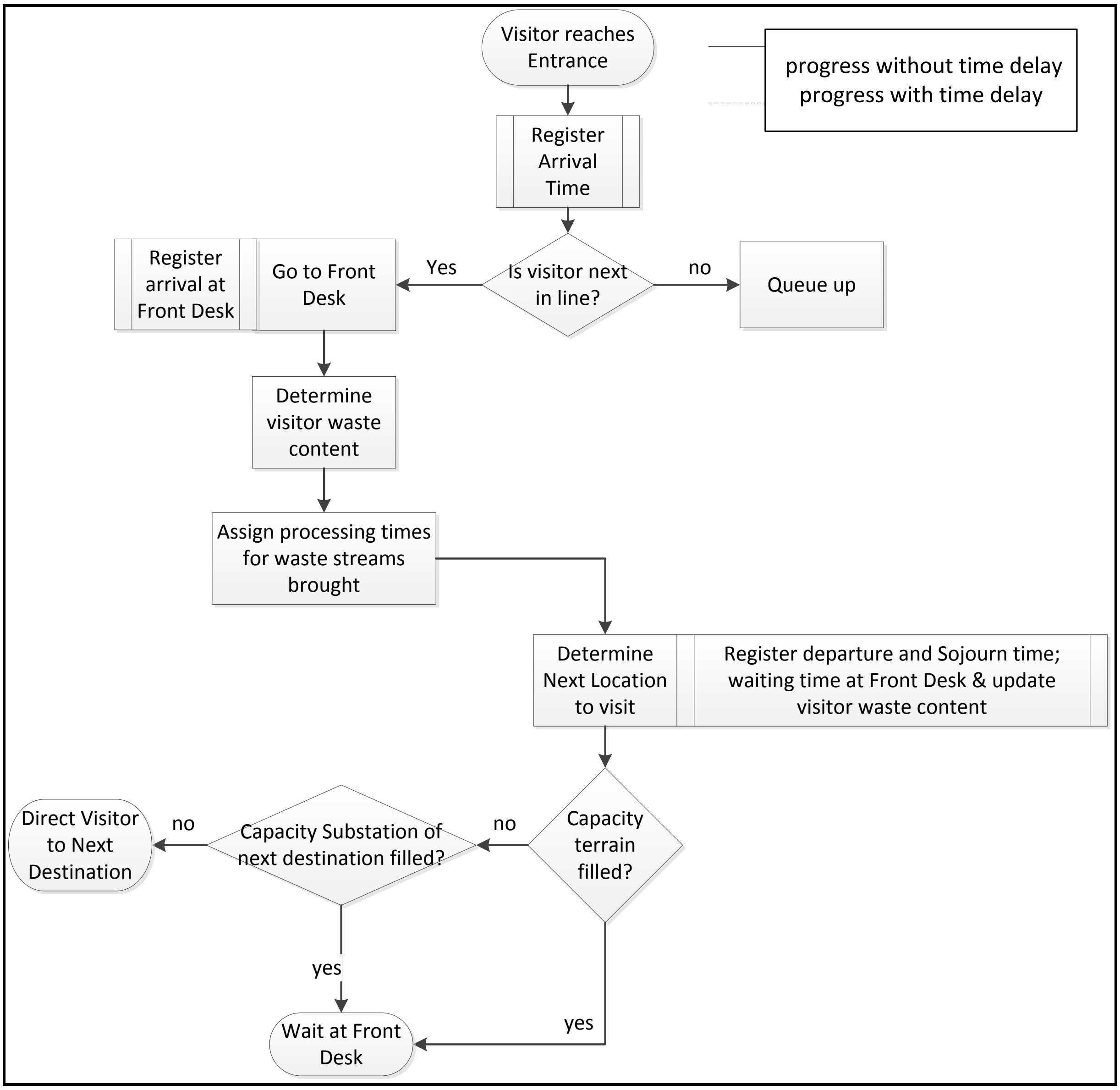

Figure 25 Logic flow of the process a visitor upon arrival at the entrance

What happens at these substations is described below. At every waste disposal station there can be two types of substations. The first is like the free area at the waste disposal station we collected our data at. There is a central parking area from where the visitors can dump waste in all the containers dedicated to the waste streams located there. This may happen in any random order. This substation is usually located at the location of the small chemical depot of the waste disposal station. That is why we have called this flow process as that of the small chemical depot. This process can be observed in

Figure 26. Upon arrival, the arrival time is registered and the availability of the small chemical depot is updated. If there is a free parking spot the visitor can park there, if not the visitor will have to wait in a buffer space (usually the driveway). Upon arrival at a parking spot the staying (processing) time in that spot is calculated by adding the processing times of all the waste streams he brought that are located at the small chemical depot area. Once this time is known, the departure is scheduled. When the visitor prepares to leave the small chemical depot area, the next destination to visit is determined. Just like at the departure at the front desk the departure time is registered, the sojourn time and waiting time are calculated and the waste content is updated. If there is space available at the next destination the visitor is allowed to move on, if not he will have to wait at his current location.

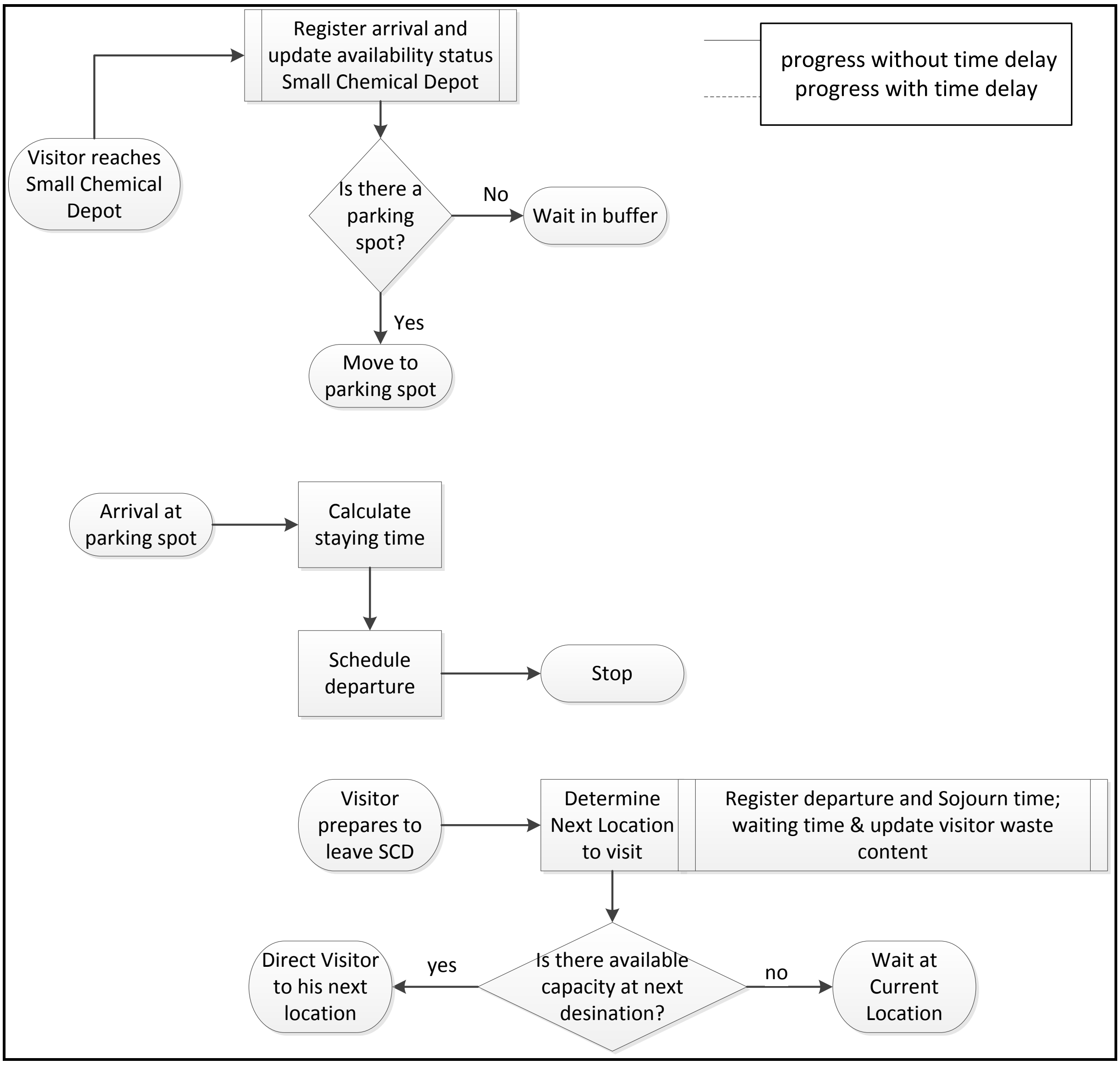

Figure 26 Logic flow of process upon visitor arrival at Small chemical depot, a parking spot there and upon departure

The other substations are of a different type. They are more like the classical platform design of the Modulo Bèton system. There is a fixed number of containers and at each of these containers there is parking space for two cars or for one big vehicle (a truck or a car with a trailer). The process at these type of substations is different (see Figure 27). Upon arrival the visitor checks whether there is a free parking spot close enough to the container of the waste stream he has to dump waste at. If there is no space available the visitor waits at the buffer. If there is space available the visitor moves to that spot and the arrival time is registered. The staying (processing) time is calculated and the departure time is determined. When the visitor prepares to leave the parking spot the same processes take place as at the small chemical depot and the front desk. However, one process is added. Upon the departure of a visitor from a parking spot at one of these substations capacity is freed for other visitors that had been waiting for processing and as the visitors are handled on a first come first served basis this departure event triggers a backward search. The other containers and the buffer of the respective substation are checked first. Then previous substations are checked and finally the front desk is checked. From these visitors the first one whose arrival at the front desk was registered is sent through. Other visitors that are blocked but who arrived later at the waste disposal station are moved on to the buffer space of the respective substation if there is space available. In other words the blocked visitors are sent through according to the “First Come First Served” principle.

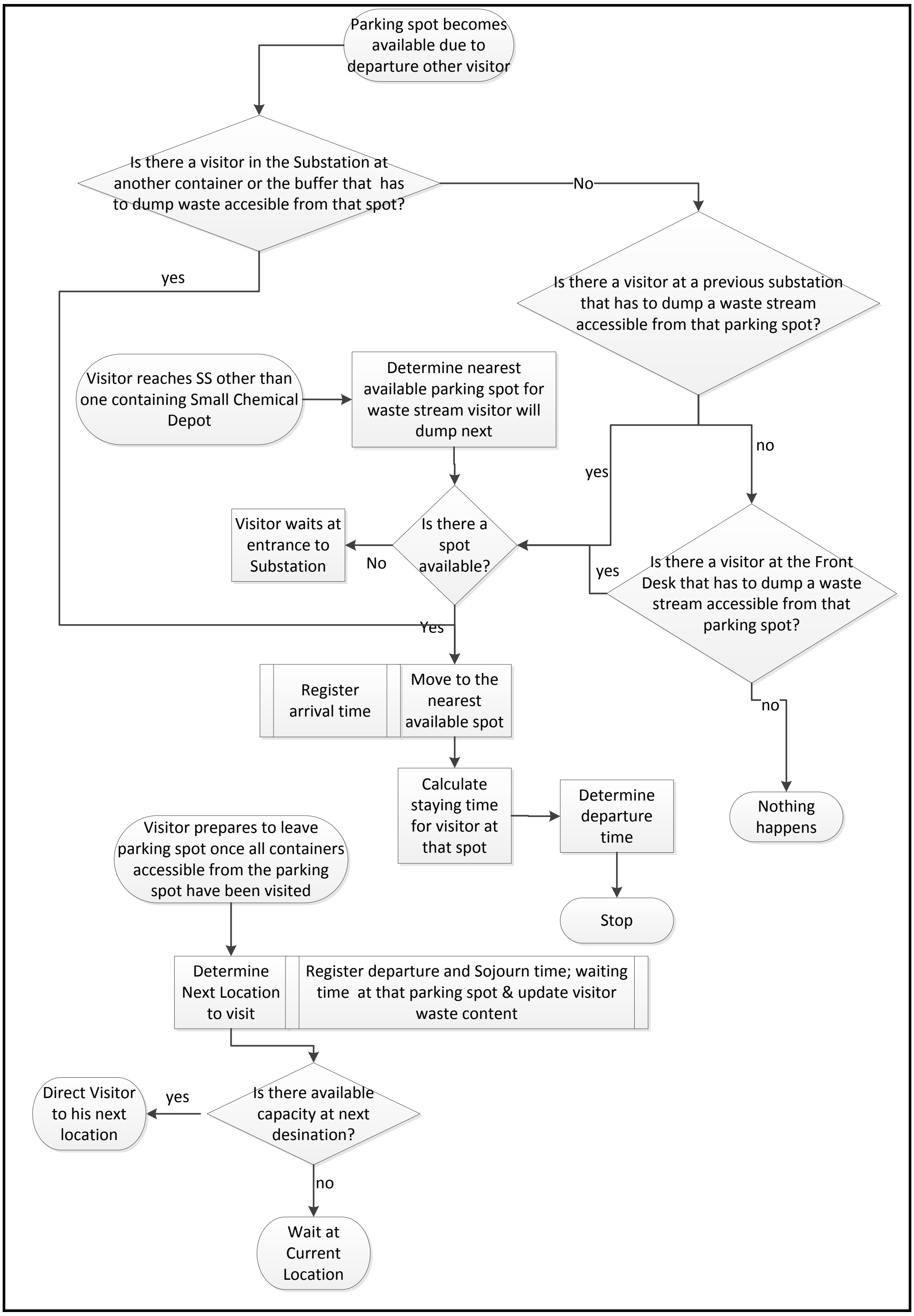

Figure 27 Logic flow of process upon visitor arrival at a substation other than the SCD, upon departure and when a parking spot becomes available

Once a visitor has dumped all the waste he brought to the waste disposal station he leaves the waste disposal station and upon departure the performance measurement statistics are recorded.

4.4.2 Details on arrival rate and self-service times of the conceptual model

In Section 4.3 we described our process for determining the arrival rate and fitting distributions to the inter-arrival times and the service times. Table 11 gives an overview of the results concerning the inter-arrival times and the service times.

Process	Bin rule	Tested Distribution and parameters	χ^2	$\chi^2_{n-1,\,0.95}$	Chosen Distribution and parameters
Inter-arrival(hr 1)	Sturges' rule	Exp(0.0277) Gamma(0.84, 0.0189)	472.25 875.61	18.31	Exp(0.0277)
front desk	Sturges' rule	Exp(0.1011) Gamma(0.85, 0.0857)	293.82 316.30	15.51	Empirical
weighing	Sturges' rule	Exp(0.0768) Gamma(1.87, 0.1435)	434.34 465	15.51	Empirical
A and B grade wood	Sturges' rule	Exp(0.0071)	11.03	11.07	Exp(0.0071)
asbestos	NA	NA	NA	NA	Exp(0.0194)
C grade wood	NA	NA	NA	NA	Exp(0.0055)
car tires	NA	NA	NA	NA	Exp(0.0231)
chemical waste	Sturges' rule	Exp(0.0194)	6.77	11.07	Exp(0.0194)
Crudegarden waste	Sturges' rule	Exp(0.0039)	8,63	12.59	Exp(0.0039)
crude home waste	Sturges' rule	Exp(0.0110) Gamma(1.85, 0.0203)	13.67 2	12.59	Gamma(1.85, 0.0203)
crude waste	Sturges' rule	Exp(0.0169) Gamma(1.68, 0.0283)	14.23 7.62	12.59	Gamma(1.68, 0.0283)
debris	Sturges' rule	Exp(0.0085)	2.09	9.49	Exp(0.0085)
E-waste	Sturges' rule	Exp(0.0104)	6.82	11.07	Exp(0.0104)
gas concrete	NA	NA	NA	NA	Exp(0.0047)
glass plate	NA	NA	NA	NA	Gamma(2.63, 0.0341)
glass bottles	Sturges' rule	Gamma (3.86, 0.0423)	4	11.07	Gamma (3.86, 0.0423)
gravel	NA	NA	NA	NA	Exp(0.0085)
Hard Plastic	Sturges' rule	Exp(0.0103)	3.2	11.07	Exp(0.0103)
Mattresses	Sturges' rule	Exp(0.0112) Gamma(0.86,0.0096)	11.13 9.39	9.49	Gamma(0.86,0.0096)
old metal	Sturges' rule	Exp(0.0097)	6	12.59	Exp(0.0097)
paper and carton	Sturges' rule square root rule	Exp(0.0075) Gamma (1.55, 0.0116) Gamma (1.55, 0.0116)	33.15 14.27 18.7	12.59 15.51	Empirical
plaster	NA	NA	NA	NA	Exp(0.0039)
roofing waste	NA	NA	NA	NA	Exp(0.0059)
soft plastic	Sturges' rule Square root rule	Exp(0.0110) Gamma (1.46 ,0.0160)	31.06 18.21 33.33 20.3	12.59 14.07	Empirical
styrofoam	Sturges' rule	NA	NA	NA	Gamma(3.42, 0.0406)
textile	Sturges' rule	NA	NA	NA	Exp(0.0099)

Table 11 Overview of waste streams and their chosen distributions

4.4.3 Visitor profiles

The visitors of the waste disposal station are not all identical. They may arrive by the same modelled distribution, but they are different entities entirely. There are several characteristics upon which customers can differ:

1. Type of vehicle (small or large);
2. The number of different waste types brought;
3. Waste types brought to the station affect several things for several reasons:
   a. Are these located at the paid or free substations;
   b. Which containers to visit;

The first three of these characteristics were measurable and the results can be viewed in tables 7 to 9 in Section 4.3.2.3. The last characteristic was difficult to measure. We could not within the data observe a significant correlation although we have clearly observed the influence at the waste disposal station. However, we decided to include it in the model, but not use it for the experiments, because of the lack of clarity regarding the relationship. It may be that with more data a relationship can be observed and the factor can be included correctly in the model, but until then we will ignore it. Since we do not have an indication as to what fractions of the visitors bringing waste from a few streams actually spends more time on dumping those waste streams we will use a rate of zero. We will do the same for visitors bringing a lot of different waste streams.

4.4.4 Assumptions and simplifications

In creating this model we are fully aware that we have based this model on our interpretation of the real system (the waste disposal station). Since we do not have all information on waste disposal stations, or how these operate in Canada, we decided to make assumptions that allow us to create a computer model that serves our needs. Furthermore, there are characteristics of the waste disposal station, from our perspective, that, if taken into account, would complicate our model needlessly. Therefore certain simplifications seemed in order.

Robinson (2004) advocates creating models that are as simple as possible yet contain enough detail to be credible and useful. He argues that simple models have many advantages:
1. They are easy to understand and therefore easier in use;
2. They are flexible and can be adapted easier to suit multiple situations or changes therein;
3. They require less data;
4. They run faster;
5. The results are easier to interpret.

In order to keep an easy overview, the assumptions and simplifications that have been made are divided in the major process groups that can be observed in Section 4.4.1.1, Section 4.4.1.2, and others (visitor characteristics). Each has been argued upon and justifications have been given to clarify their necessity.

Assumptions made for the entrance process:
1. There are no breakdowns of the system, i.e., we assume that once installed, any (electrical) systems like an electronic gate, work without failure. Since we have no information on these breakdowns or what the repair times might be, ignoring this is necessary.

2. No visitors drive by if they observe that there is a queue at the entrance, i.e., no visitors are lost to the system. It is possible that in reality visitors' behaviour is such that they may decide to actually postpone their visit. However, measuring how many visitors are dissuaded by long queues is difficult and time consuming. Visitors may after all have differing views on when a queue is too long. That is why we have assumed an identical response to queues. Visitors join in every case.

Simplifications made for the entrance process:
1. If there is no space available for a visitor at the first substation he needs to visit the visitor will wait at a buffer after the entrance and before the respective substation. In reality cars drive to the first container where they need to dump something. If there is no space there, they will wait on the side of the road or behind the current occupant of the filled space. Since this would require modelling extra buffer space for each container it seems prudent to model one buffer space for each of the substations that serves this purpose.
2. There is enough space in front of the entrance to accommodate any number of visitors (infinite buffer). Realistically this is impossible, but for the purpose of the model it is not necessary to put a limit on this. The output may show that long driveways are needed to prevent traffic from the waste disposal station from disrupting traffic on the public road. Modulo's clients may then decide how to alter their waste disposal design to reduce the length of this queue.
3. The server at the entrance always has resources, i.e., there is always an employee present to do the intake process for visitors. In case of emergencies this post may be abandoned. Since this means that events out of the ordinary take place ignoring them is reasonable.
4. At closing time no new visitors are admitted at the queue in front of the entrance. Usually the employees at a waste disposal station work until closing time. They do not admit any visitors that arrive after closing time. If there is a queue at closing time, then they get those visitors on the terrain, but they do not allow any new visitors.

Assumptions made for the process at substations:
1. Visitors park in the first available spot from where they can visit the first container they need to visit. If no spot is available the visitor waits in the buffer. In reality it may well be that visitors decide to drive past that container and drive or walk back later. Since this behaviour is difficult to accurately capture it is reasonable to assume the former to be true.
2. There is enough space for visitors to drive past parked cars. This may be inaccurate as it prevents blocking from occurring.
3. The entire waste disposal station has a limited capacity. As there is only a fixed number of parking spots, a capacity upper limit is placed on the waste disposal station and the substations. Since this exact number may be difficult to measure and would be different for each site, it seems logical to decide upon a fixed number for a generic model. This maximum is not to be confused with the fourth variable mentioned in Section3.2.2.1. This maximum is the absolute maximum of cars that the station can possibly contain. The maximum that is a "variable" is a maximum that clients might want to maintain themselves in order to improve the flow of the visitors through the waste disposal station. The more cars are present on the site the more likely it is that blocking occurs. Blocking slows down the entire station and is thus best avoided by making sure that it is never too busy on the waste disposal station.

Simplifications made for the substations and the process there:

1. Visitors visit stations in a fixed order. In reality most visitors do not have all their waste sorted and park at the first open place on the terrain near a container they need to visit. It could be that this is before or after that container. In any case, the visitor will walk between all containers that are easily accessible from their parked car. This results in too many random patterns. So for modelling purposes it is simpler to dictate a fixed routing for all visitors.
2. The next waste stream, substation and container to visit are determined as soon as a current location is left (the front desk, a container, etc.). This is unrealistic (for the containers), as a visitor only sees whether a parking spot is available at a container as he reaches the next substation. However, for modelling purposes we have decided to program it this way.
3. To ensure that there is a possibility for cars to “drive” past cars that are blocked, as the next waste stream they need to visit and the buffer have no free capacity, a fictional buffer has been created with infinite capacity right before roads leading to the substations. We realize this is unrealistic as well, but there was no other way of ensuring that lockdowns do not occur (blocked roads due to capacity being occupied at a substation at the end of the waste disposal station in by a visitor who is still at the beginning of the waste disposal station), we had to explore options that were readily applicable.
4. Visitors may walk up to a certain number of containers from their parking spot to throw away waste. This limitation is logical, since operators at waste disposal want to reduce walking to ensure safety and increase the flow of visitors through the station, as they believe too many walkers will reduce the flow. Also it is a fact that visitors cannot carry heavy loads for large distances. For simplicity reasons it is reasonable to set a fixed walking distance for each separate waste stream.
5. Travel times within substations are not taken into account. These depend heavily on the distance between the containers visitors visit subsequently and on their driving speed. This could be measured, but since that would take some time we have chosen to ignore it for now.
6. In this model we do not account for double visits (going back) in case a visitor forgets something. No container or substation is visited two times. Since we have decided upon a fixed visiting order to simplify programming, allowing backtracking would take away any advantage gained by that simplification.
7. In the model overflow bins have not been taken into account. This will have an influence on the result as the parking places located in front of them are not used by the visitors. In real life visitors may park in front of these containers in order to visit waste streams located at nearby containers.

Assumptions made about the visitors:

1. We assume that all visitors in the system have a citizenship pass or some other identification for control. In reality some visitors do not have a pass and these can get a day pass if they have a sound explanation for wanting to bring waste without a pass. Since we do not know how often this occurs we may assume that all visitors in the model are allowed to visit.
2. We do not specifically account for the influence of the amount of waste visitors bring. I.e. there is no attribute that gives information on how much waste visitors bring. We assume that, by analysing server times at the containers and allotting a distribution to the different servers, this issue is covered. Other influences related to the amount of waste brought are unknown, since we were unable to clearly demonstrate these correlations, so we assume that the only effect is observed in the time it takes visitors to dump their waste.

3. We assume that no contamination occurs. I.e., the visitors throw the waste they have in the correct containers. The effects of incorrect behaviour or the frequency of these occurrences is unknown and therefore we assume that the containers are visited and used correctly.
4. Waste brought by visitors is usually sorted; sometimes, however, it is not. We assume that the differences caused by lack of sorting beforehand, is reflected in the variance observed in the dumping times. Another consequence of badly sorted waste may be incorrect dumping at the waste disposal stations. Since we assumed this would not occur it is logical that the only effect is observed in the dumping time.

Simplifications made for the visitors:
1. Time spent by visitors looking for either a place to park or the location of the waste streams they brought with them are not taken into account. Since these depend heavily upon the visitors' behaviour we have made no attempt to measure this.
2. The arrival process is estimated by utilising data from the system of the partnering waste disposal company.

After completing the conceptual model we programmed said model in a software tool in order to demonstrate its use. Chapter 5 describes the programmed simulation model briefly. It also elaborates on the validation process and the experimental design used to demonstrate the model's usefulness.

4.5 Summary

In this chapter we conclude the answering of the research questions. We started with the first steps towards creating a conceptual model in the first section. We translated our problem into a queueing problem and determined the variables and input parameters and output of our model. In Section 4.2 we described a real case of a waste disposal station. We have collected data at that waste disposal station and the collection process and the analysis of the collected data are described in Section 4.3. After determining the form of our model (in queueing terms) and the variables, the input parameters and the output all that remained in order to start programming the model is clearly describing the content of our model. This means that we needed to describe the processes that are part of our model. We also had to provide details (values) for the input parameters. The final step of creating the conceptual model was to determine the assumptions and simplifications needed to make a translation to a programmed model. All of these steps were taken care of in Section 4.4. So, at the end of this chapter we have answered all the research questions needed to program a simulation model that can analyse a waste disposal station based on design decisions.

Chapter 5 Simulation Model and Experimental Design

After creating a conceptual model of a general waste disposal station, aided by studying a waste disposal station in the Netherlands, a model was programmed using the software tool Plant Simulation. In Section 5.1 we describe this model and verification and validation of this model is discussed. In Section 5.2 we describe the experimental design of our simulation study. We have split our simulation study into two stages. Stage one focusses on the site in we collected our data at and is the first test of the programmed model. Can it be used to give advice on how to improve an existing waste disposal station? This will be covered in Section 5.2. In Stage two, however, we will describe and demonstrate how our model may be used to design a good waste disposal station upon a clients' request for a request for proposal. In section 5.3 we describe the (experimental) steps taken to come to a good design. In the next chapter we perform these steps in a design process.

5.1 The Simulation Model

In this section we first describe the Simulation model programmed in Plant Simulation briefly. Afterwards, we first perform some verification checks, to see whether the model performs the way we intended, before we discuss the steps taken to validate the model. During the validation we check whether the model gives output that is a reliable representation of reality.

5.1.1 The programmed simulation model

As stated earlier, the software "Plant Simulation" was used to implement our simulation model. In Figure 28 the waste disposal station is depicted as it is modelled in Plant Simulation. Plant Simulation is an object oriented simulation tool. We modelled the waste disposal station using a combination of objects (processors for the entrance, exit and the substations, and buffers for buffer-space). The option for tracks (objects depicting roads) and transporters (type of moving object) made it possible to provide a realistic graphic outlook. Figure 29 (see next page) presents the administrative tables (input, output and information tracked for simulation purposes), and the objects containing operational code and the control code used to run the simulation model and collect data.

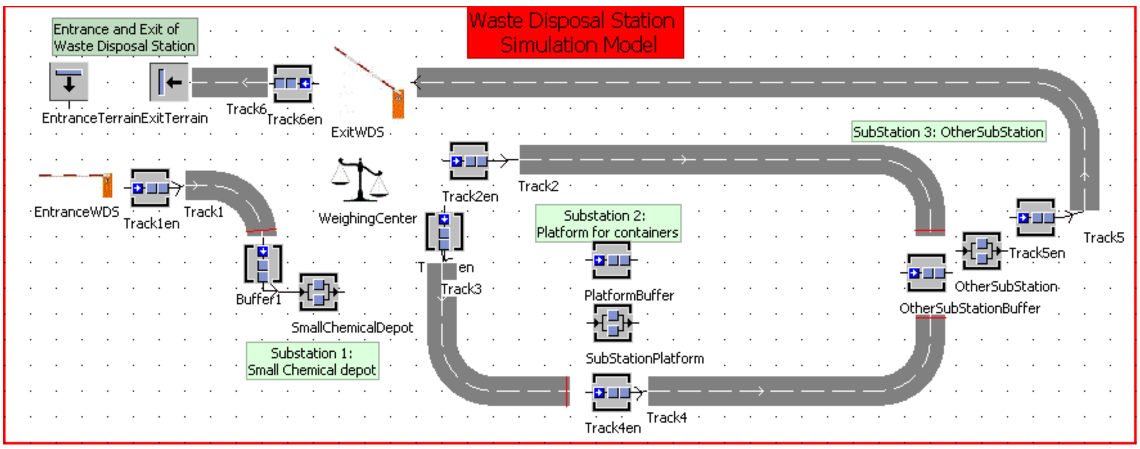

Figure 28 Overview of the visual part of the programmed simulation model

In objects called variables and table-files, information can be stored for use in the model as input or output data or control variables. Objects called methods contain all the code that is used to run the simulation model. Further details of this model can be found in Appendix J

5.1.2 Verification

Before we proceed to validate our model to see whether the results of the model approach those of reality we need to check whether our simulation model actually performs the way we intended. In short we need to verify whether the programming in our model is correct.

To start off we analysed the arrival rates of each hour to see whether we did indeed generate enough arrivals. We calculated the mean and compared it to that of the input data. The results (see Table 12) show that the realised arrival rate closely resembles that of the input data.

Next we checked whether the ratio of paid-waste-bringing, free-waste-bringing visitors and the visitors bringing both paid and free waste are implemented correctly in the model. This turned out to be the case (see Table 13).

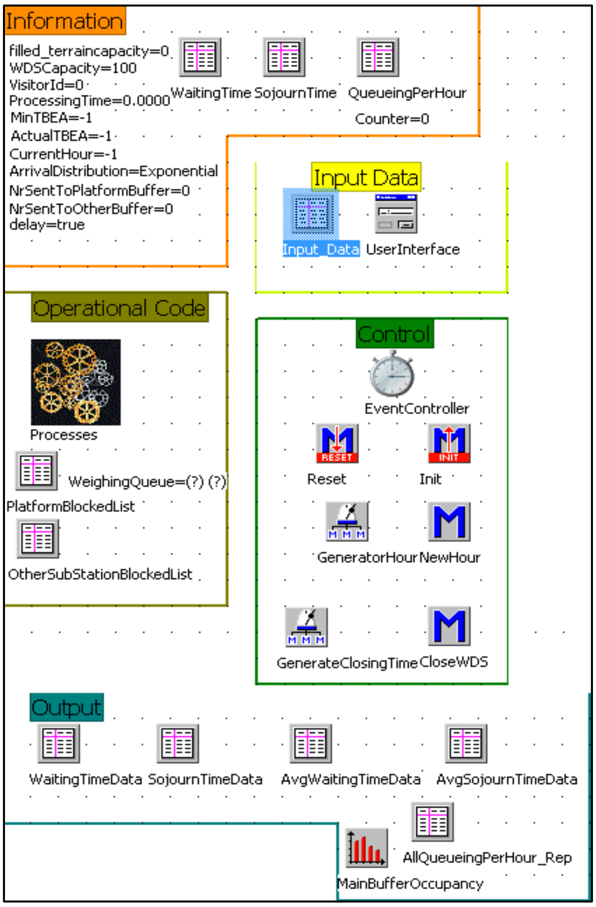

Figure 29 Overview of the control of the simulation model

Arrival rate verification check			
hour	realised rate/hour	theoretical rate/hour	absolute relative difference
1	98.3	100	0.0170
2	116.8	116	0.0069
3	127.14	127	0.0011
4	114.82	116	0.0102
5	119.26	117	0.0193
6	114.84	115	0.0014
7	69.54	71	0.0206

Table 12 Verification of the realised arrival rate

Paid, free, both check			
	paid	free	both
realised frequency	18657	9703	9634
realised ratio	0.49105	0.25538	0.25357
theoretical ratio	0.48773	0.25514	0.25713
abs relative difference	0.00681	0.00095	0.01386

Table 13 Verification of the realised paid-free-both ratio

After these ratios we took a look at the waste streams. We analysed their service times (compared mean of realised service times with input data; see Table 14) and we took a look at their frequency of occurrence (see Table 15). Looking at the difference of the frequency of occurrence we observe a clear difference. However, this can be explained by the fact that we programmed our model so that after a waste stream is selected the frequency table is mutated so that the selected waste stream cannot be chosen again. This changes the probabilities and therefore resulting frequencies are different from the theoretical ones. When looking at the comparison of the mean times of the realised service times and the input data we can observe that the biggest difference of 45.94 percent manifested for Gravel. Since this is one of the waste streams whose service time (mean and distribution) was based on that of another waste stream (debris) and whose frequency was very low we can reason that with more observations (more simulation runs) the difference would be smaller. The second largest difference is observed for RoofingWaste (21.62 percent).The other (relatively) large errors were observed for AnBGardeWood (16.87 percent) and CarTires (12.27 percent). We have no clear cut explanation for these differences. However, since all the other waste streams show an error of less than five percent we may conclude that the service times assigned are correct.

Mean service time verification			
Waste Streams	**realised average**	**theoretical average**	**absolute relative difference**
AnBGradeWood	163.8430	140.1944	0.178684
Asbestos	54.5814	51.6154	0.057464
C_gradeWood	189.9732	181	0.049576
CarTires	48.6471	43.33	0.122711
ChemicalWaste	52.3090	51.62	0.013348
CrudeGardenWaste	257.9564	256.77	0.004621
CrudeHomeWaste	90.4363	91.15	0.007830
CrudeWaste	59.3080	59.23	0.001317
Debris	117.5676	117.5	0.000576
E_Waste	94.7048	95.82	0.011639
GasConcrete	218.6128	211.25	0.034853
GlassBottles	91.2278	91.25	0.000244
GlassPlates	77.9423	77.17	0.010007
Gravel	171.4828	117.5	0.459428
HardPlastics	96.5759	96.7	0.001284
Mattresses	91.6387	89.22	0.027109
OldMetal	103.1141	102.67	0.004325
PaperNCarton	133.0971	133.04	0.000430
Plaster	243.3298	254.5	0.043891
RoofingWaste	206.1363	169.5	0.216143
SoftPlastics	92.7086	90.92	0.019672
Styrofoam	91.2030	84.25	0.082528
Textile	104.9528	101.06	0.038520

Table 14 Verification of the realised service times of the waste streams

Waste stream Frequency verification				
Waste streams	**realised frequency**	**realised probability**	**input probability**	**absolute relative difference**
AnBGradeWood	5879	0.0724	0.1012	0.2849
Asbestos	43	0.0005	0.0001	2.7657
C_gradeWood	1604	0.0198	0.0112	0.7558
CarTires	663	0.0082	0.0042	0.9354
ChemicalWaste	2676	0.0330	0.0366	0.0987
CrudeGardenWaste	11035	0.1359	0.1181	0.1504
CrudeHomeWaste	8001	0.0985	0.0745	0.3220
CrudeWaste	3912	0.0482	0.0309	0.5572
Debris	5514	0.0679	0.0464	0.4633
E_Waste	6429	0.0792	0.1111	0.2873
GasConcrete	860	0.0106	0.0056	0.8828
GlassBottles	2564	0.0316	0.0337	0.0644
GlassPlates	762	0.0094	0.0084	0.1122
Gravel	28	0.0003	0.0001	1.4521
HardPlastics	5081	0.0626	0.0422	0.4832
Mattresses	4143	0.0510	0.0323	0.5775
OldMetal	4007	0.0493	0.0591	0.1645
PaperNCarton	6835	0.0842	0.1251	0.3275
Plaster	843	0.0104	0.0056	0.8456
RoofingWaste	806	0.0099	0.0056	0.7646
SoftPlastics	5881	0.0724	0.1012	0.2847
Styrofoam	1741	0.0214	0.0225	0.0471
Textile	1905	0.0235	0.0239	0.0187

Table 15 Verification of the realised frequencies of the occurrence of all waste streams

Apart from the verification steps described above our model has also undergone a thorough debugging process during which we have ascertained that the visitor's characteristics are updated correctly and the way they are steered through the system is conform the way described in the conceptual model. We have also thoroughly checked the times (sojourn- and waiting time) that are written to the output tables and have made sure that these are indeed the correct times.

With these verification steps performed satisfactory we can now move on to the validation of the model.

5.1.3 Validation

For validation purposes, the main participating waste disposal station has provided data concerning the arrivals and departures at the waste disposal station to enable calculation of the sojourn time of visitors. Since part of this data was provided in excel-files and part in txt-files, data-steps were needed to merge the datasets. For this purpose the software tool R has been used (in Appendix F the used code can be viewed). The datasets were merged using the visitor's pass-code. Since some clearly scanned their pass multiple times a day, these duplicates had to be sorted out to determine the right sojourn time. Using logic (for matching instances that are close to one another for instance) the moments of scanning were matched.

Upon calculating the sojourn time, according to the described method, it became clear that only the sojourn time of visitors visiting only the paid or both the paid and the free area could be calculated, as only these have a registered departure time. To get a holistic view data we measured at the waste disposal station to determine the sojourn time for visitors visiting only the free area. When this was achieved, a general sojourn time was calculated. This has been compared to the average sojourn time as calculated by the programmed model using several settings (see Table 16). For a correct validation we need to select data of the same period with the same length (so also three days) as the period over which our measurements were done on which we based our input data. To meet this requirement we have selected three days (the last Saturday of May and the first two Saturdays of June).

The first simulation run was done with all the parameters set according to the real case. The results show a sojourn time of 407.02 seconds. This shows a difference of 17.32 percent. The standard deviation of our measurement is about one and a half minute larger than the standard deviation of the real life data. When we took a look at the distributions (see Figures 30 and 31) of the simulation results and the real life data we can observe the following:

1. The shapes seem to be similar;
2. The bin ranges illustrate that the simulation results are consistently lower;
3. The simulation results are from a much larger number of observations.

		Mean total Sojourn Time (sec)	St. dev. total Sojourn Time (sec)
1	Real life paid&both	548.04	372.62
2	Real life free	321.44	226.79
3	Avg (weighted avg 1 & 2)	489.77	341.13
4	Real life paid	483.35	379.75
5	Real life both	678.73	321.18
6	**Avg2 (weighted avg 2, 4 & 5)**	**492.28**	**331.64**
7	**Simulation result**	**407.02**	**343.15**

Table 16 Validation of the model through the mean total sojourn time and the variance thereof

The difference in the mean sojourn time may be the result of several causes:

1. We were unable to measure all the visitors that came in on those days. It may well be that the collection of observations we were able to gather was not representative enough for the model.
2. The time it takes for visitors to park or find their way on the waste disposal station is not taken into account in the simulation model, nor is the travel time between containers at one single substation. Travel times between substations are approximated by upholding a consistent ratio (7:1) of the real travel distances and the track lengths in the simulation model (see Table 17) and the average speed drivers maintain and the speed settings of the transporters in the model.
3. We suspect that there might be correlation between the number of waste streams brought and the type of waste and the quantity of waste brought and by extension the time needed to dump said waste. However, with the observations that we have available we are unable to prove this. Quite logically we do not see people going to the waste disposal station to drop off a few plastic bottles, resulting in them staying for less than 20 seconds. Our simulation model has generated some of those instances where sojourn time got as low as thirteen seconds!

	Real life	Model
Entrance-small chemical depot	20m	3.14m
Weighing scale-Other substation	64m	9.14m
Other substation- Platform	100m	14.14m
Weighing scale – Platform	120m	17.14m
Car speed	15km/hour	0.6 m/s

Table 17 overview of the road length and assumed average speed in real life and in the model

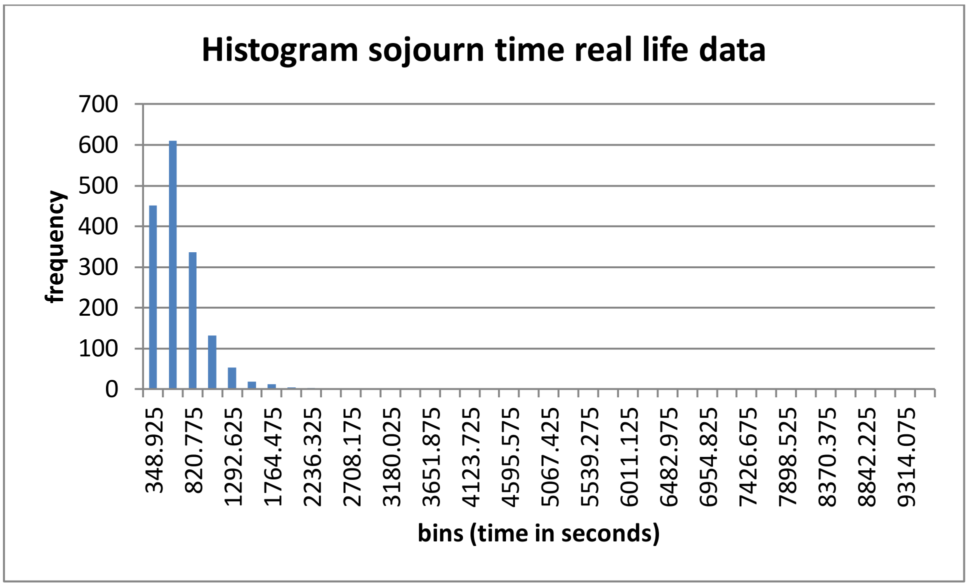

Figure 30 Histogram sojourn time of visitors from real life data

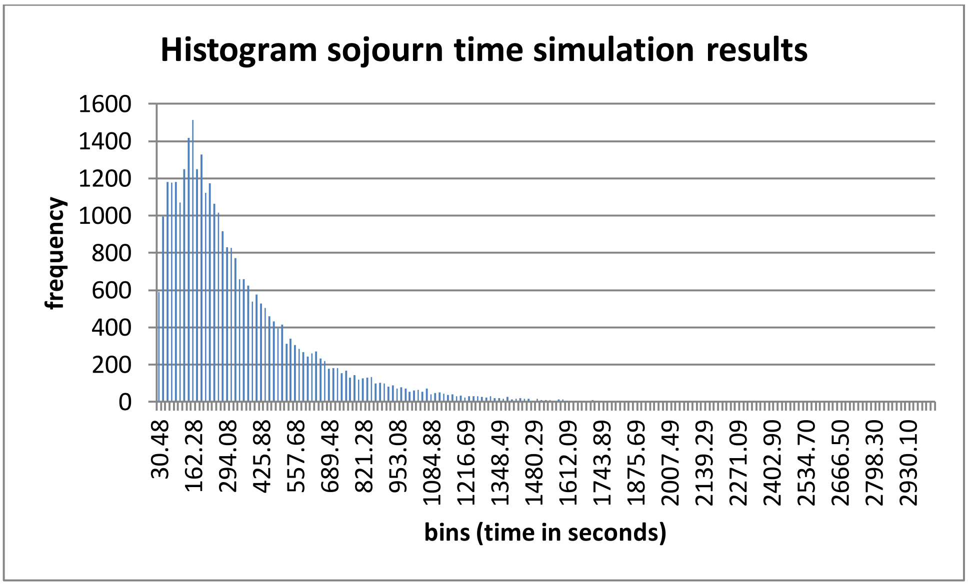

Figure 31 Histogram sojourn time of visitors through simulation

Since variation is the cause for queueing we deemed it very important that the variation matched the real life data better. However, several attempts to generate a smaller variance were unsuccessful. In the end we had to accept that the assumptions and simplifications made prior to the creation of the simulation model resulted in a model that is in some ways significantly different from reality. Some causes for an increased variability are:

1. The assumption stating that visitors wait until the waste stream they need to visit has a free spot may result in unrealistically long waiting times. In reality the visitor may have driven off to another waste stream they need to dump.
2. The simplification that dictates a fixed order instead of a flexible order for ease of programming may result in too rigid behaviour of visitors. This may cause unnecessary delay which in turn increases the variance in sojourn time.
3. The model does not allow visitors to flexibly change the next waste stream they are going to visit. In real life visitors have this option which they use frequently when some containers they need to visit are busy yet others they need to visit are not.

In order to generate sojourn times that are closer to those of reality we have decided to add a delay factor to the simulation model that is representative of the delay people experience while looking for a parking spot and driving between containers at the same substation. We have decided to use deterministic delay factor that is added after the departure of a visitor at every container he visits. We have decided upon a deterministic delay to keep the increase in variability minimal. We have tried approaching the validation data by varying the delay factor. Eventually we decided to take a mean delay time of 35 seconds. After utilizing this delay factor we have realised a sojourn time of 487.15 with variance 167,299.49. This means that the difference with the mean has been reduced to 1.04 percent. The new difference in variance means that the standard deviation from the simulation is now approximately four minutes higher than that of the validation (real life) data.

5.2 Experimental Design

Before we can proceed to use the programmed simulation model just described, we will need a plan on how to use the model. In other words, we need to have a design on how to perform experiments with the simulation model to achieve our goal. This goal may be to find out how to improve an existing waste disposal station or how to create a good design for a waste disposal station while still in the design phase of a project. In Section 5.2.1 we first come to a decision on the number of replications we need to do to generate reliable results for decision making. Furthermore we describe the various variables that we can vary in order to find a good configuration of design parameters.

In Section 5.2.2 we make a plan for conducting the experiments on the basis of which we could give advice on how to improve the waste disposal site we studied. In this first phase of testing the simulation model we focus on finding ways to improve the site without doing a complete overhaul. This means that we will be limited in the range in which we can keep our variables. Important to keep in mind is the fact that the waste disposal station under scrutiny is not of modulo design. So the site is less flexible when it comes to making alterations.

5.2.1 Introduction

Type of simulation:

At all the waste disposal stations visited in the Netherlands we learned that the busiest day of the week is always the Saturday. Therefore a study to analyse whether a design can handle the flow coming to the waste disposal station should be based on the busiest moment. If the system can handle the busiest day with a high probability then the slower-, less-crowded days should not be a problem.

Based on this reasoning we have decided to only simulate Saturdays in in our model. Now, it may well be that visiting patterns are different in Canada, but since no data was accessible for those sites within the time frame of this project, we have decided to use a Dutch Waste Disposal Station to validate our model. This means, that we have to make sure that for validation purposes our model represents the situation as good as possible. Unavoidably we therefore need to incorporate behavioural patterns of Dutch citizens.

Since we are only simulating the Saturday and then "jump" to the next Saturday our simulation is of the type terminating simulations. It has a natural end. This means that we do not need to determine what the warmup period is (the time needed for the system to reach a steady state). We only need to determine the number of replications we need in order for our results to have sufficient accuracy.

Number of Replications:

Law has described a method to determine the number of replications one would need to perform in order to be sure that their results would be reliable. His method would ensure that the half width of the confidence interval of a chosen variable of interest (usually a KPI) divided by its absolute mean is not larger than a chosen absolute relative error (γ'). In general a smaller confidence interval ensures more accurate results.

$$\gamma' = \frac{\gamma}{(\gamma+1)}$$

By selecting the KPI with the highest ratio of variance/mean, we can determine the number of replications that will ensure a small enough confidence interval for ensured reliable results. After running the simulation for the current settings of the waste disposal station studied, we have observed a ratio of 171.72 for the waste stream gravel (see Table 18 for the ratios of variance over mean of sojourn time of all the substations and the waste streams). Since this KPI clearly has the widest confidence interval we used that setting to test whether we had run enough replications of the simulation. Testing concluded that the fifty replications we initially tested for were enough to provide a small enough confidence interval. The relative error measured was 0.0233, which was smaller than the absolute relative error at a 0.975 confidence level (γ = 0.025) (see Table 19). Therefore we can be confident that a number of fifty will yield results that are accurate enough.

	Entrance WDS	Small Chemical Depot	Weighing Scale	SubStation Platform	OtherSub Station	ExitWDS
Mean	16.99	194.46	16.50	356.90	261.64	11.35
Variance	5.19	125.99	1.38	4346.69	272.71	0.89
Variance/Mean	0.31	0.65	0.08	12.18	1.04	0.08
	AnB Grade Wood	**Asbestos**	**C_grade Wood**	**CarTires**	**Chemical Waste**	
Mean	138.35	22.79	198.92	48.87	52.33	
Variance	127.34	1363.80	1769.86	103.52	39.48	
Variance/Mean	0.92	59.85	8.90	2.12	0.75	
	CrudeGar-denWaste	**Crude Home Waste**	**Crude Waste**	**Debris**	**E_Waste**	
Mean	356.90	92.54	62.03	140.60	94.32	
Variance	4346.69	34.11	23.66	188.44	75.59	
Variance/Mean	12.18	0.37	0.38	1.34	0.80	
	Gas Concrete	**Glass Bottles**	**Glass Plates**	**Gravel**	**Hard Plastics**	
Mean	216.44	90.84	77.95	76.46	118.67	
Variance	2815.38	40.05	142.28	13128.91	235.01	
Variance/Mean	13.01	0.44	1.83	**171.72**	1.98	
	Mattresses	**Old Metal**	**Paper Carton**	**Plaster**	**Roofing Waste**	
Mean	101.32	102.44	132.80	241.06	202.60	
Variance	216.75	75.14	84.76	3578.06	1570.56	
Variance/Mean	2.14	0.73	0.64	14.84	7.75	
	SoftPlastics	**Styro-foam**	**Textile**	**Total Sojourn Time**	**Total Sojourn Time 2**	
Mean	92.49	83.39	105.07	377.10	487.7607	
Variance	42.13	68.89	175.26	669.92	1410.004	
Variance/Mean	0.46	0.83	1.67	1.78	2.89	

Table 18 Overview of all sojourn time (mean in seconds, variance in seconds^2 and variance/mean in seconds)

Υ	0.1	0.05	0.025
Υ’	0.091	0.0476	0.024

Table 19 Overview of the absolute relative error (γ’) as function of the significance level (γ)

List of possible experimental factors

There are quite some variables that can be changed in our model. This is mostly a result of the chosen main objective of this project. The main goal was to develop a generic model that could be fit on any waste disposal station (design) in order to assess its performance based on queueing times and queue lengths. Be that as it may the variables one could change are:

1. the set of ***w*** different waste streams that will be collected;
2. the capacity setting ***cws*** of each of these waste streams (in containers and parking spots);
3. the location of the waste streams of the ***l*** locations available;
4. the capacity of the entrance gate ***ce***;
5. the capacity of optional weighing stations ***cw***;
6. the capacity of buffer zones for each substation, entrance and weighing station.

5.2.2 Improving the studied waste disposal station

If one wishes to assess all the variables mentioned at the end of Section 5.2.1, it would result in a massive number of experiments that would need to be done in order to analyse all the possible effects of the variables. Therefore we can reduce these options logically. First of all, the different waste streams are actually input from the municipality who wishes to have a waste disposal station built, so we need not make a selection of waste streams. Another variable we may disregard for the time being is the capacity of the entrance and weighing stations. Most waste disposal stations in the Netherlands have a single queue at these positions. And the effect of more capacity at these points seems rather straightforward, namely the number of cars entering the site would increase which would result in a reduction of queues at the front end of the waste disposal station. If, however, the interior of the system is not designed well all this extra flow has no space to unload his or her waste from which would result in a need for more buffer space or more capacity on the site itself.

Therefore, the first decision we made was to primarily focus on the decisions regarding the interior of the waste disposal station. If these could be fine-tuned to such a degree that they can handle a specific flow of visitors, due to a good understanding of the capacity needs for a given number of visitors, then upscaling in order to deal with a larger number of visitors should be fairly straightforward. This still leaves us with three groups of variables. The capacity chosen for the waste streams that were selected, the location of these containers, and the size of the buffer zones for the substations. Since the buffer zones are mostly an expression of the amount of space made available due to the length of the roads between the substations the decision has been made to disregard it for now. The location of some of the waste streams is usually fixed (see Section 2.4), but this leaves us with nearly half of the waste streams to allocate. Since this variable would also provide us with a very large number of settings that could be explored we have decided to pass it by as well. The chosen focus for the simulation is therefore primarily the capacity of the waste streams.

In the process of selecting experimental factors we decided to first look at the theory behind the growth of waiting time. Going back to Section 3.2 we can observe the formulae used to calculate the waiting time at a substation (or even a container).

F1:

$$E(Wq_m) = \frac{\rho_m * \left(S^2{}_{Y_m} + S^2{}_{X_m}\right) * X_m}{2(1-\rho_m)} * exp\left\{\frac{-2(1-\rho_m)\left(1-S^2{}_{Y_m}\right)^2}{3\rho_m * \left(S^2{}_{Y_m} + S^2{}_{X_m}\right)}\right\}, if\ S^2{}_{Y_m} \leq 1$$

$$E(Wq_m) = \frac{\rho_m * \left(S^2{}_{Y_m} + S^2{}_{X_m}\right) * X_m}{2(1-\rho_m)}, if\ S^2{}_{Y_m} > 1$$

In this formula the expected waiting time ($E(Wq_m)$) at a substation grows as the utilization (ρ_m) grows. Other important influencers are the variance (squared coefficients of variance) of the inter-arrival time at the substation and the service time at the substation and the service times at the substation or container. It can be observed from the formula above that waiting time is an increasing function in the utilization, the variance of inter-arrival times and service times and the service time itself. The waste streams that are therefore worth looking at are those where the utilization is high, the service time is high and the variance of the service time is high.

Some waste streams were brought a lot and might cause congestion (theoretically) if they did not have enough capacity. In Section 3.3.2 one can observe the top five waste streams when it comes to their popularity (see Table 20). However, we observed, while collecting data, that stations that got a high utilization would not necessarily cause congestion. The waste streams with a long dumping time and a large range of dumping times seemed to be the culprits of congestion. Therefore, we decided to look more closely at the mean dumping times of all waste streams and their variance as well. The top 5 of each of these measurements can be observed in Table 20 as well.

However, if we look more closely at the theory we can observe that the squared coefficient of variance of the service time at a substation is dependent mostly on the waste streams visited at that substation and their mean service time there.

F8: $$S^2{}_{X_m} = \frac{\sum_{p=1}^{P}\sum_{o=1}^{Op} w_{pom} * X^2{}_{po} - \left[\sum_{p=1}^{P}\sum_{o=1}^{Op} w_{pom} * X_{po}\right]^2}{\left[\sum_{p=1}^{P}\sum_{o=1}^{Op} w_{pom} * X_{po}\right]^2} + \sum_{p=1}^{P}\sum_{o=1}^{Op} w_{pom} * X^2{}_{po}$$

The variance of inter-arrival times, however, is more complicated. It is dependent on the squared coefficient of departure times at the substations (or containers) previously visited, which in turn depends on the squared coefficient of variance of the service time of that substation (or container) and the squared coefficient of the inter-arrival time at that substation (or container) (Formulae F9-F15). This clearly illustrates that the variance of the service time at a substation (or container) goes on to influence the variance at the other subsequent substations and therefore also the waiting time of the entire site.

Looking at all the data we can make a selection of variables to experiment with. We can theorize that waste streams that are brought frequently yet have a relatively small dumping time do not influence the sojourn time a lot. These waste streams cannot influence the sojourn time a lot through a direct impact (service time), or an indirect impact (squared coefficient of variance). Waste streams where we have observed a large mean dumping time are interesting, but if the observed variance is small then these waste streams will not have a large effect either. Their effect is small as steady processes can be planned upon with quite some reliability. So variance is very important to take into account. Therefore, we have decided to select waste streams with a high mean dumping time and a high variance, but only if they are frequently dumped. This decision was strongly influenced by observing the high variance in dumping time of “Plaster” and “GasConcrete”. They were remarkably high. However, as we have observed only four visitors from the recorded 316 bringing these waste streams, we discarded them. It is quite easy to get a high variance in these occasions as you would need only one visitor with very little of a specific waste stream and another with a lot of the same waste stream to get a huge variance.

	Top 5 popularity [in amount]	**Top 5 mean time [in seconds]**	**Top 5 variance time [in seconds^2]**
1	PaperNCarton [89]	CrudeGardenWaste [257]	Plaster [90149]
2	CrudeHomeWaste [84]	Plaster [255]	GasConcrete [80391]
3	CrudeGardenWaste [79]	C_gradeWood [181]	C_gradeWood [40874]
4	AnBGradeWood [72]	RoofingWaste [170]	CrudeGardenWaste [39327]
5	Soft Plastics [72]	AnBGradeWood [140]	AnBGradeWood [15139]

Table 20 Potential high interest waste streams

CrudeGardenWaste and AnBGradeWood were selected as specific waste streams for experimentation. However, since a lot of waste streams are located at a substation containing the “Small Chemical Depot”, some of which have a high frequency and/or mean dumping time and/or variance in the dumping time we have selected this substation as well.

This means that for our main experiments we have 3 actual potential experimental factors:

1. Capacity for CrudeGardenWaste;
2. Capacity for AnBGradeWood;
3. Capacity at the substation where the “Small Chemical Depot” is located.

After reviewing the waiting times of all the waste streams present at the waste disposal station we made the discovery that AnBGradeWood seemed to have enough capacity as its waiting time had an average of seconds. Therefore, we discard this experimental factor for now when it comes to increasing its capacity. We have, however, decided to see what the effect would be of reducing the capacity for that waste stream. Looking at the other waste streams though, we have seen that only three waste streams located at the platform (debris, hard plastics and plaster) have an average waiting time above three seconds. We have decided to study whether reducing the capacity of AnBGradeWood with one and in turns increasing the capacity of these waste streams by one will have a positive impact on the waiting times and even the sojourn times. Furthermore, we state that other waste streams with a capacity larger than 1 with a low average waiting time might also keep operating fine with less capacity. Therefore we decided to reduce the capacity of CrudeWaste and CrudeHomeWaste while testing the increase of the capacity for Debris, HardPlastics and Plaster.

Since for an existing waste disposal station it is often not possible to do a complete overhaul we will perform a neighbourhood search one factor at a time to assess its impact. It is important to keep in mind that since the number of container spaces is fixed, increasing the capacity for one waste stream means decreasing capacity for another. After reviewing the waiting times of all the waste streams present at the waste disposal station, the waste streams with a capacity higher than one and relatively low waiting time were selected for experimentation. Table 21 lists the experiments that were ultimately selected.

Experiments	Waste Stream / Substation selected for increase	Waste Stream selected for decrease
1	CrudeGardenWaste +1 (to 4 containers)	NA
2	CrudeGardenWaste +2 (to 5 containers)	NA
3	Debris +1 (to 2 containers)	AnBGradeWood -1 (to two containers)
		CrudeWaste -1
		CrudeHomeWaste -1
4	HardPlastics +1 (to 2 containers)	AnBGradeWood -1 (to two containers)
		CrudeWaste -1 (to one container)
		CrudeHomeWaste -1 (to one container)
5	Plaster +1 (to 2 containers)	AnBGradeWood -1 (to two containers)
		CrudeWaste -1 (to one container)
		CrudeHomeWaste -1 (to one container)
6		Small Chemical Depot -1

Table 21 Overview of all the experiments of the experimental design

Other Interventions:

Aside from these experiments, however, we still have an interest in some of the other variables. It may be interesting to see what the effect is of isolating a popular waste stream with a high mean and variance in dumping time like CrudeGardenWaste. Currently it has a dedicated substation and is separated from all the other waste streams. We are interested in observing what would happen if a stream like that was not isolated. Another interesting intervention to analyse based on an observation made at the studied waste disposal station, concerns the buffer size in front of substations. One Saturday while measuring the service times of visitors at the main entrance and the weighing station the following observation was made. Since the main entrance to the system and the weighing station were located at opposite sides of a crossroads with only space for about three normal cars (two cars if one of them is a small truck or has a trailer) in between, and the other two parts of the crossroads led to the substation of the "Small Chemical Depot" and the exit of the site, this crossroad could get busy and be a centre for blocking. It seems therefore interesting to observe what the effect would be of having enough space between these areas. Another interesting idea caught our attention when visiting a waste disposal station (the one at Woerden). They decided to close off the site to visitors whenever it became too busy on the waste disposal station and visitors were getting in each other's way. This sparked the idea of analysing the effect of putting a capacity limit on the site and potentially substations. By doing this one could control the inflow of visitors to the site minimizing the possibilities for congestion and simultaneously realising optimal flow through the waste disposal station.

Based on these we decided to perform four additional interventions to analyse independent from the capacity oriented experimental factors and independent from each other:

1. Analysing the effect of mixing all the waste streams located at the paid side of the waste disposal station (specific details concerning location of containers will be determined later on). To meet this purpose we will place the "CrudeGardenWaste" at three different places of the "OtherSubStation".

2. Analysing the effect of making sure containers of one and the same waste stream are not located next to each other. This effect is studied by concentrating the containers of one waste stream next to each other.
3. Analysing the effect of increasing the buffer size in front of the weighing station
   For this intervention we use a neighbourhood search as well. However, since running the base case showed that for near 100 % of the time the buffer in front of the weighing station is empty this hardly seems necessary. Instead we will analyse the effect of reducing the space at said location.
4. Analysing the effect of placing a capacity max on the entire site. Based on the number of containers at the site studied we have decided to put the initial capacity maximum on 40 cars (there are 40 containers at the site), but we have decided to vary this variable between 10 and 70 with steps of 5. If we observe that there hardly is any change when increasing the capacity we will drop the experiments with the higher capacity level.

5.3 Experimental Design for Waste Disposal Design Process

Having a simulation model that works is the first step. However, in order for such a model to be useful Modulo will need a structured plan to use this model in a design process. Designing a plan of execution for evaluating possible designs that is generic enough to be used in any waste disposal design process, is a challenge. It is a challenge, because every single case is different and client wishes may have quite some impact. Therefore, we have decided to first revisit all we know of the design process to see how we might fit a series of experiments into this process. As a start we have used the knowledge from Chapter 2 to structure a design process with the use of experiments to evaluate alternative designs in mind.

Steps in the new design process:

1. Gather high level requirements and client wishes:
   a. Waste stream selection, their collection requirements and volumes;
   b. Visitor characteristics – only citizens or also private companies;
   c. Demographic data – service area and population size;
   d. Collection policies concerning paid and free waste dumping;
   e. Desired layout (form) of the site and platform;
   f. Desired routing;
   g. Performance targets concerning average queue lengths, waiting times, etc.
2. Use a list of requirements and client wishes to create a layout plan:
   a. Number of sub stations needed;
   b. The overall layout (U-flow, line-flow or o-flow, etc.);
   c. Area needed for the site;
   d. Road requirements;
   e. Number of entrance and exit gates;
   f. Presence and location of weighing scales;
3. Use demographic data and waste volumes to decide upon initial sizing for waste streams.
4. Use current practice to perform an initial allocation of the waste streams.
5. Configure a base case simulation model of the waste disposal station based on layout plan, determined capacities and allocation.

6. Analyse the performance of the base case model to find points for improvement. Once the performance of the base case model has been determined steps can be taken to find an ideal design logistically and according to client wishes.

Some of the steps in the design process need more elaboration. Step 5, concerning the creation of the base case is done in several steps. First we calculate the amount of container time that is needed to serve all the visitors that are expected to dump waste for each waste stream. Based on these numbers we can estimate how many containers are needed per waste stream (step 3). For this calculation we need to keep in mind though that there are different types of visitors regarding the amount of space they require. We have visitors driving normal cars and visitors coming with a large vehicle or a trailer. This needs to be taken into account as well when calculating the number of containers that is needed. After determining the needed capacity we can turn our attention to the allocation (step 4). If the municipality (client) wishes to split the collection into those that are free to dump and those for which we have to pay, this is done first. Once that division is made the waste streams are divided into the desired number of substations. Usually three substations are used. One is located around the chemical waste hand-in (usually the free area) and one will be the platform built according to the 'modulo' concept. The final substation is usually located after the platform, but could also be located before the platform. The division of waste streams located at the platform and not at the platform is based on the distinctive containers used to dump these waste streams in (see Section 2.4). 30 m^3 containers are usually placed at the platform. Any smaller containers are placed elsewhere. After these steps the input for the base case model is complete. This is all inserted into a simulation model as input and then we have our base case model.

Step 6 can basically be substituted with the general experimental design that is described through a set of steps below.

Steps for improving initial design:

1. Determine better allocation of waste streams by performing swaps according to a local search method and several design rules based on developed knowledge. This means swapping waste streams' container location. Several heuristics may be used to find better allocations. E.g. steepest descent or simulated annealing with or without tabu. If, after finding the best possible design with the current capacity settings, performance targets have not been met then go to step 2;
2. Attempt to isolate problem cases (like crude garden waste) to see whether this has a positive impact.
3. Analyse the effect of utilising a max for the number of cars present on the waste disposal station at all times.
4. Analyse the effect of altering buffer sizes (road capacities) in case of extreme low or high utilisation of buffer spaces (neither are desired (extreme low means excess capacity you pay for and extreme high means congestion issues on the roads in reality)).
5. Try swapping the order of the substations. This step should be done sparingly (not more than k-1 times; k being the number of substations).
6. Determine the waste stream with largest waiting time in the optimal setting of the base case. Increase its capacity by one, unless there is reasonable doubt as to whether that waste stream has not enough capacity. In other words, try to find a waste stream that may be the cause for most of the problems and increase the capacity of that waste stream by one. The new container is inserted at a spot where improvement is expected. This may be an educated guess based on

the performance after the latest improvement step. Find the best allocation for that setting. Repeat steps three to five until the desired performance is achieved.

The design rules used to generate a good base case can change over time as the model is used more and insight, experience and certain design concepts are developed that prove to be beneficial to performance. These same developed principles can be used to select swaps in the project phase where the base case model is improved until the desired performance is guaranteed.

5.4 Summary

After answering all our sub-questions we were able to program a simulation model. While verifying and validating this model we found out that our programmed model had some flaws in it as the performance indicator (sojourn time) used for validation measured a value different from real life data. As a response we took some counter measures to ensure more realistic outcomes. Upon finishing our programmed simulation model we formulated an experimental design to test our model in an attempt to improve a waste disposal station. We also formulated a general plan for use in a design process of a waste disposal station. In the next chapter the results from running experiments are provided and analysed.

Chapter 6 Experimental Results and Implications

This chapter discusses the results of the experiments whose design has been discussed in Chapter 5. Section 6.1 focusses on the results of the experiments described in Section 5.2. This means that the focus is on improving an existing waste disposal station without doing a complete overhaul. Special focus is first given to the capacity of several waste streams that have shown potential for improvement based on the waiting time and sojourn time observed as outcome of the results of the base settings of the simulation model. In Section 6.2, advice is given on how to ultimately decide upon the dimensioning of the site. Also some general advice is given concerning allocation. The final section describes how the simulation model and a general experimental design, described in Section 5.3, are utilised in a design process to come to a good design for a waste disposal station.

6.1 Experimental Results

This section primarily pays attention to the waste disposal station studied. First we try to improve the performance by looking at the substation where only “CrudeGardenWaste” is located. Afterwards, we take a look at the “OtherSubStation”. More specifically, we look at some of the other waste streams there that show potential for improvement (based on the current value of the waiting time and sojourn time of these waste streams). Then, we analyse the effect of reducing capacity at the “SmallChemicalDepot”. Finally we take a look at other interventions (described in Section 5.2).

6.1.1 Crude garden waste at the “SubStationPlatform”

In order to determine the right amount of containers for the crude garden waste substation, which is currently three, we analyse the effect of incrementally increasing the capacity by 1. Just by looking at the average sojourn time (see Table 22) at the platform (substation platform) and the waste stream in question (crude garden waste) we can see that increasing the capacity does indeed reduce the sojourn time and its variance, as was expected (see Table 22). The total sojourn time also reduces, though relatively less than at the substation. Interesting to see is that the effect of increasing the capacity to four containers (+1) seems to be larger than the effect of increasing the capacity to five containers. The sojourn times for the other substations and waste streams do not change as much, so we have decided to mainly analyse the changes observed for crude garden waste more thoroughly.

		Sojourn time; mean (sec), variance (sec^2)		
		SubStation Platform	Crude Garden Waste	Total 2 (including driving time between substations)
base case (3 containers)	Mean	355.06	355.06	487.47
CrudeGardenWaste +1	Mean	306.61	306.61	454.33
CrudeGardenWaste +2	Mean	294.36	294.36	448.60
base case	variance	82246.13	82246.13	162805.09
CrudeGardenWaste +1	variance	66060.43	66060.43	122802.13
CrudeGardenWaste +2	variance	63312.63	63312.63	118367.38

Table 22 Simulation results of the sojourn time at the platform and the entire site of the base case

After performing a pairwise analysis and constructing a paired t- 95% confidence interval, the results (see Table 23) clearly show that there is a significant reduction in sojourn time for "CrudeGardenWaste". We can also once again clearly see that the decrease in sojourn time is larger for the first time the capacity was increased (from three to four containers). The waiting times show the same pattern (see Table 23). Strange enough the decrease in waiting time seems to be much larger than the decrease in the sojourn time. However, this could be caused by the fact that the service rate (determined by the number of visitors processed per day) is higher when the capacity for crude garden waste is increased. This means that the visitors that were processed "extra" could have had a sojourn time close to the mean, but a waiting time that was much lower. This may have resulted in this strange phenomenon.

A pairwise analysis concerning the change in total sojourn time showed that the decrease in sojourn time for the waste stream CrudeGardenWaste cannot be translated directly to an equal decrease in the total sojourn time. So, apparently there is an effect on the utilization and hence also on the sojourn time at other waste streams. Since this is spread over several waste streams the results there were observed to be minimal. Yet, in total the effect of the other waste streams lead to a reduction of the improvement in total sojourn time that could have been realised.

The results for the total waiting time (See Table 23) illustrate the same conclusions mentioned earlier.

	C I decrease sojourn time garden waste	C I decrease waiting time garden waste	C I decrease total sojourn time	C I decrease total waiting time
Comparison base case with CrudeGarden+1	48.45 ±0.32	119.84 ± 0.57	33.14 ± 0.16	33.73 ± 0.16
Comparison CrudeGarden+1with CrudeGarden+2	12.25±0.09	21.38 ± 0.12	5.74 ± 0.04	5.79 ± 0.04

Table 23 Pairwise comparison to analyse decrease in sojourn time for crude garden waste after increasing capacity for crude garden waste by one and two containers

6.1.2 The "OtherSubstation"

At the "OtherSubStation" we have chosen four experimental factors. Three of these factors can be increased (Debris, HardPlastics and Plaster) and one can be decreased (AnBGradeWood). We have grouped these into three sets of experiments. One for each of the waste streams selected for increase.

6.1.2.1 Debris

The first waste stream selected for increase at the "OtherSubStation" is Debris. It was one of the few waste streams within the "OtherSubStation" with a substantial waiting time. Comparing the several options selected in Section 5.2.2, we can observe (see Table 24) that almost none of these options showed a decrease in the total sojourn time. Increasing the capacity for Debris of course reduced the average sojourn time for that waste stream. However, this is merely a local improvement as it does not lead to a decrease in the total sojourn time. This is not the case for the simulation where we increased the capacity of Debris with one and decreased the capacity of CrudeWaste with one. However, this decrease seems to be so small that it hardly seems worth the effort of changing. To analyse this difference more thoroughly, to see whether it is actually statistically significant, we have decided to do another pairwise analysis for Debris+1, CrudeWaste-1.

After creating a 95%-confidence interval of the paired differences of the results generated with the different model settings we see that zero does not lie in this interval (0.81, 0.84). In other words this means the observed decrease is statistically significant. However, the improvement is so small that it hardly warrants making the change in reality.

	Sojourn Time (sec)					
	Other SubStation	AnBGrade Wood	Crude Home Waste	Crude Waste	Debris	Total Sojourn Time 2
base case	260.59	138.31	91.91	61.61	138.78	487.47
Debris +1, AnB -1	258.55	146.32	91.86	61.05	118.10	487.75
Debris +1, CrudeWaste -1	259.09	138.73	93.10	69.33	122.97	486.96
Debris +1, CrudeHomeWaste -1	261.30	139.46	105.12	62.02	119.66	489.26

Table 24 Overview of sojourn time for several capacity changes at the other substation (increase in debris)

When looking at the waiting times in Table 25, we observe that the waiting time is also smaller, although slightly. The waiting time for Debris shows a sharp reduction, but in total the waiting time does not improve that much. We have once again performed a pairwise analysis and once again zero is not included in the confidence interval (1.17, 1.21). So once again the difference in waiting time is statistically significant, but not sufficiently large enough to execute the change in capacity in real life.

	Waiting Time (sec)				
	Other SubStation	Crude HomeWaste	Crude Waste	Debris	Total Waiting Time
base case	14.33	1.52	1.89	22.78	72.93
Debris +1, CrudeWaste -1	12.34	2.70	9.63	6.24	71.75

Table 25 Overview of waiting time for change in capacity at other substation (debris+1, crudewaste -1)

6.1.2.2 HardPlastics

The second waste stream selected at the "OtherSubStation" for experimentation was HardPlastics. We can be very brief for this waste stream as none of the experiments showed a reduction in sojourn time (see Table 26); therefore we will not perform a more thorough analysis. Since the current setting features only one container for hard plastic we cannot reduce the capacity to study its effect as each waste stream needs a capacity of at least one container.

	Sojourn Time (sec)					
	Other SubStation	AnBGrade Wood	Crude Home Waste	Crude Waste	Hard Plastics	Total Sojourn Time 2
base case	260.59	138.31	91.91	61.61	138.78	487.47
HardPlastics +1, AnB -1	259.17	146.38	91.62	61.20	97.73	488.06
HardPlastics +1, CrudeWaste -1	261.69	138.52	92.65	68.73	112.26	488.72
HardPlastics +1, CrudeHomeWaste -1	262.70	139.41	104.47	61.67	100.46	490.09

Table 26 Overview of sojourn time for several capacity changes at the other substation (increase in hard plastics)

6.1.2.3 Plaster

The final waste stream selected for experimentation at the "OtherSubStation" was Plaster. This waste stream showed the same lack of potential for improvement through the experiments selected (see Table 27). And once again, as there is only one container for plaster in the current setting, we cannot reduce the capacity.

	Sojourn Time (sec)					
	Other SubStation	AnB Grade Wood	Crude Home Waste	Crude Waste	Plaster	Total Sojourn Time 2
base case	260.59	138.31	91.91	61.61	138.78	487.47
Plaster +1, AnB -1	263.55	146.58	356.12	91.52	240.10	490.99
Plaster +1, CrudeWaste -1	261.44	138.58	356.08	92.71	241.46	488.54
Plaster +1, CrudeHomeWaste -1	263.85	139.90	359.70	103.37	241.82	497.83

Table 27 Overview of sojourn time for several capacity changes at the other substation (increase in plaster)

6.1.3 The "SmallChemicalDepot"

At the "SmallChemicalDepot", coincidentally also the free area of the waste disposal station, there is one central area for parking from where visitors can walk up to the containers dedicated to the waste streams they have brought. The capacity here is measured solely in parking spaces and the number of parking spaces is unrelated to the number of containers placed there. Since the current state of the "SmallChemicalDepot" yields a very small average waiting time, we have decided to study whether the number of parking spaces could be reduced.

	Avg # visitors per day	Service rate	Sojourn Time (sec) Entrance WDS	Small Chemical Depot	Total
base case (16 parking spots)	743.32	0.97	16.97	194.64	487.47
SCD -1	743.32	0.97	17.00	194.72	487.78
SCD -2	743.32	0.97	17.00	194.72	487.78
SCD -6	743.32	0.97	17.00	194.78	487.81
SCD -8	743.2	0.97	17.00	195.65	488.60
SCD -9	732.14	0.96	17.12	197.43	492.35
SCD -10	698.44	0.92	17.32	204.26	493.09
SCD -11	643.98	0.84	20.47	221.63	503.93
SCD -12	397.1	0.52	44.03	272.64	548.88

Table 28 Overview of sojourn time for several capacity changes at the Small Chemical Depot

	WaitingTime (sec) EntranceWDS	SmallChemicalDepot	Total
base case	6.28	4.07E-11	72.93
SCD -1	6.30	4.06E-11	73.24
SCD -2	6.30	4.06E-11	73.24
SCD -6	6.30	0.07	73.27
SCD -8	6.31	0.93	74.09
SCD -9	6.41	2.86	76.90
SCD -10	6.60	9.35	78.51
SCD -11	9.75	27.80	89.95
SCD -12	33.31	81.55	132.54

Table 29 Overview of waiting time for several capacity changes at the other substation (increase in debris)

In the base case, the capacity of the small chemical depot is sixteen. Table 28 shows that no apparent differences occur until the capacity of the "Small Chemical Depot" is reduced by half. The difference in sojourn time is still relatively small though. However, we have observed that due to a combination of less capacity and a problematic crossroad, fewer visitors were able to get through to the rest of the waste disposal station for processing. This effect becomes clearer when capacity is reduced further. First the average daily visitors let through reduces with about 10 (capacity reduced by nine), but when the capacity is reduced by ten this increases to about 44. And when the capacity is reduced by twelve, the number of visitors processed is reduced to 397 (a reduction of 346). The increase in sojourn time starts relatively small. However, fewer visitors were processed and the visitors not processed were the visitors who would have waited a long time at the entrance due to the "Small Chemical Depot" being very busy. In conclusion, with the current arrival rate it is unwise to decrease the capacity of the "Small Chemical Depot" with more than six parking places. This still leaves some overcapacity to deal with extremely busy moments.

When looking at the waiting time, (see Table 29) one can see that the increase also starts only slightly (for the "Small Chemical Depot") at a reduction of six. The waiting time increases exponentially until the average waiting time is equal to 33 seconds at the entrance, 81 seconds at the "Small Chemical Depot" and 132 seconds in total for the entire site. Note that this average is calculated only for visitors that actually got through to the rest of the site.

6.1.4 Further interventions

The other interventions we have decided to test for the improvement study of the waste disposal case are discussed in this section. We have executed based on, and compared with, the base case. This means that the changes for improvements identified in the earlier parts of Section 6.1 are not taken into consideration yet. In total we have decided to test four interventions. First, we look at what would happen if we locate the busiest and most time consuming waste stream with one of the largest variance in the service time (crude garden waste) and relocate it. At the moment it is located at a separate substation. We are interested in what happens if it is placed at the “OtherSubStation” where all the other waste streams (that require payment) are located. This should give us an idea of what the impact is of isolating such a waste stream to make sure its busy process does not affect other waste streams too much. Afterwards we take a look at what would happen if we place all containers of one waste stream in adjacent spots. This should give us an idea of the impact of spreading containers of one waste stream throughout the waste disposal station. The third intervention we study is the impact of the crossroad that is so inconveniently located. What would happen if we decrease its capacity? That is, what would happen if fewer cars can wait in front of the weighing scale? The final intervention studied is the effect of limiting the number of visitors on the site. Can this lead to an improvement of the flow of visitors through the system?

6.1.4.1 Placing CrudeGardenWaste at the “OtherSubStation”

One of the interventions we want to analyse is the effect of placing the busiest waste stream with the highest mean service time and variance in the service time together with the other waste streams. The goal was to see whether isolating a waste stream like this has a positive effect on the mean sojourn time, the waiting time and the length of queues. Surprising enough the results presented in Table 30 illustrate that isolating “CrudeGardenWaste” has had a negative effect on the total sojourn time (for the complete table including all waste streams see Appendix G). We observe that the total sojourn time is lower when crude garden waste is located with all the other paid waste streams at one substation.

	Sojourn time (sec)			
	base case	CrudeGardenWaste at end of OtherSubStation	CrudeGardenWaste in middle of OtherSubStation	CrudeGardenWaste in between AnBGradeWood
EntranceWDS	16.97	16.99	16.99	16.95
SmallChemicalDepot	194.64	194.70	194.71	194.61
WeighingScale	16.59	16.61	16.61	16.63
SubStationPlatform	355.06	NA	NA	NA
OtherSubStation	260.59	359.46	350.42	350.20
ExitWDS	11.39	11.52	11.41	11.41
Total Sojourn Time 2	487.47	454.27	447.63	447.94

Table 30 Overview of sojourn time at several locations of the waste disposal station influenced by the location of crudegardenwaste

Since this did not meet our expectations we decided to take a look at other performance indicators. First we looked at the total number of observations. Table 31 shows that interestingly enough the flow seems to have deteriorated as well after isolating “CrudeGardenWaste” (which is done in the base case). After placing “CrudeGardenWaste” at the “OtherSubStation” (at several locations) we have seen that in each of these cases (placing said waste stream at the end of the substation or in the middle, or between containers of another busy waste stream) the number of visitors processed during the simulation had increased. Keeping this in mind these phenomena are suddenly logical from a modelling point of view. One of the assumptions and one of the simplifications could have had an influence in reaching the observed results. First of all, the model was programmed in such a way that there is potential for cars to drive past busy stations, so the blockages that might occur in real life are not so visible in the model. Also, the driving times within substations are ignored resulting in smaller sojourn times at the "OtherSubStation". These considerations triggered our interest in the difference in the recorded average queue length of the several settings.

	Avg # visitors processed daily	Service rate
base case	743.32	0.97
CrudeGardenWaste at end of OtherSubStation	745.18	0.98
CrudeGardenWaste in middle of OtherSubStation	745.34	0.98
CrudeGardenWaste in between AnBGradeWood	746.22	0.98

Table 31 # visitors processed by the waste disposal station simulation for different scenarios

In Table 32 these differences are analysed through creating 95% confidence intervals of the differences. First we see the influence on the buffer space in front of the "OtherSubStation". In all cases it is clear that the number of busy moments has increased as the average queue length at the buffer is higher for all the cases where crude garden waste is located at the "OtherSubStation".

	Queue at OtherSubStation Buffer	Queue at Track2 fictive buffer
Comparison base case - CrudeGardenWaste in the middle	-0.0278 , -0.0276	0.0000 , 0.0001
Comparison base case - CrudeGardenWaste at the end	-0.0528 , -0.0525	0.0511 , 0.0512
Comparison base case - CrudeGardenWaste between AnBGradeWood	-0.0150 , -0.0149	0.0524 , 0.0526

Table 32 Change in queue length at the buffer of the othersubstation for several different locations of crudegardenwaste

The second observation (see Table 32) interestingly enough shows that the queue length for the fictive buffer is higher for the base case than for the other cases studied in this section. This illustrates that the increase in arrival rate at specifically the OtherSubStation was not so high, as in most cases the buffer space was enough to deal with this extra flow of visitors.

In short, the results hint at an improvement in average sojourn time if all paid waste streams are located at one and the same substation. However, we suspect that, due to the assumptions and simplifications that lie at the base of our model, the results we generate in this case are not an accurate representation of reality. Therefore we think this experiment should be executed with a model that more closely represents reality in order to see whether indeed isolating a busy waste stream has a negative effect on the sojourn time. Logically this seems unreasonable as isolating said waste stream should result in more space for both the isolated waste stream as the group of other waste streams (buffer and parking spots). This should lead to less blocking, therefore a better flow through the station and hence a smaller sojourn time.

6.1.4.2 Concentrating all waste streams

The next phenomenon tested was concentrating all containers of a waste stream. This means that all containers of "AnBGradeWood" are placed next to each other. The same is done for all waste streams with more than one container. The results show an increase in sojourn time for nearly all waste streams (see Table 33 for a selection of the results and for the complete table including all waste streams see Appendix H). This was expected as concentrating the waste streams reduces the positive effect of shared capacity (in parking spaces) on the sojourn time. If three containers placed next to each other have different waste streams, e.g., AnBGradeWood, crude waste and crude home waste, then the visitors parking in front of the middle container can quite easily visit three waste streams from their parking spot. If these containers had all been dedicated to wood, then the middle parking spot would only be appealing for a visitor bringing wood. In the table gravel especially has a very large notable increase. This may be attributed to the fact that as the visitors bringing busy waste streams have effectively less parking spots to dump waste from, the pressure on other neighbouring waste streams will increase tremendously. This was the case for gravel.

To see whether the observed difference is significant (for the total sojourn time) we have performed a pairwise analysis. The confidence interval of the paired differences (-2.34 ±0.02) does not contain zero, the (negative) difference is indeed statistically significant. Also since the entire confidence interval is negative it illustrates that concentrating the waste streams has indeed a negative effect on the sojourn time. The difference is, however, relatively small.

Analysing the pairwise differences of the total waiting time showed a negative mean, and since the 95%-confidence interval (-0.42 ± 0.03) does not contain zero we may conclude that the difference in total average waiting time is statistically significant.

	Sojourn time (sec)	
	base case	Concentration of waste streams
EntranceWDS	16.97	16.99
SmallChemicalDepot	194.64	194.74
WeighingScale	16.59	16.60
SubStationPlatform	355.06	356.19
OtherSubStation	260.59	262.33
ExitWDS	11.39	11.39
Total Sojourn Time 2	487.47	490.13
AnBGradeWood	138.3077	140.5027
C_gradeWood	195.7248	198.7477
CrudeHomeWaste	91.90635	96.0734
Debris	138.7823	137.9814
Gravel	69.52585	172.6252
HardPlastics	116.2547	109.4592

Table 33 Sojourn time at several locations of the wds and a selection of waste streams when waste streams are concentrated

6.1.4.3 Reducing the space at the crossroads

Reducing the space for the buffer mainly increased the sojourn time at the front gate (see Table 34 and for the complete table including all waste streams see Appendix I). This was to be expected as we have programmed our model to not let visitors past the entrance gate if the buffer in front of the weighing station is full. When looking at the waiting time though, we also see an increase in the waiting time for the weighing itself. This was also once again expected. Pairwise analyses showed a few things (see Table 35). First, all of the differences for the total sojourn time and waiting time are statistically significant. The mean difference is negative in both cases, suggesting that decreasing the buffer space has a negative effect. This exact same situation was observed for the sojourn time and waiting time at the entrance.

	Sojourn time (sec)		Waiting time (sec)	
	base case	WeighingBuffer -1	base case	WeighingBuffer -1
EntranceWDS	16.97	18.96	6.28	8.25
SmallChemicalDepot	194.64	194.53	4.07E-11	4.06E-11
WeighingScale	16.59	15.26	5.73	10.87
SubStationPlatform	355.06	362.47	182.2	193.14
OtherSubStation	260.59	260.38	14.33	14.07
ExitWDS	11.39	11.42	2.53	2.56
Total Sojourn Time 2	487.47	491.98	72.93	80.88

Table 34 Sojourn time and waiting time of the base case and WDS after reduction buffer at weighing scale

	Confidence interval
Comparison sojourn time base case - WeighingBuffer-1	-4.01 ± 0.18
Comparison waiting time base case - WeighingBuffer-1	-7.48 ± 0.17
Comparison entrance sojourn time base case - WeighingBuffer-1	-1.94 ± 0.03
Comparison entrance waiting time base case - WeighingBuffer-1	-1.93 ± 0.03

Table 35 pairwise comparison of sojourn time and waiting time of the entire site and at the entrance

6.1.4.4 Limiting the number of visitors

The final intervention we test is installing a limitation on the number of visitors that are allowed to be present on the site at all times. The size of the terrain is kept the same, but as soon as the limit is reached cars that arrive subsequently have to wait in front of the entrance of the waste disposal station. The results presented in Table 36 illustrate that the sojourn time increases as the capacity of the waste disposal station decreases. However, there is little in the model that takes the effects of extreme busy moments into account. There is the waiting time of course, but in reality manoeuvring becomes more difficult as more cars are present. This could potentially result in slower driving, slower processing, and even blocking. Since none of these effects have been taken into account in the programmed model, the potential benefits of reducing the number of cars on the waste disposal station cannot be observed.

	Total Sojourn Time 2 (sec)
MaxCap 20	547.38
MaxCap 40	487.85
MaxCap 60	487.78
Base Case (100)	487.47

Table 36 Overview of total sojourn time under influence of policy limiting # cars on the site

6.2 Implications

In summary we have learnt several things from the experiments done. We have found ways to improve the waste disposal station of our main case by making capacity changes. By increasing the capacity for crude garden waste we were able to reduce the average total sojourn time by a sound eight percent. The other waste streams that were selected for the experiments did not show as much potential for improvement (none of the changes yielded much improvement). However, since for these waste streams the base case did not show a lot of waiting time (compared to crude garden waste) this was to be expected. Interestingly enough experimentation showed that the capacity of the small chemical depot area could be reduced by half without a serious increase in sojourn and waiting time. However, when this reduction becomes larger than ten containers serious issues start to manifest. The sojourn time and waiting time increase considerably and the waste disposal station can handle a lot fewer visitors per day. Clearly blocking occurs at the front of the waste disposal station resulting in a lower throughput.

We have also determined other interventions that can improve the performance of a waste disposal station in general. We have seen that having enough space between separate parts (entrance and weighing scale) of the waste disposal station is very important. If that space is not sufficient, blocking occurs and the throughput of the waste disposal station can be a lot smaller than the design's potential. Another key intervention is making sure that the containers of waste streams are spread out to ensure maximum accessibility from the parking spots. However, this warrants more research. It seems very logical that waste streams that are placed near one another influence each other's sojourn time. E.g., if containers of waste streams that hardly get any visitors are place right next to each other, then these containers will not be utilised enough. If, however, a busy waste stream and a slower one are placed in each other's vicinity then the parking spots in front of the container for the slow waste stream will be utilised by visitors coming for the busy waste stream. This means that, as there are effectively more parking spaces that can be used for dumping by the visitors coming for the busy waste stream, the waiting time for that busy waste stream should reduce. Also, if the pressure on the parking spots utilized for several waste streams is not too high, the overall waiting time and sojourn time should become lower as a result. Otherwise the waiting time may increase a lot for the other resulting in either a smaller improvement or no improvement.

Another very important lesson we learnt was that the focus should not always be primarily on "problematic" waste streams. These waste streams are brought by a lot of visitors, take a long time to dump and have a high variance in dump time. Instead an initial design should be formulated based on the clients' wishes and several design rules. Then, after simulating that design, its weak points (if present) should be pinpointed. Once these weak points have been identified, one can postulate ways to improve the design to deal with these weaknesses (if the weakness is due to a design decision that can be influenced). Then these 'interventions' can be tested to see whether making design changes would indeed improve the performance.

In conclusion, the waste disposal station studied has a better performance if there is room enough for ten cars to dump crude garden waste at the same time (space equivalent to 5 containers). Furthermore, the other substation with paid waste streams performs well enough (the small improvement of less than a second that is possible is not worth the effort of change). The small chemical depot can be reduced in size if there ever needs to be space for more containers or roads to get rid of the problematic crossroad. Apart from these points, there is not a lot of improvement possible while keeping the layout of the site mostly the same.

6.3 Performing the Experiments for a Waste Disposal Design Process

In this section we attempt to generate a new design for the waste disposal station we have studied so far. The idea is to generate this design based on knowledge we have gathered on the waste disposal stations and the demographic data and waste diversion policies provided by the waste disposal company managing the waste disposal station we have studied so far. The first step in this process is to generate a new base case model starting with determining the necessary capacity for all waste streams, substations and buffers. This is done in Section 6.3.1. Then, in Section 6.3.2, we simulate this base case model and based on the result we commence with an improvement plan to improve the base case model. Several steps of the improvement plan (described in Section 5.3) are executed to demonstrate the workings of the developed improvement plan.

6.3.1 Creating a base case design

After performing the necessary calculations, the capacity has been determined for all waste streams and the small chemical depot area where there is a central parking area. Interestingly, the capacity is in all cases either lower or equal to the current settings of the waste disposal station under study (see Table 37). This can be attributed to the fact that we decided to base our initial capacity on the number of visitors that go through the waste disposal station per hour on average based on daily data. This means that if all cars arrived at the waste disposal station perfectly spread out over the day then this capacity should be enough. In reality, however, there is a lot of variation in the arrivals.

Waste Stream / Substation	# containers needed (Paid streams) or parking spots (SCD)
A and B grade wood	1
C grade wood	1
car tires	1
crude home waste	1
crude waste	1
debris	1
crude garden waste	2
gas concrete	1
gravel	1
hard plastic	1
mattresses	1
plaster	1
roofing waste	1
SCD	10

Table 37 Overview of container capacity of all the waste streams and parking site at the small chemical depot

The second step in creating a base case design is to determine the allocation of the waste streams. The first allocation decision to make is connected to a waste diversion policy. Which waste streams will be free to dump and for which waste streams will visitors have to pay? For this division we hold to the current waste diversion policy of the waste disposal company whose waste disposal station we have studied. The division is therefore the same as mentioned in Section 4.2. The second allocation decision concerns the division of the paid waste streams into those that are collected at the platform and those that are not collected at the platform. This decision was based on current practice in the Netherlands. This does not mean that no other options are available, but these rules provided us with a reasoned choice. According to current practice some waste streams are collected in containers with a size of $30m^3$. These are all placed at the platform. Other waste streams are collected away from the platform. A municipality could decide to collect waste streams using certain containers which will then influence their allocation to a substation, but for this case we will follow the container choice provided in Section 2.4. The resulting allocation can be found in Table 38. For a start we have decided to concentrate all waste streams. This means we place all containers of one waste stream next to each other.

Waste Streams	Substation (placement)
AnBGradeWood	Platform (4, 5)
Asbestos	Small chemical depot
C_gradeWood	Platform (6)
CarTires	Other substation (2)
ChemicalWaste	Small chemical depot
CrudeGardenWaste	Platform (7)
CrudeHomeWaste	Platform (3)
CrudeWaste	Platform (2)
Debris	Other substation (6)
E_Waste	Small chemical depot
GasConcrete	Other substation (3)
GlassBottles	Small chemical depot
GlassPlates	Small chemical depot
Gravel	Other substation (4)
HardPlastics	Platform (1)
Mattresses	Other substation (5)
OldMetal	Small chemical depot
PaperNCarton	Small chemical depot
Plaster	Other substation (1)
RoofingWaste	Other substation (7)
SoftPlastics	Small chemical depot
Styrofoam	Small chemical depot
Textile	Small chemical depot

Table 38 Overview of the locations of the waste stream

Since we have no experience making decisions about roads (and indirectly the buffer size of the site) we have opted to use the buffer sizes with capacity as large as was set for the base case model studied in Section 6.1. We will make one exception though. Since the crossroad mentioned in the previous sections (Section 5.2 and Section 6.1) is intuitively a weak point in the current design, we enlarge the capacity of the road (buffer) before the weighing station to eight. Using these allocation and capacity decisions together with the input data we have extracted (Section 4.3) we have a new base case model which we will analyse and improve in Section 6.3.2.

6.3.2 Creating a suitable design; improving the base case model

Performance base case

After running the simulation for the new base case it is clear that the performance is lower than it should be. The number of visitors processed (on average 341 a day) is clearly much lower than the average number of daily visitors it is supposed to handle (on average 763 on a Saturday). The waiting times show that there clearly is not enough capacity at the platform substation (see Table 39). Collectively, the average waiting time there is more than a stunning eleven minutes (664 seconds). Looking at the performance of the separate waste streams located at that substation (see Table 40), all of them have a high average waiting time. We suspect that not a lot of improvement will be gained in this case if we perform simple swaps. Therefore we immediately start with increasing the capacity for some waste streams in an attempt to improve the performance. Earlier in Section 5.2, we stated that we should first focus on the waste streams that are brought a lot, have a large processing (dump) time and also a high variability in the processing time (see Table 20 in Section 5.2.2). We can now check whether that has the most impact. Following that rule we will start increasing the capacity for crude garden waste and A and B grade wood with one.

Improvement step 1: adding capacity for "CrudeGardenWaste" and "AnBGrade Wood"

By just placing these two containers (one for "CrudeGardenWaste" and one for "AnBGradeWood") we have reduced the average waiting time at the platform with about 47% to 6 minutes (see Table 39). We have also improved the flow in such a way that on average 407 visitors were processed per day (20358 visitors in 50 runs). Interestingly enough, we observe that the waiting time at the substation platform is higher than for the entire site. This is caused by the fact that some visitors may not have visited the platform. In other words, the average of the total waiting time contains more observations than just those of visitors that visited the platform where the waiting time was relatively high.

Upon inspecting the average waiting time of the waste streams located at the platform (see Table 40) again we can observe that the waiting times have been reduced sharply. We suspect that the capacity is still not enough, but will demonstrate some of the other improvement steps. We will start by performing some swaps. Since we demonstrated that spreading waste streams improves the accessibility of waste streams we will start by swapping an "AnBGradeWood"-container with a "CrudeWaste"-container

Improvement step 2: swapping a "AnBGradeWood"-container and a "CrudeWaste"-container

After swapping "AnBGradeWood" and "CrudeWaste" we have seen that the flow has once again improved to an average of 448 per day (22420 visitors in 50 runs). We have seen that swapping the containers of "AnBGradeWood" and "CrudeWaste" has improved the performance for these waste streams (see Table 40). The waiting time for some of the other waste streams has increased ("CrudeGardenWaste", "C_gradeWood" and "HardPlastic"). This is probably caused by the fact that pressure on these waste streams has increased while the pressure for the other waste streams has decreased. This pressure could also be caused by an increase in the number of visitors that are processed daily. We know from experience that isolating a problem case, limiting the number of visitors present on the waste disposal station and increasing the buffer size had little effect on the performance. For this reason we do another capacity increase improvement step. CrudeHomeWaste and HardPlastics have the highest waiting time. Apart from "AnBGradeWood" and "CrudeGardenWaste" they and CrudeWaste have the highest frequency. Their mean service time – variance ratio is similar and therefore all of them are potential candidates for a capacity increase. We decide to select "CrudeHomeWaste" and "HardPlastics"

Improvement step 3: increasing capacity "CrudeHomeWaste" and "HardPlastics" with one container each

After increasing the capacity of "CrudeHomeWaset" and "HardPlastics", the waiting time increased for nearly all the waste streams at the platform (see Table 40). However, the number of visitors processed has once again increased to about 529 per day. In other words the service level has improved. This leads us to conclude that either the capacity is not nearly enough or the allocation should be handled differently. An idea that has not been tested so far is to make sure that busy waste streams and slow waste streams should be balanced. To this end we will relocate plaster and mattresses to the platform to test this idea.

Improvement step 4: relocate plaster and mattresses to the platform

Since the number of visitors processed decreased to 475 per day, when we relocated plaster and mattresses to the platform, we will not enforce this step since it was apparently not successful. The average waiting time may have decreased, but the service level decreased as well. The importance of the service level becomes clearer upon some extra elaboration. Since we remove all observations from the simulation results that have not been processed completely, a lot of the visitors that have a high waiting time are not included in the results. That is why in cases of a lower service level the waiting times may be lower than in cases where the service level is high.

Since we were unable to book progress with this step, we decided to swap "C_gradeWood" and "AnBGradeWood" instead.

Improvement step 5: swap C_gradeWood with AnBGradeWood

After swapping "C_gradeWood" and "AnBGradeWood" more visitors were processed (an average of 540 a day), so improvement has been realised. However, since the waiting times are still relatively high we have decided to once again increase the capacity.

Improvement step 6: Increase capacity CrudeGardenWaste to 5 containers and increase capacity of CrudeWaste by 1

Adding containers until the capacity of CrudeGardenWaste is equal to five containers and "CrudeWaste" has a capacity of two improves the performance considerably (see Table 40). The number of visitors that is processed has become an average of about 695 a day. The waiting times at the platform have also decreased considerably.

Improvement step 7: swapping the locations of the platform and the othersubstation

After swapping the substations where paid waste is dumped we once again observe improvement on more than one level. The total number of visitors processed has once again increased (on average 718 per day) and there has been a lot of improvement in the waiting times. Clearly the order of the substations has an impact on the performance as well. The average waiting time at the platform may have increased the total average waiting time has decreased by half a minute. The waiting time of the waste streams located at the platform (that has now been placed at the location of the othersubstation) has decreased immensely.

	Entrance WDS	Small Chemical Depot	Weighing Scale	SubStation Platform	OtherSub Station	ExitWDS	Total
Base case 2	48.22	0.51	53.26	664.99	1.85	1.48	304.73
Improvement step 1	11.50	0.07	17.29	360.26	2.35	1.65	11.50
Improvement step 6	6.04	0.03	4.4	121.49	6.29	2.39	82.07
Improvement step 7	6.02	0.03	4.05	151.7	5.13	2.35	51.17

Table 39 Waiting time of several parts of the WDS

	AnBGrade Wood	C_grade Wood	CrudeGarden Waste	CrudeHome Waste	CrudeWaste	HardPlastics	Service level
Base case 2	446.59	193.65	234.01	546.98	378.74	796.59	0.45
Improvement step 1	220.91	132.43	95.03	328.67	233.18	383.22	0.53
Improvement step 2	176.38	151.21	142.12	315.04	146.15	424.13	0.59
Improvement step 3	239.91	190.86	180.73	289.9	212.59	302.83	0.69
Improvement step 4	211.96	171.71	166.11	245.78	217.20	196.66	0.62
Improvement step 5	268.75	260.55	240.67	391.76	321.2	296.65	0.71
Improvement step 6	70.08	85.59	41.11	104.67	81.23	94.65	0.91
Improvement step 7	3.48	6.31	2.76	1.83	1.02	4.49	0.94

Table 40 Waiting time of waste streams at the platform and the service rate of the WDS

We have now performed several steps to change the design in order to improve the performance concerning queueing. Further improvement is without a doubt still possible and we have not demonstrated all steps mentioned in the improvement plan of Section 5.3, but the goal of this section was to illustrate how the general steps described there can be used to generate a better design. Therefore we leave it at this instead of performing more steps in an attempt to find the ideal design.

6.4 Summary

After performing and analysing the outcomes of a number of experiments we have learned some important lessons. First of all we have determined which design decisions have the largest impact on the performance. First among these is the sizing of waste streams (how many containers are placed for each waste stream). Second is the order in which substations are located. A substation where waste streams are located that are brought by most visitors, have a long dumping time and a large variance therein should be placed at the end of the waste stream in order to minimize its effect on processes of other substations. Another decision that has some impact is the allocation of the waste streams. Containers of waste streams should be balanced when it comes to the business of the waste streams dumped at them. Also, if a waste stream is represented by more than one container, these containers should be spread out over the substation in order to maximize accessibility. Some of the other lessons learned concern assumptions and simplifications made before we started programming. Some of them resulted in a model that is in ways significantly different from reality. These should be given extra attention when Modulo starts developing their own simulation tool.

Chapter 7 Conclusions and Recommendations

This chapter provides the conclusion of this report. It also provides recommendations on how the results of this project may be used to improve the waste disposal design process for Modulo Béton Canada.

7.1 Conclusions

After doing research, by analysing existing waste disposal stations and studying literature, modelling and simulation, we were able to answer the following research question:

"What model is an adequate way to calculate the waiting times and queue lengths at waste disposal stations?"

This question is answered through answering several sub-questions. The first sub-question is: "Which factors are taken into account when designing a waste disposal station?". We have answered this question in Chapter 2. After reviewing a lot of factors and considerations provided by experts from several waste disposal companies we have created a list of four main decisions. The first of the factors concerns the wishes of the client, e.g., which waste streams are brought to the site and which of these waste streams are free and which are not. The layout (line flow, O flow, S flow, etc.) of the site (aesthetic) is also discussed. Other decisions concern the capacity of the site (how many cars should it be able to handle) based on demographic data, the sizing (the number of containers used for each waste stream) and the allocation of containers (where to place the containers of each waste stream).

The next sub-question was: "Which quantitative model(s) can be used to model a waste disposal facility realistically and how should they be employed?". After studying the literature, we found an article describing an analytical model by Vandaele et al. (2002) that may be used to estimate the queueing results. We say estimate, because one of the assumptions enforced by the use of the model, results in a model whose characteristics deviate from some of the characteristics of a waste disposal station. The model assumes unlimited buffer space between servers. Another issue was the requirement of the model of a transition matrix that describes the routing of visitors through the system. We did not have data to construct this transition matrix and collecting said data would have taken more time than we had available. Instead of using the analytical model of Vandaele et al. we have opted to use a simulation model.

The final sub-question, "What data input is needed for the simulation model and how may this data be collected?", is answered in Chapter 4 where we describe our process towards reaching a conceptual model. Part of this process is describing which data is needed to provide input. We have also described the methods used for collecting said data and processing it to generate input data. We have determined arrival rates (for several distinct hours), service rates (for the entrance, weighing and dumping processes of all the waste streams) and visitor information (vehicle type, waste streams brought, etc.).

By answering these sub-questions and making some additional assumptions and some simplifications we were able to construct a conceptual model. In order to completely answer our research question we have translated this conceptual model into a program. We were able to construct a simulation model, in the software package plant simulation, and test it. After testing said model we designed a plan of how someone could use the programmed simulation (or a similar) model to design a logistically sound waste disposal station. The first step in this plan is creating a base case scenario based on information provided by the client. This involves gathering demographic data and data about waste volumes. Client wishes are also listed. Then, using this data and information, current experience can be used to decide upon decisions like capacity, sizing and allocation. Once the base case is formulated, a first simulation is done to assess the initial design. If the performance is not good enough, then improvement steps are taken iteratively until the desired performance is realised. These improvement steps are:

1. Swapping containers of waste streams to generate a better allocation;
2. Isolating problematic waste streams;
3. Limiting the number of visitors on the site;
4. Changing buffer sizes (road capacities);
5. Changing the order of the substations of the waste disposal station;
6. Increasing the capacity of waste streams that have insufficient capacity.

During the experiments we performed we have learnt that some of these improvements steps are more effective than others. We have learnt that especially increasing the capacity of waste streams improves the performance. The order of substations also has a huge effect on the performance. The substation with the waste streams that are brought by many visitors, whose dumping time is relatively large and for who the variance in the dumping time is also large should be placed last. This reflects the theory from the analytical model of Vandaele et al. (2002). Especially variance of processes influences the waiting time of processes that visitors need to perform afterwards. So, if the processes with the largest variance are done last their variance will not influence other processes. While making swaps we have learned that, to maximize the accessibility of waste streams, containers of one waste stream should be spread out over the substation where the waste stream is located.

Once the desired capacity is realised the waste disposal station is designed from a logistic perspective. Afterwards this logistic design should be fit into a physical design. By now it should be clear that quite some weight rests on the simulation model used to perform simulations based on which the design is built. However, some of the assumptions and simplifications made in order to program the simulation model used in this research study may have been too stringent. We will discuss these in Section 7.2.

7.2 Discussion

As mentioned before, some of the assumptions and simplifications made in order to enable us to program a simulation model may have had an unforeseen effect on the usibility of the model. Some of these have been discussed in Section 5.1, where we realised, while validating, that the sojourn time measured was significantly different from data provided by the participating waste disposal company. The first simplification discussed concerned the necessity of having visitors visit the substations and the waste streams there in a fixed order. We have also discussed the drawback of the assumption stating that visitors wait until a spot becomes available at the waste streams they need to visit next as well.

There are other assumptions and simplifications that need to be discussed as well. First of all the assumption that states that there is enough space for cars to drive past parked cars is not realistic. Especially on a platform, if cars wait for others that are busy dumping from a spot where they want to park next, it may be that in some cases there is simply not enough space left for cars to drive past. One simplification we used concerned the moment when the next waste stream and container to be visited is determined. We have programmed our model to do this as soon as the visitor is processed at the entrance and when he arrives at a parking spot (in front of a container). This means that a reservation on space is made whilst the visitor is actually busy unloading waste at another container. This is not realistic, but it simplified the modelling a lot. Beforehand we did not know it would have such a large negative effect on the realism of the model outcomes. As our limited time did not allow us to improve upon this drawback we continued with the model as is, but we are aware of the consequence.

Another point that needs discussing is the data collection method. We have measured data at a waste disposal site with a team of 3-5 students. Since we were not able to follow all visitors on a single day it may well be that the data we collected does not represent reality. The way we measured may also cause the data to be inaccurate. We measured using stopwatches, however, in some cases we were forced to count ourselves due to the visitors' behaviour. Specifically the cases where some throw several waste streams (e.g., soft plastic, old iron and paper) away at the same time (they start with plastic, switch to paper, go back to plastic, switch to old iron, go back to paper, etc.). This behaviour made it impossible to make accurate stopwatch measurements, so we had to resort to counting along ourselves. The same holds for cases where a "visitor" (car) actually consists of several people resulting in several dump processes being done simultaneously. This complicated the measurement of the service times for all those waste streams. Having more manpower available to do the measurements might have resulted in better input data.

The final point we address here are inaccuracies that may have been caused by the programmed model. Since waste disposal stations (especially the platform) feature a form of shared capacity that could not be modelled accurately by using a standard object from the plant simulation library we had to develop a way to model this shared capacity. We have used a combination of table-files to determine which waste streams could be visited from which parking spaces. Then, by keeping track of which parking spaces are occupied (administrative wise) we could at any moment determine whether a visitor could access a parking spot at a container from where he could dump the waste he had brought. However, this method cannot accurately account for the time lost traveling between containers located at the same substation. The tracks we have used to model roads have a limitation as well. Cars cannot drive past one another once they are on one and the same road. To create the possibility for cars to drive past blocked cars (waiting cars) we have placed 'fictive' buffers at the beginning of each track. Only visitors whose next destination is free are allowed to drive on to the tracks. Others will have to wait in the fictive buffer. We realise this is not very realistic, but we saw no other way to allow for this drive by option while using only standard objects of the plant simulation software package. There are two possible solutions for dealing with this issue. More advanced programming could allow for a drive by option while still providing visual aid. Another option would be to not use animated simulation at all. In other words, the simulation model can be programmed as a black box simulation model where you provide the input (design, parameters and variables) and output is generated that can be used to assess the performance of the design.

7.3 Recommendations

From our research, we conclude that a programmed tool in the form of a simulation model could be very powerful and helpful in the design process for Modulo Béton. All our findings will be helpful in creating such a commercial tool.

We do have some guidelines for the process of creating such a tool. First of all, Modulo will need an experienced programmer to translate the needs and specifications of the model created during this project into a model that will satisfy the needs of Modulo. That programmer needs to be well versed in a programming tool that can facilitate the needs of the model and should document his progress and work well in order to facilitate future improvements to the commercial tool.

The data used as input to the model should be more extensive. We suggest that data collection is performed at several waste disposal stations using larger data collection teams in order to generate reliable input data. Since there are no waste disposal stations of Modulo's design yet in Canada we advocate collecting data elsewhere at Modulo sites in, e.g., the Netherlands or Germany. Once waste disposal stations are sold in Canada, agreements can be made with the clients (municipalities) that enable Modulo to collect data from these sites in order to get more reliable data to be used as input data for future design projects. In exchange modulo could offer discounts on future changes made to the sites.

We also have some suggestions for making sure that the tool used for commercial purposes represents reality better than the model programmed during this project. First of all there should be a way to account for the time that is spent driving between locations where visitors decide to park. A way to do this is to use a distance matrix to accurately assess (given an average driving speed) the time visitors spend driving between containers. This distance matrix may also be used to determine the walking distances visitors employ when dumping waste. A limit could be placed on how far visitors may walk for each waste stream. This would be primarily based on the average weight of the waste from that waste stream. A very important improvement is changing the moment the next container to visit is determined. This should at least be delayed until the visitor reaches the substation where the next waste stream he visits is located. In reality that would be the moment when visitors can see which containers have free parking space in front of them. Another possible improvement on this same topic would be to introduce flexible decisions. This would mean that visitors can change their minds about which waste stream to visit next if it seems that they will need to wait for other cars for a long time. This is much more realistic as it happens in real life all the time. Choosing a margin for the maximum amount of time visitors are willing to wait will be difficult as it depends on human behaviour. Another possible point for improvement could be to use a probability matrix to assess in which order waste streams are visited. In real life visitors often do not visit all waste streams in a strict order. Determining the order in which cars that are waiting for a spot to become free can be improved as well. E.g., a parking place, that facilitates dumping of a waste stream the waiting visitor intends to dump next, can be put on hold until there is enough space there for the visitor who was first in line to park there. This way of coding prevents smaller cars from squeezing in if the first visitor waiting in line came in a large vehicle that needs more space and there is only just enough free space for a small vehicle. The final improvement we suggest is another way of providing an idea about the queue lengths at the substations. Currently we calculate an average per hour based on the average occupancy over a period of time. Averages may be very small if most of the time there are no queues. However, we deem it important to know more. Therefore, adding a performance measure that tracks the queue length in such a way that percentiles can be created to determine what fraction of the time what queue lengths manifest.

One final recommendation concerns the use of the model in a design process. The first step in this process is to generate an initial design of the waste disposal station. This step also involves making a decision regarding the number of containers that should be placed for each of the waste streams present on the waste disposal station. We based this decision on the average number of visitors coming to the waste disposal station per day and on the average time spent at each waste stream. However, since there is quite some variability in the arrivals of visitors at a waste disposal station we highly recommend using the average number of arrivals of one of the busier moments of the day. This will generate an initial design that is closer to the design required to deal with peak arrivals than a design that is based on an average over an entire day. After all, an average day contains busy moments and not so busy moments. The average number of visitors during a busy hour is therefore bound to be higher than the average number of visitors during the entire day. When an initial design is formed its performance is assessed. If the performance is good simulation studies can be done to see whether a suitable performance can be achieved with less capacity. If the performance is not good enough the design needs to be improved. For this purpose we developed a detailed plan on how to perform experiments with the simulation model in order to improve the design.

Steps for improving initial design:

1. Determine better allocation of waste streams by performing swaps according to a local search method and several design rules based on developed knowledge. This means swapping waste streams' container location. Several heuristics may be used to find better allocations. E.g. steepest descent or simulated annealing with or without tabu. If, after finding the best possible design with the current capacity settings, performance targets have not been met then go to step 2;
2. Attempt to isolate problem cases (like crude garden waste) to see whether this has a positive impact.
3. Analysing the effect of utilising a max for the number of cars present on the waste disposal station at all times.
4. Analysing the effect of altering buffer sizes (road capacities) in case of extreme low or high utilisation of buffer spaces (neither are desired (extreme low means excess capacity you pay for and extreme high means congestion issues on the roads in reality)).
5. Try swapping the order of the substations. This step should be done sparingly (not more than k-1 times; k being the number of substations).
6. Determine waste stream with largest waiting time in optimal setting of the base case. Increase its capacity by one, unless there is reasonable doubt as to whether that waste stream has not enough capacity. In other words, try to find a waste stream that may be the cause for most of the problems and increase the capacity of that waste stream by one. The new container is inserted at a spot that where improvement is expected. This may be an educated guess based on the performance after the latest improvement step. Find the best allocation for that setting. Repeat steps three to five until the desired performance is achieved.

7.4 Further Research

We have several issues we wish to address for further research. The first group concerns the input data and several possible correlations therein. The second group concerns the impact some input parameters have on the model output. The third and last group is about the operating policy mentioned in Section 4.1.2 we were unable to study.

Correlations in input data

The next group concerns certain correlations. These correlations were either overlooked or we were unable to prove them. First, the correlation between the different waste streams brought could be looked into. It seems logical that visitors bring a certain number of waste streams based on other factors. E.g., if they are doing construction or maintenance work in the house they may have crude home waste, plaster, paint (small chemical waste), etc. If they are doing garden maintenance they may bring crude garden waste, C-grade wood, debris (tiles), etc. Therefore it seems interesting to know these correlations in order to include them in the input parameters. It may be the case that this will have an impact on the results. The second and final group of correlations we are interested in is that between the time spent dumping waste and the number of different waste streams brought by a single visitor. This stems from the idea that a visitor bringing a lot of waste streams needs to divide the limited space in his car between those waste streams and can probably, on average, bring less of these waste streams compared to a visitor bringing few waste streams. Taking these correlations into account may result in more realistic distributions for the service times of the waste streams which in turn could result in more realistic waste disposal station sojourn times of visitors.

Input parameters

For several of the input parameters there exists uncertainty on how much impact they have on the simulation results and what the nature of this impact is. First of all, we have not thoroughly studied the effect each buffer space has on the results. It may be interesting to see what this affect could be. Another parameter that comes to mind is the walking limit assigned to each and every visitor. Will that have a lot of impact on the results? The final parameter actually consists of three parameters. Together they represent the free-paid-both ratio. This ratio describes what fraction of the visitors brings waste for only the free area, what fraction brings only paid waste and what fraction brings waste for both areas. To assess these effects, an extensive sensitivity analysis should be performed.

Operating policies

There was one operating policy that we were interested in as they could have an impact on the waiting times. It concerns different gate policies that could be employed to deal with congestion issues. We considered three possibilities for gate policies. The final policy entailed letting the system run without interference. The other two policies manipulated the admittance of visitors to the site. The first of these states that in case of serious congestion no new visitors would be allowed on the terrain until the total number of visitors on the waste disposal site (beyond the entrance gate) was once again below a certain critical number. The other manipulation policy forced the system to only admit a new visitor once another visitor leaves the system. The goal of these policies is to minimise the negative effects congestion may have on the queueing times of visitors at a waste disposal station.

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Appendix A the Complete List of Assumptions from Buzacott & Shantikumar (1985)

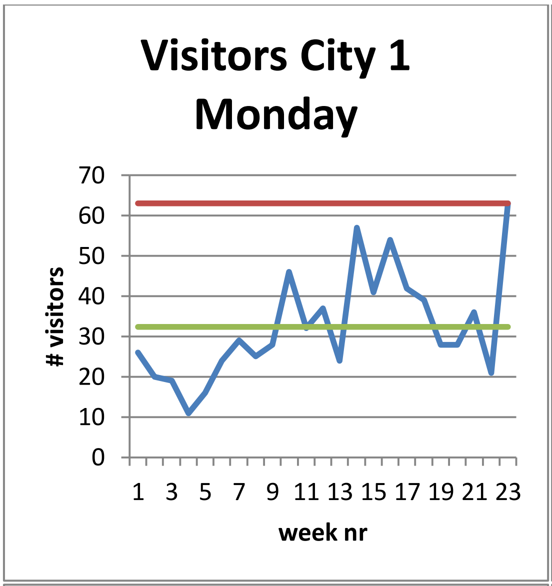
Job based assumptions

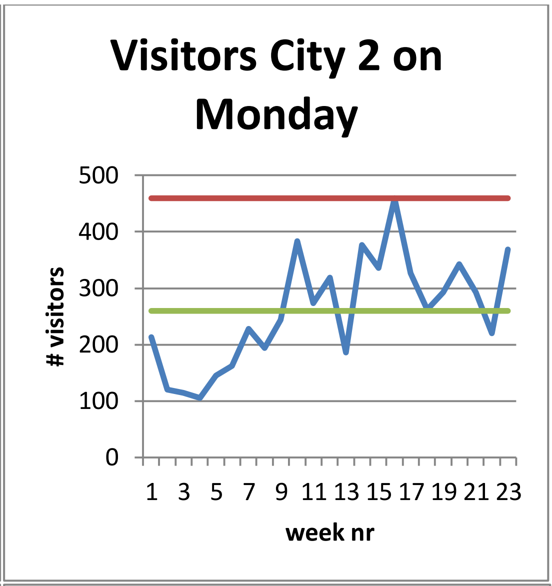
J1. Jobs arriving in the system go directly to the dispatcher and each job is released as soon as it enters the dispatch area. (However, in special models, this assumption is altered)
J2. The characteristics of each job are statistically independent of those of all other jobs.
J3. Each job consists of specified operations, each of which is performed by only one machine.
J4. Each job has a technological order of processing which can be described by a probability transfer matrix. This order can be determined when the job enters the dispatch area.
J5. Each job requires a finite process time for each operation. The processing time of all jobs at a machine are identically and independently distributed with known distribution function. The processing times can be determined before they are served.
J6. Each job has to wait between machines and thus in-process inventory is allowed. (In special cases this assumption is altered)

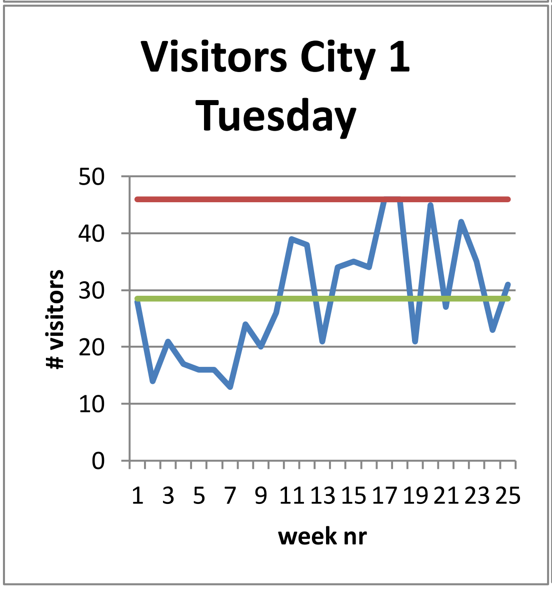
Machine Based Assumptions

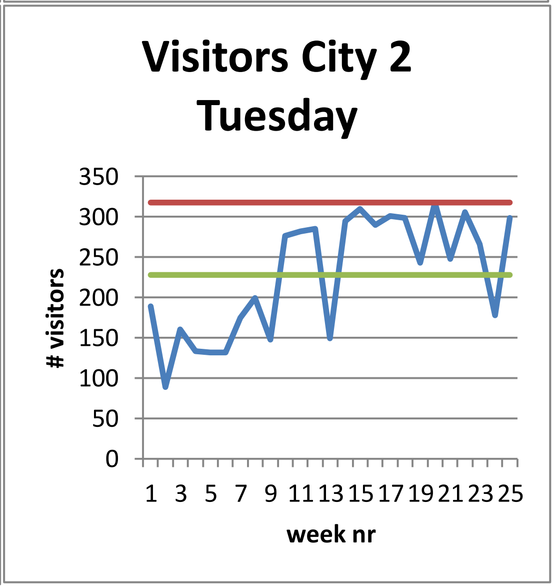
M1. Each machine center consists of only one machine; that is, the shop has one machine of each type.
M2. Each machine in the shop operates independently of the other machines and thus is capable of operating at its own maximum output rate.
M3. Each container is continuously available for processing jobs and there are no interruptions due to breakdowns, maintenance or other such cases.

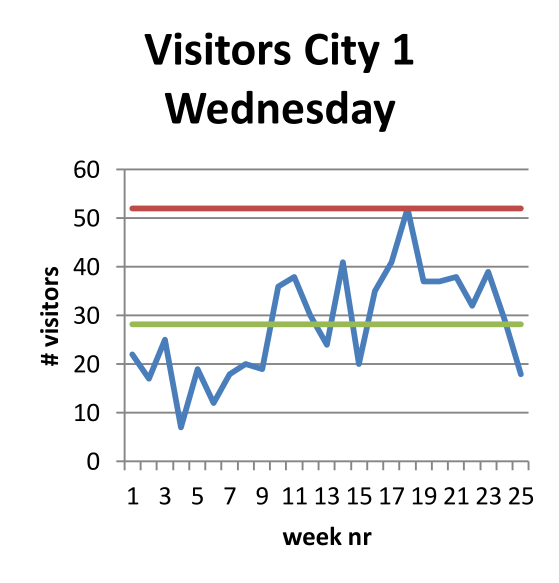
Appendix B Graphs of Visitor Quantity Analysis

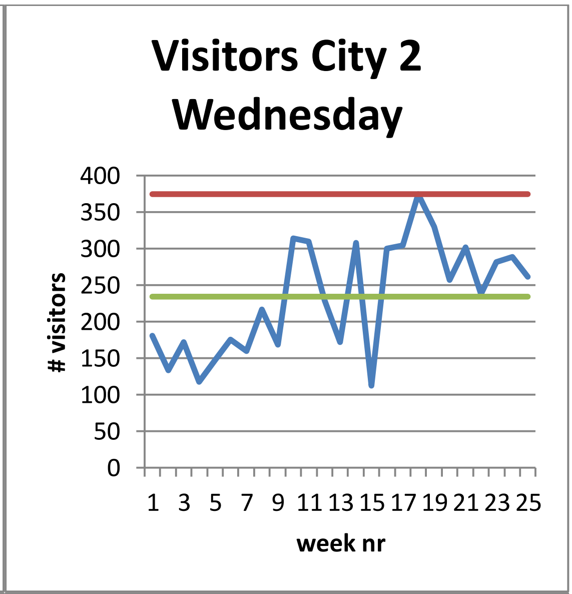


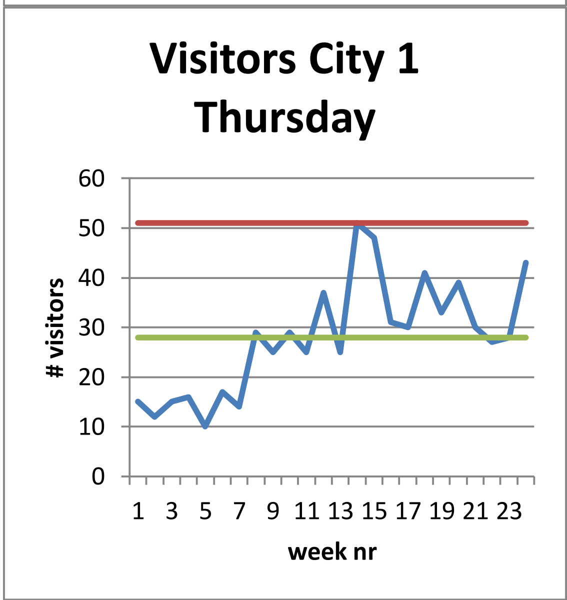


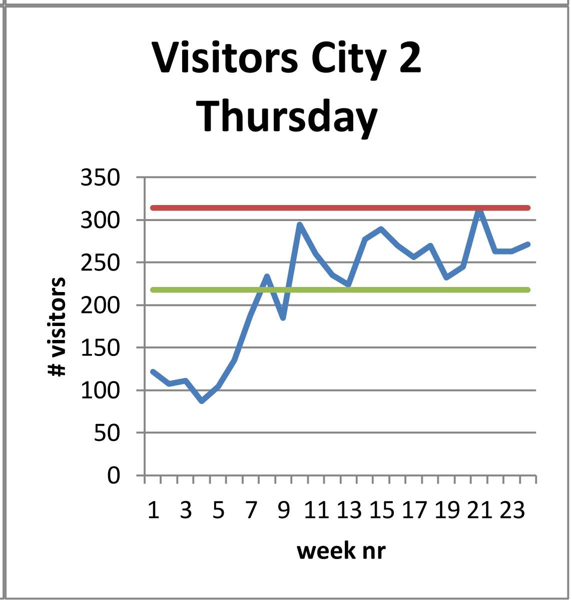




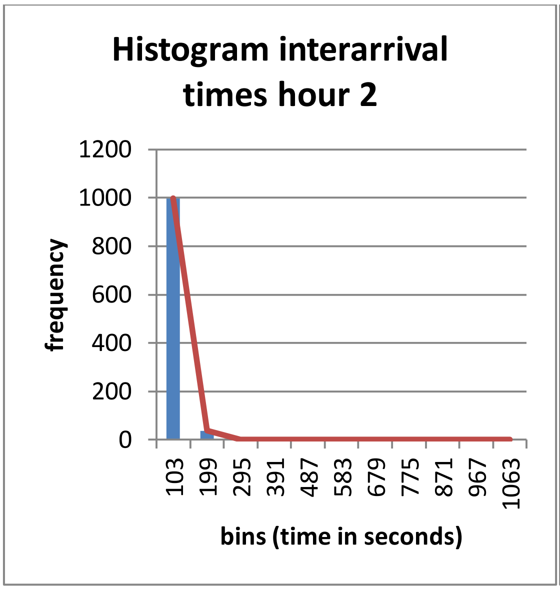

Visitors City 1
Wednesday
visitors
0 10 20 30 40 50 60
1 3 5 7 9 11 13 15 17 19 21 23 25
week nr

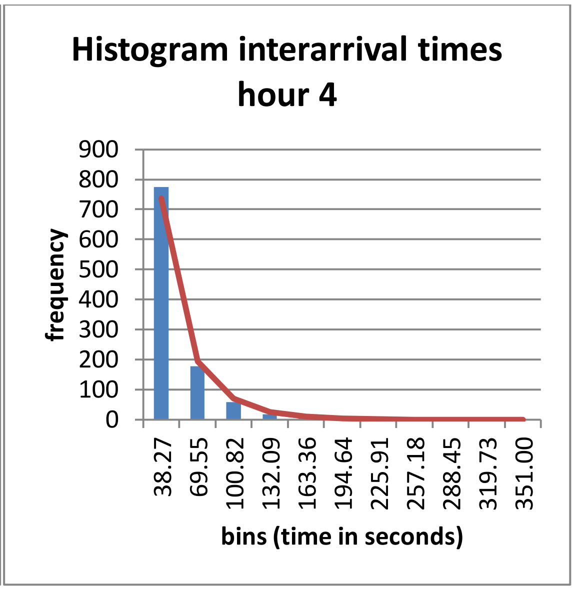

Visitors City 2
Wednesday
visitors
0 50 100 150 200 250 300 350 400
1 3 5 7 9 11 13 15 17 19 21 23 25
week nr

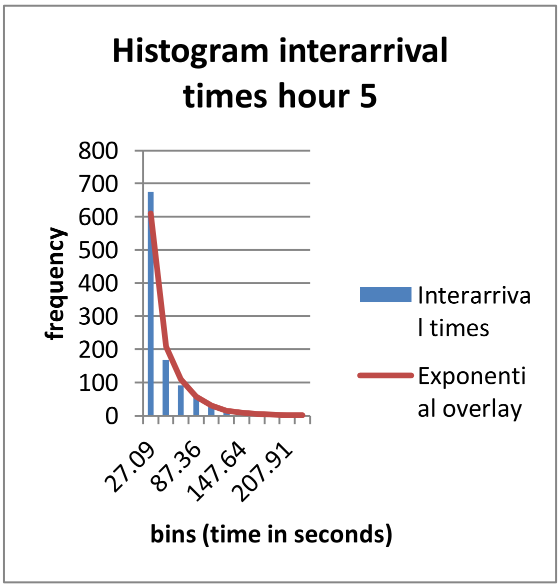

Visitors City 1
Thursday
visitors
0 10 20 30 40 50 60
1 3 5 7 9 11 13 15 17 19 21 23
week nr

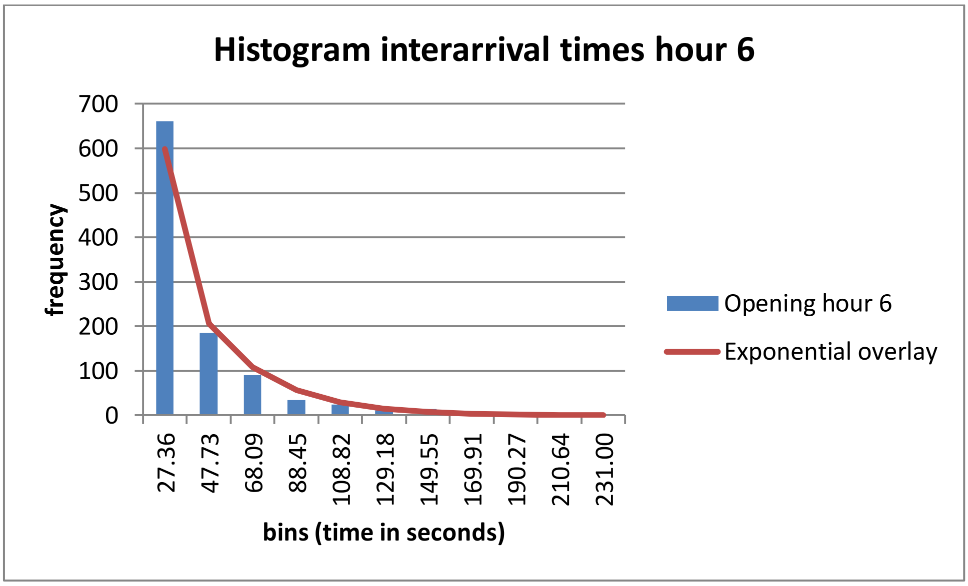

Visitors City 2
Thursday
visitors
0 50 100 150 200 250 300 350
1 3 5 7 9 11 13 15 17 19 21 23
week nr

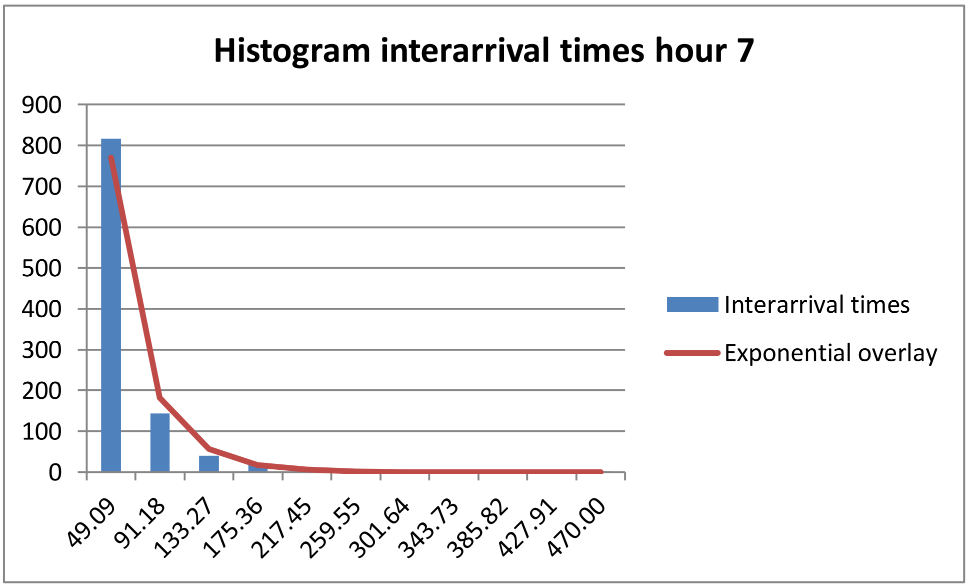
Appendix C Inter-arrival Times



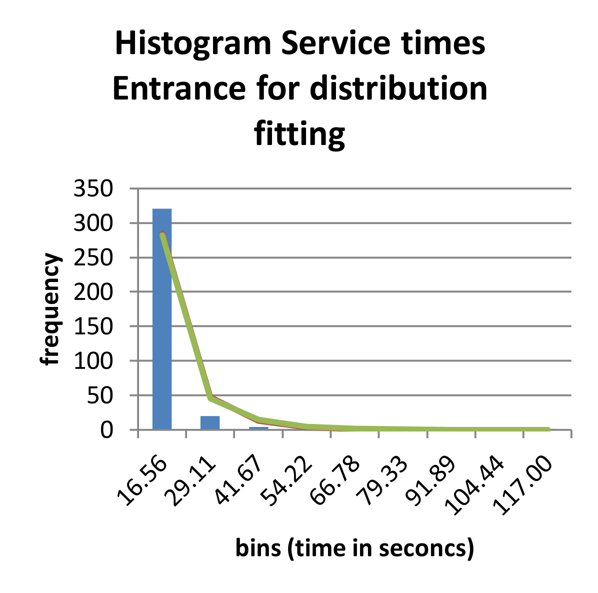


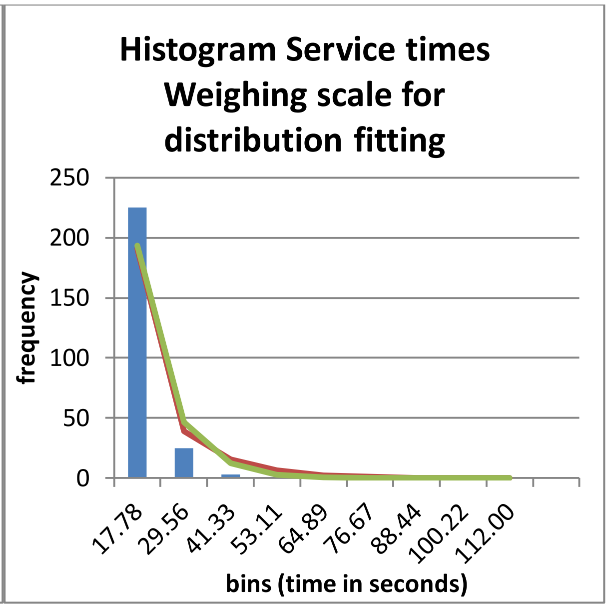


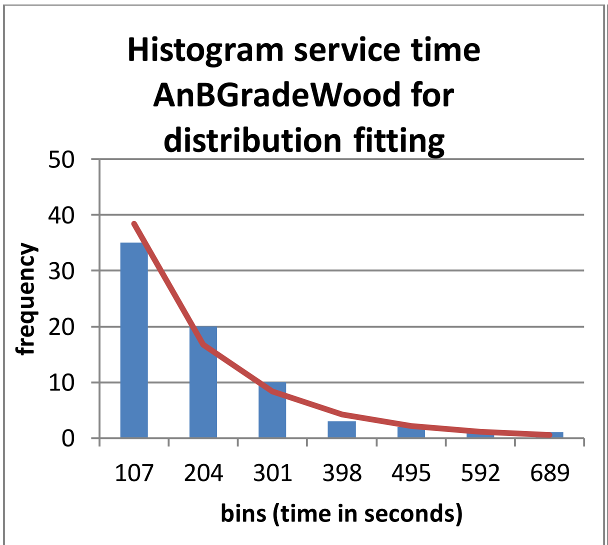

Histogram interarrival times hour 6
frequency
700
600
500
400
300
200
100
0
27.36
47.73
68.09
88.45
108.82
129.18
149.55
169.91
190.27
210.64
231.00
bins (time in seconds)
Opening hour 6
Exponential overlay

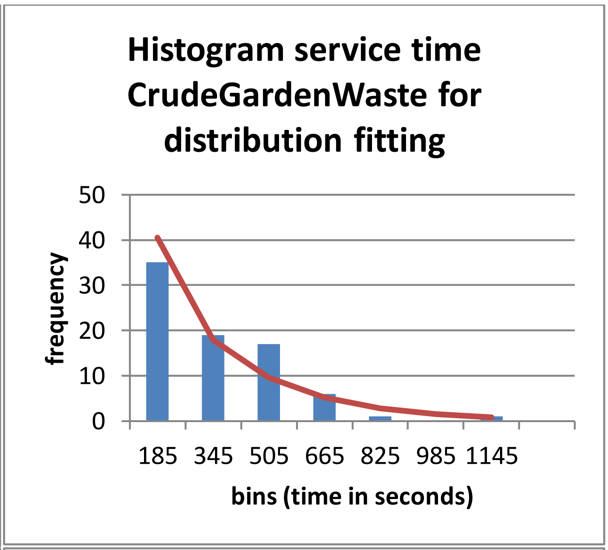

Histogram interarrival times hour 7
900
800
700
600
500
400
300
200
100
0
49.09
91.18
133.27
175.36
217.45
259.55
301.64
343.73
385.82
427.91
470.00
Interarrival times
Exponential overlay

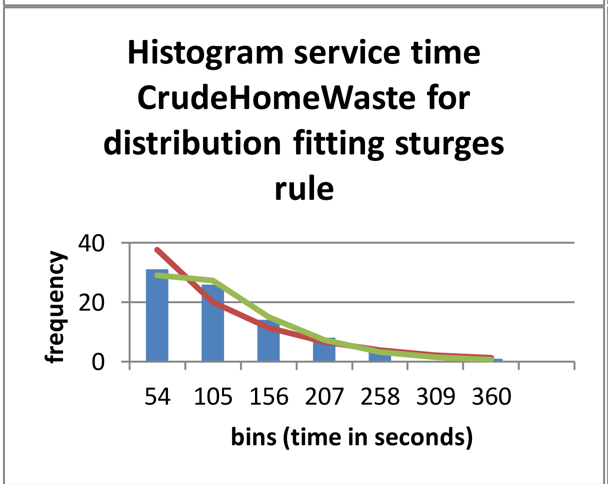
Appendix D Service Times for Dumping Waste Streams

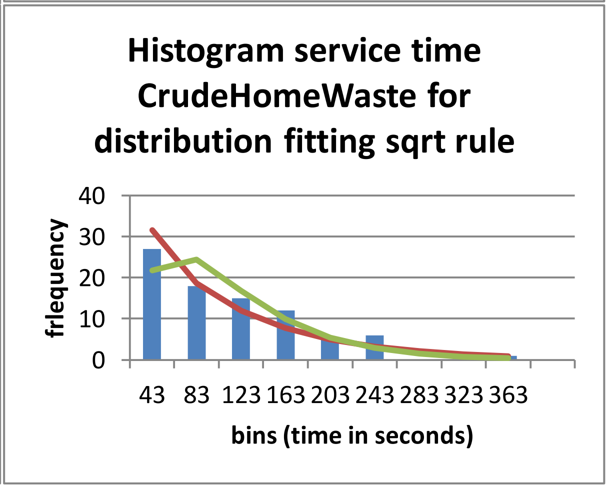


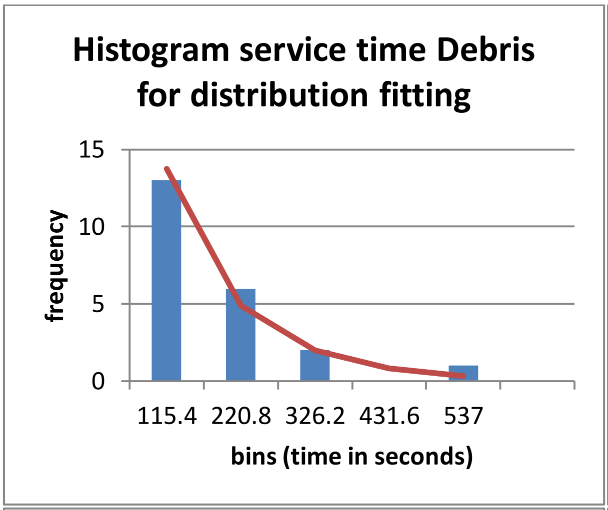


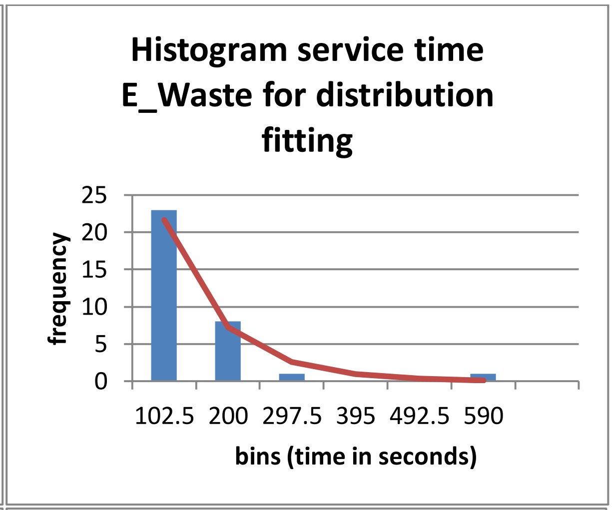


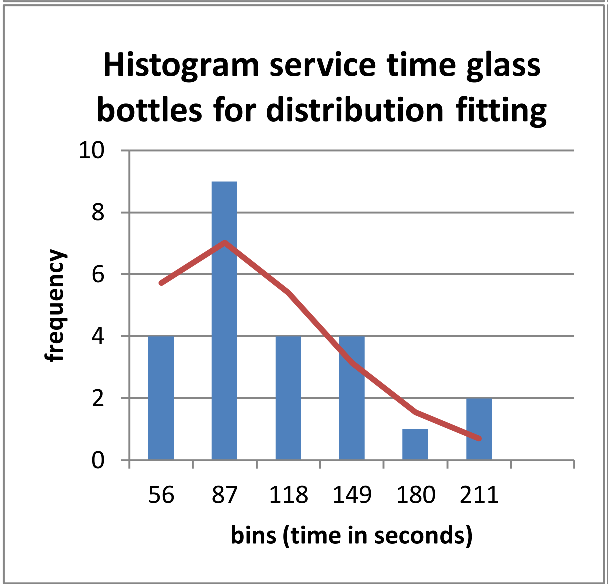


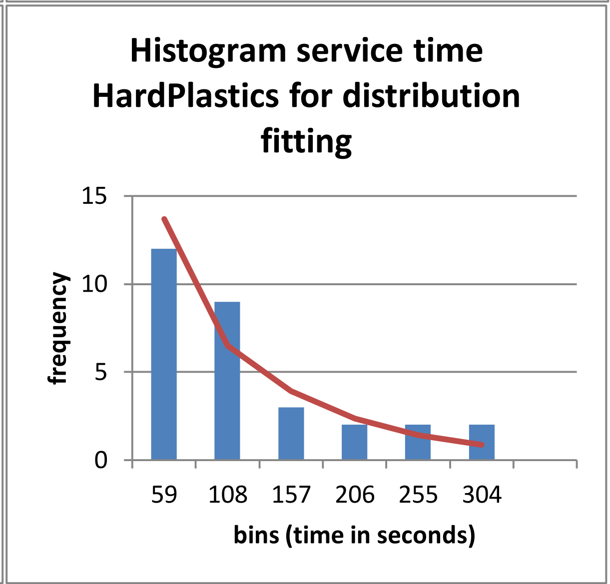


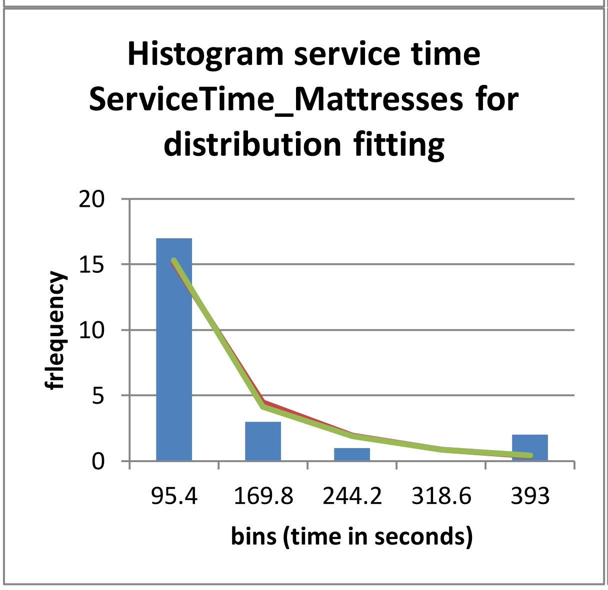


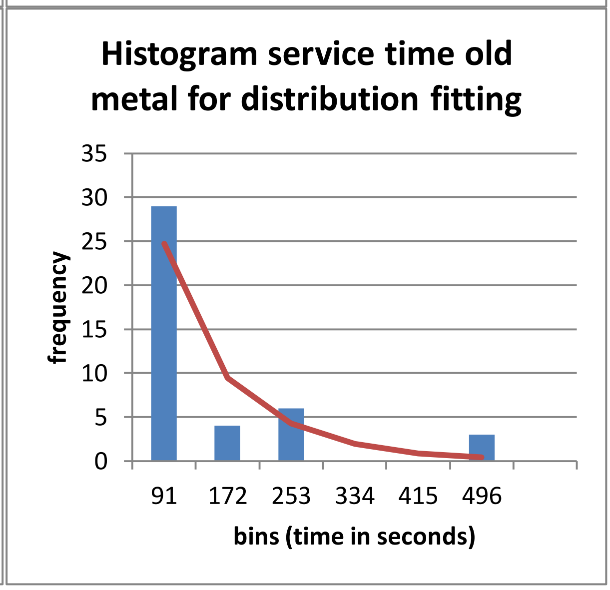

Histogram service time Debris for distribution fitting
15
10
5
0
frequency
115.4 220.8 326.2 431.6 537
bins (time in seconds)

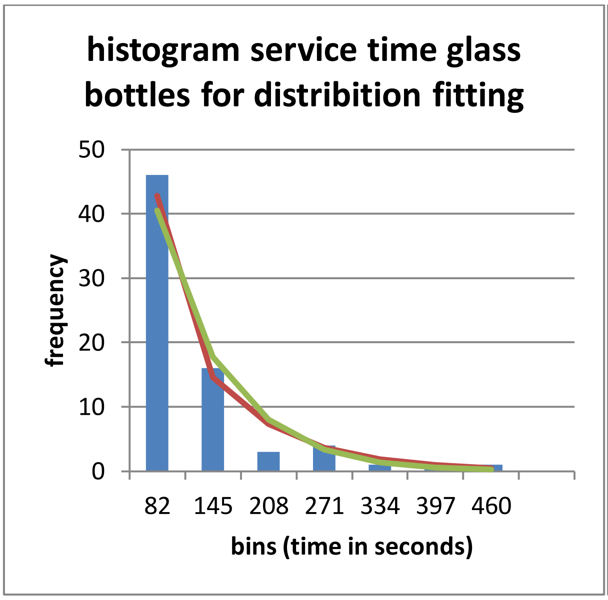

Histogram service time E_Waste for distribution fitting
25
20
15
10
5
0
frequency
102.5 200 297.5 395 492.5 590
bins (time in seconds)

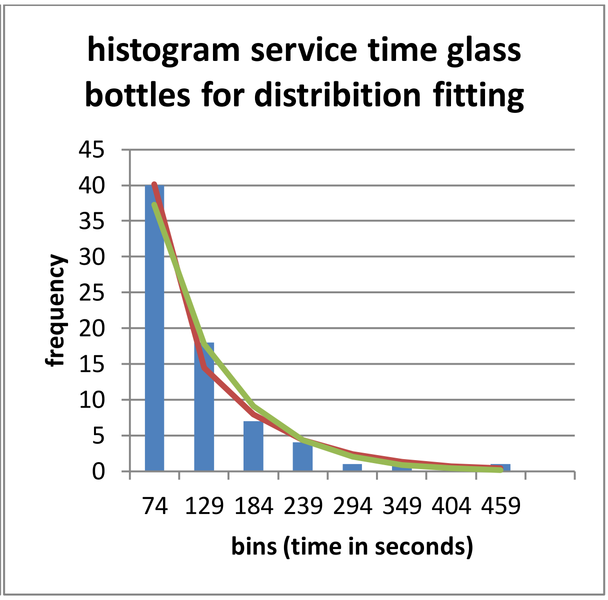

Histogram service time glass bottles for distribution fitting
10
8
6
4
2
0
frequency
56 87 118 149 180 211
bins (time in seconds)


Histogram service time HardPlastics for distribution fitting
15
10
5
0
frequency
59 108 157 206 255 304
bins (time in seconds)

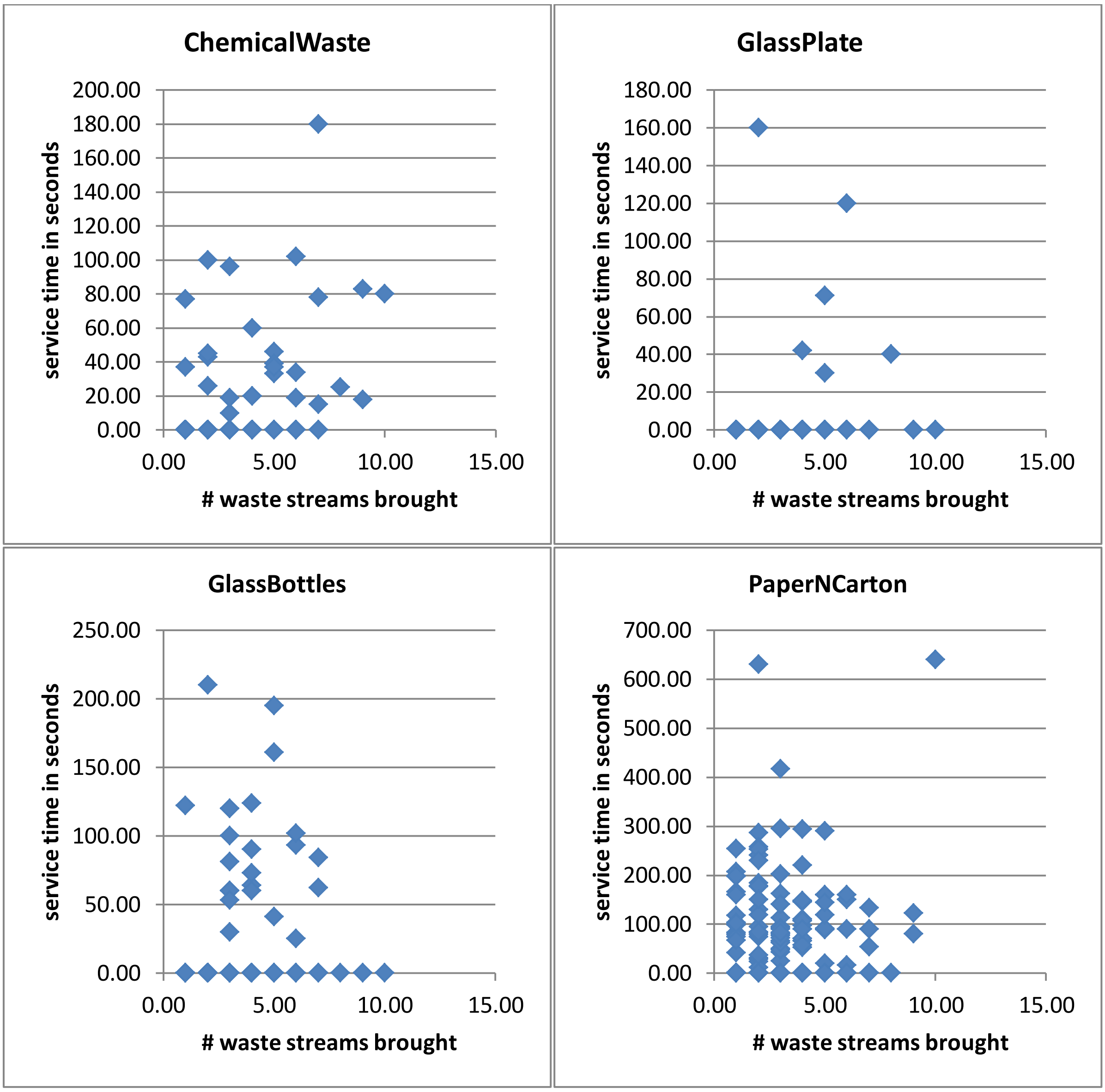

Histogram service time ServiceTime_Mattresses for distribution fitting
20
15
10
5
0
frlequency
95.4 169.8 244.2 318.6 393
bins (time in seconds)

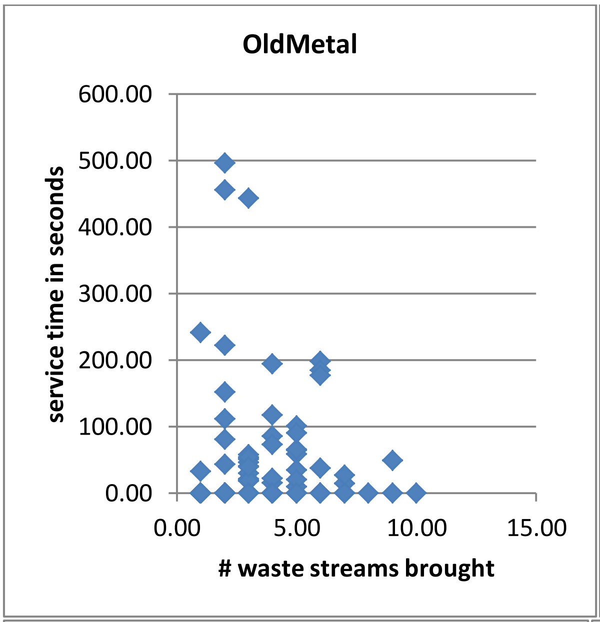

Histogram service time old metal for distribution fitting
35
30
25
20
15
10
5
0
frequency
91 172 253 334 415 496
bins (time in seconds)

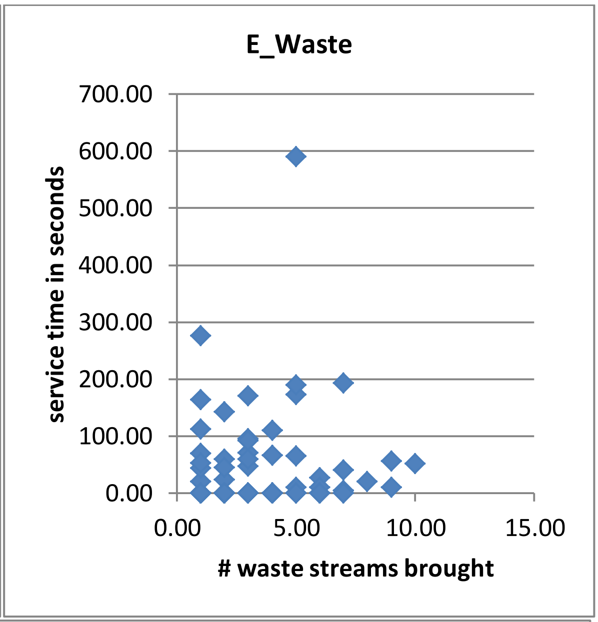

histogram service time glass bottles for distribition fitting
50
40
30
20
10
0
frequency
82
145
208
271
334
397
460
bins (time in seconds)

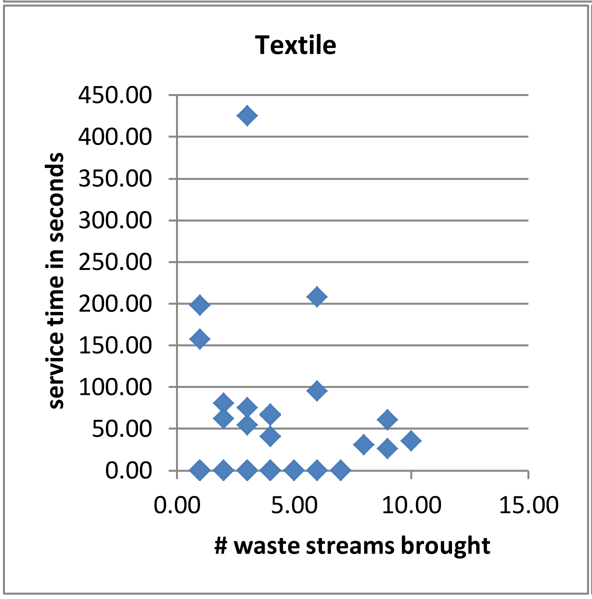

histogram service time glass bottles for distribition fitting
45
40
35
30
25
20
15
10
5
0
frequency
74
129
184
239
294
349
404
459
bins (time in seconds)

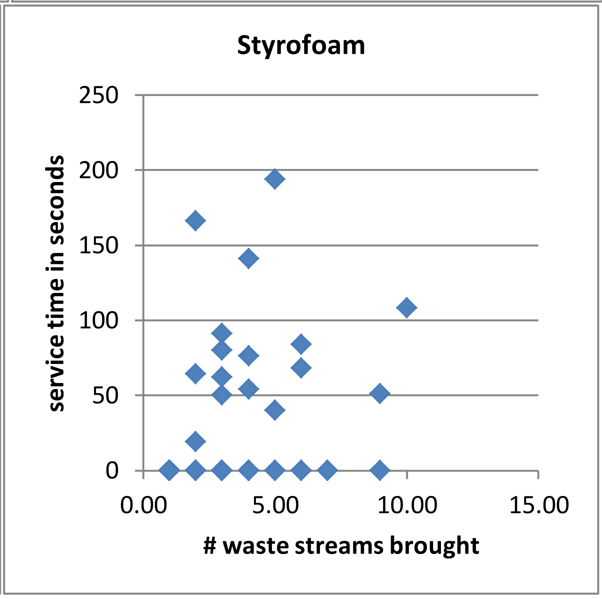
Appendix E Correlation # Waste Streams Brought and Service Time per Waste Stream

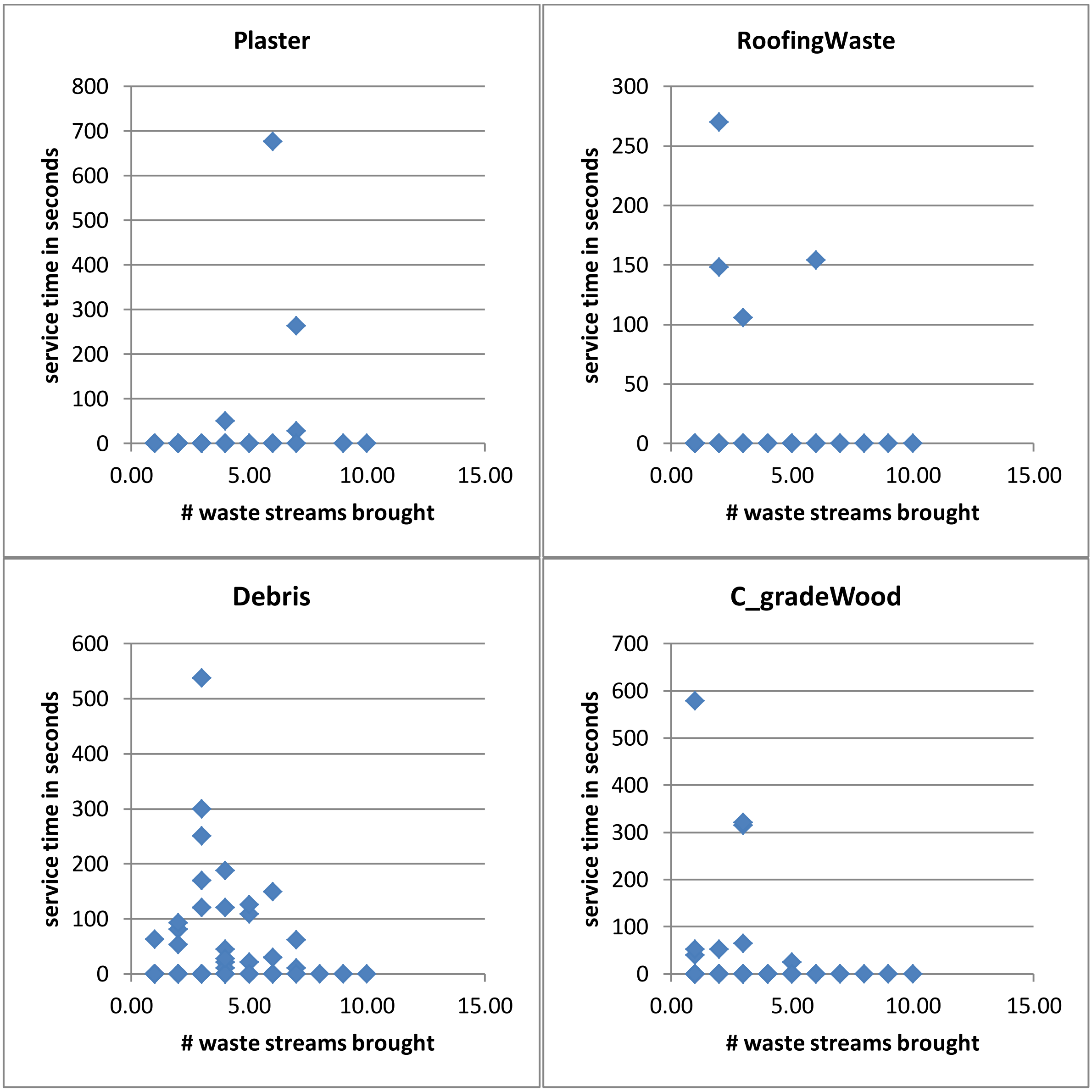


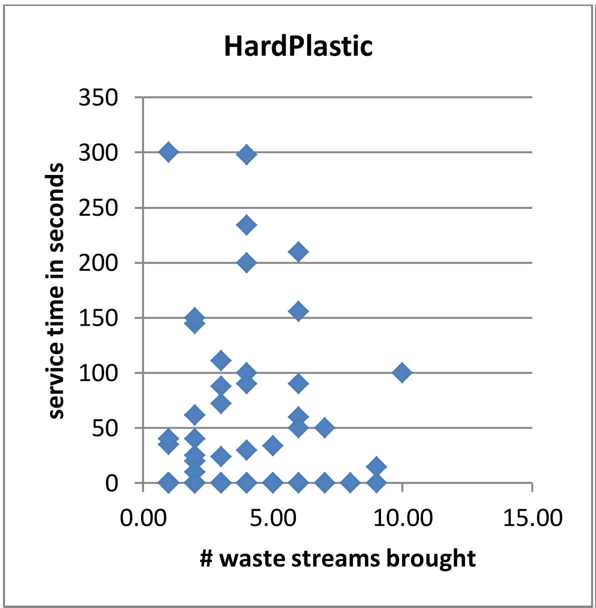

OldMetal
service time in seconds
600.00
500.00
400.00
300.00
200.00
100.00
0.00
0.00
5.00
10.00
15.00
waste streams brought

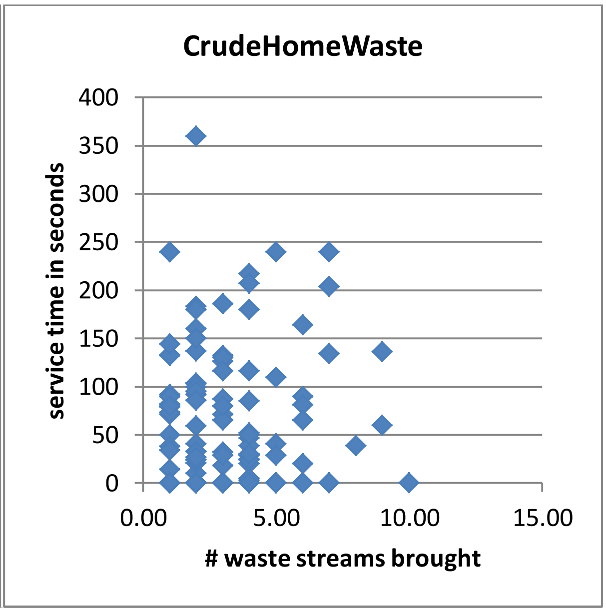

E_Waste
service time in seconds
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
0.00
5.00
10.00
15.00
waste streams brought

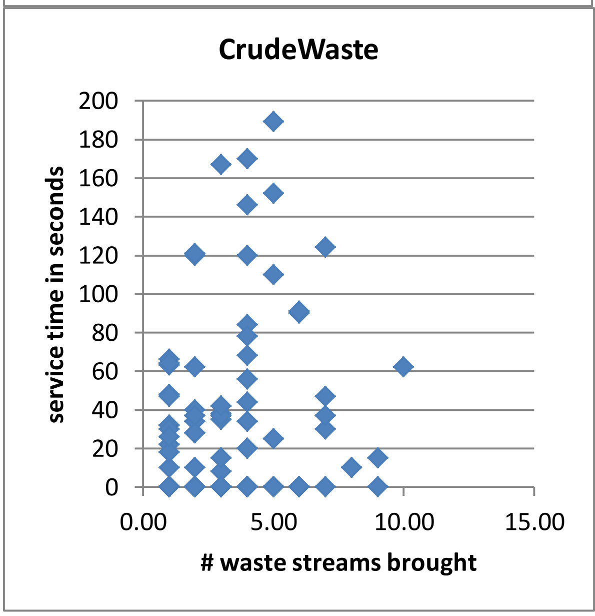

Textile
service time in seconds
450.00
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
0.00
5.00
10.00
15.00
waste streams brought

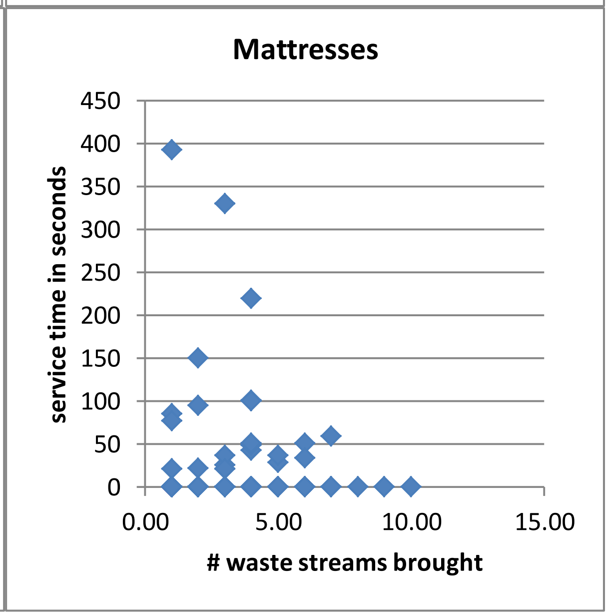

Styrofoam
service time in seconds
250
200
150
100
50
0
0.00
5.00
10.00
15.00
waste streams brought


Plaster
800
700
600
500
400
300
200
100
0
0.00
5.00
10.00
15.00
service time in seconds
waste streams brought
RoofingWaste
300
250
200
150
100
50
0
0.00
5.00
10.00
15.00
service time in seconds
waste streams brought
Debris
600
500
400
300
200
100
0
0.00
5.00
10.00
15.00
service time in seconds
waste streams brought
C_gradeWood
700
600
500
400
300
200
100
0
0.00
5.00
10.00
15.00
service time in seconds
waste streams brought









Appendix F R-code for data manipulation

```
## This series of code should read in the datafiles with arrivaltimes at the front desk and the weighing center.
## Afterwards the data should be linked by row, however, duplicates (at the weighing center) should be erased
## I should do the analyses per der day and then add it back together

arrival_data_Entrance<- read.table("pathname of file", header=TRUE, stringsAsFactor=FALSE)

arrival_data_Weighing<- read.table("C pathname of file ", header=TRUE, stringsAsFactor=FALSE)

## I need to split the data in separate sets for the Saturdays

arrival_data_Entrance_June07<-arrival_data_Entrance[which(arrival_data_Entrance$Date=="07/06/2014"), ]
arrival_data_Entrance_June14<-arrival_data_Entrance[which(arrival_data_Entrance$Date=="14/06/2014"), ]
arrival_data_Entrance_June21<-arrival_data_Entrance[which(arrival_data_Entrance$Date=="21/06/2014"), ]
arrival_data_Entrance_June28<-arrival_data_Entrance[which(arrival_data_Entrance$Date=="28/06/2014"), ]
```

```
arrival_data_Entrance_May03<-arrival_data_Entrance[which(arrival_data_Entrance$Date=="03/05/2014"), ]
arrival_data_Entrance_May10<-arrival_data_Entrance[which(arrival_data_Entrance$Date=="10/05/2014"), ]
arrival_data_Entrance_May17<-arrival_data_Entrance[which(arrival_data_Entrance$Date=="17/05/2014"), ]
arrival_data_Entrance_May24<-arrival_data_Entrance[which(arrival_data_Entrance$Date=="24/05/2014"), ]
arrival_data_Entrance_May31<-arrival_data_Entrance[which(arrival_data_Entrance$Date=="31/05/2014"), ]


## do the same for the arrivals at the weighing center

arrival_data_Weighing_June07<-arrival_data_Weighing[which(arrival_data_Weighing$Date=="07/06/2014"), ]
arrival_data_Weighing_June14<-arrival_data_Weighing[which(arrival_data_Weighing$Date=="14/06/2014"), ]
arrival_data_Weighing_June21<-arrival_data_Weighing[which(arrival_data_Weighing$Date=="21/06/2014"), ]
arrival_data_Weighing_June28<-arrival_data_Weighing[which(arrival_data_Weighing$Date=="28/06/2014"), ]
arrival_data_Weighing_May03<-arrival_data_Weighing[which(arrival_data_Weighing$Date=="03/05/2014"), ]
arrival_data_Weighing_May10<-arrival_data_Weighing[which(arrival_data_Weighing$Date=="10/05/2014"), ]
arrival_data_Weighing_May17<-arrival_data_Weighing[which(arrival_data_Weighing$Date=="17/05/2014"), ]
arrival_data_Weighing_May24<-arrival_data_Weighing[which(arrival_data_Weighing$Date=="24/05/2014"), ]
arrival_data_Weighing_May31<-arrival_data_Weighing[which(arrival_data_Weighing$Date=="31/05/2014"), ]


## the next step is to delete any double observations
arrival_data_Entrance_June07<-arrival_data_Entrance_June07[!duplicated(arrival_data_Entrance_June07$visitorId), ]
arrival_data_Entrance_June14<-arrival_data_Entrance_June14[!duplicated(arrival_data_Entrance_June14$visitorId), ]
arrival_data_Entrance_June21<-arrival_data_Entrance_June21[!duplicated(arrival_data_Entrance_June21$visitorId), ]
arrival_data_Entrance_June28<-arrival_data_Entrance_June28[!duplicated(arrival_data_Entrance_June28$visitorId), ]
arrival_data_Entrance_May03<-arrival_data_Entrance_May03[!duplicated(arrival_data_Entrance_May03$visitorId), ]
arrival_data_Entrance_May10<-arrival_data_Entrance_May10[!duplicated(arrival_data_Entrance_May10$visitorId), ]
arrival_data_Entrance_May17<-arrival_data_Entrance_May17[!duplicated(arrival_data_Entrance_May17$visitorId), ]
arrival_data_Entrance_May24<-arrival_data_Entrance_May24[!duplicated(arrival_data_Entrance_May24$visitorId), ]
arrival_data_Entrance_May31<-arrival_data_Entrance_May31[!duplicated(arrival_data_Entrance_May31$visitorId), ]
arrival_data_Weighing_June07<-arrival_data_Weighing_June07[!duplicated(arrival_data_Weighing_June07$visitorId), ]
arrival_data_Weighing_June14<-arrival_data_Weighing_June14[!duplicated(arrival_data_Weighing_June14$visitorId), ]
arrival_data_Weighing_June21<-arrival_data_Weighing_June21[!duplicated(arrival_data_Weighing_June21$visitorId), ]
arrival_data_Weighing_June28<-arrival_data_Weighing_June28[!duplicated(arrival_data_Weighing_June28$visitorId), ]
arrival_data_Weighing_May03<-arrival_data_Weighing_May03[!duplicated(arrival_data_Weighing_May03$visitorId), ]
arrival_data_Weighing_May10<-arrival_data_Weighing_May10[!duplicated(arrival_data_Weighing_May10$visitorId), ]
arrival_data_Weighing_May17<-arrival_data_Weighing_May17[!duplicated(arrival_data_Weighing_May17$visitorId), ]
arrival_data_Weighing_May24<-arrival_data_Weighing_May24[!duplicated(arrival_data_Weighing_May24$visitorId), ]
arrival_data_Weighing_May31<-arrival_data_Weighing_May31[!duplicated(arrival_data_Weighing_May31$visitorId), ]


## Then I need to bind the datasets per day together by row; I need to find a method to do this that automatically adds NA forthe rows that are not present in both rows
Complete_data_June07<-merge(x=arrival_data_Entrance_June07, y=arrival_data_Weighing_June07, by = "visitorId", all.x=TRUE)
Complete_data_June14<-merge(x=arrival_data_Entrance_June14, y=arrival_data_Weighing_June14, by = "visitorId", all.x=TRUE)
Complete_data_June21<-merge(x=arrival_data_Entrance_June21, y=arrival_data_Weighing_June21, by = "visitorId", all.x=TRUE)
Complete_data_June28<-merge(x=arrival_data_Entrance_June28, y=arrival_data_Weighing_June28, by = "visitorId", all.x=TRUE)

Complete_data_May03<-merge(x=arrival_data_Entrance_May03, y=arrival_data_Weighing_May03, by = "visitorId", all.x=TRUE)
Complete_data_May10<-merge(x=arrival_data_Entrance_May10, y=arrival_data_Weighing_May10, by = "visitorId", all.x=TRUE)
Complete_data_May17<-merge(x=arrival_data_Entrance_May17, y=arrival_data_Weighing_May17, by = "visitorId", all.x=TRUE)
Complete_data_May24<-merge(x=arrival_data_Entrance_May24, y=arrival_data_Weighing_May24, by = "visitorId", all.x=TRUE)
Complete_data_May31<-merge(x=arrival_data_Entrance_May31, y=arrival_data_Weighing_May31, by = "visitorId", all.x=TRUE)

## Introduce a dummy variable to register double entries for visitorId
Complete_data_June07$duplicity<-duplicated(Complete_data_June07$visitorId)
Complete_data_June14$duplicity<-duplicated(Complete_data_June14$visitorId)
Complete_data_June21$duplicity<-duplicated(Complete_data_June21$visitorId)
Complete_data_June28$duplicity<-duplicated(Complete_data_June28$visitorId)
Complete_data_May03$duplicity<-duplicated(Complete_data_May03$visitorId)
Complete_data_May10$duplicity<-duplicated(Complete_data_May10$visitorId)
Complete_data_May17$duplicity<-duplicated(Complete_data_May17$visitorId)
Complete_data_May24$duplicity<-duplicated(Complete_data_May24$visitorId)
```

```
Complete_data_May31$duplicity<-duplicated(Complete_data_May31$visitorId)

## The final step is to put all the datasets together
Complete_data<-rbind(Complete_data_June07,Complete_data_June14)
Complete_data<-rbind(Complete_data,Complete_data_June21)
Complete_data<-rbind(Complete_data,Complete_data_June28)
Complete_data<-rbind(Complete_data,Complete_data_May03)
Complete_data<-rbind(Complete_data,Complete_data_May10)
Complete_data<-rbind(Complete_data,Complete_data_May17)
Complete_data<-rbind(Complete_data,Complete_data_May24)
Complete_data<-rbind(Complete_data,Complete_data_May31)

## Export the data to txt for manual copy paste to excel in order for the remainder of the analysis' steps to be performed
write.table(Complete_data$visitorId, file="output file path name", row.names=FALSE, col.names=FALSE)
write.table(Complete_data$Date.x, file=" output file path name ", row.names=FALSE, col.names=FALSE)
write.table(Complete_data$ArrivalTimeFrontGate, file=" output file path name ", row.names=FALSE, col.names=FALSE)
write.table(Complete_data$arrivaltime_at_weighing, file=" output file path name ", row.names=FALSE, col.names=FALSE)
write.table(Complete_data$duplicity, file=" output file path name ", row.names=FALSE, col.names=FALSE)

##############################################################################################################
#####################################################################################
##### After the fraction of free:paid:both for visitors has been determined I analyse the sojourn times

arrival_data_Entrance_May<- read.table("input file path name ", header=TRUE, stringsAsFactor=FALSE)

departure_data_Weighing_May<- read.table("input file path name ", header=TRUE, stringsAsFactor=FALSE)

## The data of the departures needs processing so that the departure times are in a time format
n<-nrow(departure_data_Weighing_May)
i = 1

for (i in 1:n) {
		if (nchar(departure_data_Weighing_May[i,"Departure_Time_Weighing"])==7) {
				departure_data_Weighing_May[i,"Departure_Time_Weighing"]<-
paste("0",as.character(departure_data_Weighing_May[i,"Departure_Time_Weighing"]), sep="")
				}
}


## Then I need to split the observations for the different days and join for each day and do the duplicity check; Afterwards all the data is put together

arrival_data_Entrance_May03<-arrival_data_Entrance_May[which(arrival_data_Entrance_May$Date=="03/05/2014"), ]
arrival_data_Entrance_May10<-arrival_data_Entrance_May[which(arrival_data_Entrance_May$Date=="10/05/2014"), ]
arrival_data_Entrance_May17<-arrival_data_Entrance_May[which(arrival_data_Entrance_May$Date=="17/05/2014"), ]
arrival_data_Entrance_May24<-arrival_data_Entrance_May[which(arrival_data_Entrance_May$Date=="24/05/2014"), ]
arrival_data_Entrance_May31<-arrival_data_Entrance_May[which(arrival_data_Entrance_May$Date=="31/05/2014"), ]

departure_data_Weighing_May03<-departure_data_Weighing_May[which(departure_data_Weighing_May$Date2=="03/05/2014"), ]
departure_data_Weighing_May10<-departure_data_Weighing_May[which(departure_data_Weighing_May$Date2=="10/05/2014"), ]
departure_data_Weighing_May17<-departure_data_Weighing_May[which(departure_data_Weighing_May$Date2=="17/05/2014"), ]
departure_data_Weighing_May24<-departure_data_Weighing_May[which(departure_data_Weighing_May$Date2=="24/05/2014"), ]
departure_data_Weighing_May31<-departure_data_Weighing_May[which(departure_data_Weighing_May$Date2=="31/05/2014"), ]

Complete_data_May03<-merge(x=arrival_data_Entrance_May03, y=departure_data_Weighing_May03, by = "visitorId", all.y=TRUE)
Complete_data_May10<-merge(x=arrival_data_Entrance_May10, y=departure_data_Weighing_May10, by = "visitorId", all.y=TRUE)
Complete_data_May17<-merge(x=arrival_data_Entrance_May17, y=departure_data_Weighing_May17, by = "visitorId", all.y=TRUE)
Complete_data_May24<-merge(x=arrival_data_Entrance_May24, y=departure_data_Weighing_May24, by = "visitorId", all.y=TRUE)
Complete_data_May31<-merge(x=arrival_data_Entrance_May31, y=departure_data_Weighing_May31, by = "visitorId", all.y=TRUE)

## duplicity check

Complete_data_May03$duplicity<-duplicated(Complete_data_May03$visitorId)
```

```
Complete_data_May10$duplicity<-duplicated(Complete_data_May10$visitorId)
Complete_data_May17$duplicity<-duplicated(Complete_data_May17$visitorId)
Complete_data_May24$duplicity<-duplicated(Complete_data_May24$visitorId)
Complete_data_May31$duplicity<-duplicated(Complete_data_May31$visitorId)

## create the complete dataset
Complete_data_May<-rbind(Complete_data_May03,Complete_data_May10)
Complete_data_May<-rbind(Complete_data_May,Complete_data_May17)
Complete_data_May<-rbind(Complete_data_May,Complete_data_May24)
Complete_data_May<-rbind(Complete_data_May,Complete_data_May31)

## write the necessary times to txt for manual copying to excel for analysis of the sojourn times
write.table(Complete_data_May$visitorId, file=" output file path name ", row.names=FALSE, col.names=FALSE)
write.table(Complete_data_May$Date2, file=" output file path name ", row.names=FALSE, col.names=FALSE)
write.table(Complete_data_May$ArrivalTimeFrontGate, file=" output file path name ", row.names=FALSE, col.names=FALSE)
write.table(Complete_data_May$Departure_Time_Weighing, file=" output file path name ", row.names=FALSE, col.names=FALSE)
write.table(Complete_data_May$duplicity, file=" output file path name ", row.names=FALSE, col.names=FALSE)
```

Appendix G Complete overview of sojourn times after relocating "CrudeGardenWaste" at the "OtherSubStation"

	base case	CrudeGarden Waste at end of OtherSubStation	CrudeGarden Waste in middle of OtherSubStation	CrudeGarden Waste in between AnBGradeWood
	Mean	mean	mean	mean
EntranceWDS	16.97	16.99	16.99	16.95
SmallChemicalDepot	194.64	194.70	194.71	194.61
WeighingScale	16.59	16.61	16.61	16.63
SubStationPlatform	355.06	NA	NA	NA
OtherSubStation	260.59	359.46	350.42	350.20
ExitWDS	11.39	11.52	11.41	11.41
AnBGradeWood	138.31	140.05	139.67	152.13
Asbestos	26.70	55.58	55.58	55.58
C_gradeWood	195.72	211.19	199.79	218.69
CarTires	49.24	49.50	49.47	49.68
ChemicalWaste	52.51	52.65	52.65	52.76
CrudeGardenWaste	355.06	296.51	275.21	274.21
CrudeHomeWaste	91.91	93.18	93.72	92.72
CrudeWaste	61.61	61.94	62.39	61.09
Debris	138.78	131.40	131.25	117.87
E_Waste	93.98	94.08	94.07	93.99
GasConcrete	214.65	215.41	214.76	215.74
GlassBottles	91.03	91.27	91.30	91.27
GlassPlates	78.44	77.67	77.69	77.62
Gravel	69.53	172.47	172.47	172.47
HardPlastics	116.25	110.59	109.39	107.59
Mattresses	100.56	100.48	106.86	94.92
OldMetal	102.48	102.70	102.63	102.70
PaperNCarton	132.90	133.01	133.00	132.88
Plaster	246.79	246.02	244.52	245.11
RoofingWaste	208.23	208.01	207.63	207.60
SoftPlastics	92.71	92.73	92.76	92.77
Styrofoam	83.53	83.50	83.48	83.53
Textile	104.76	104.75	104.71	104.80
Total Sojourn Time	376.05	362.42	356.39	356.11
Total Sojourn Time 2	487.47	454.27	447.63	447.94

Appendix H Complete overview sojourn times after concentrating the waste streams

	base case	Concentration of waste streams
	Mean	mean
EntranceWDS	16.97302	16.98829
SmallChemicalDepot	194.6439	194.7416
WeighingScale	16.59092	16.60036
SubStationPlatform	355.0629	356.192
OtherSubStation	260.5879	262.3251
ExitWDS	11.38592	11.38555
AnBGradeWood	138.3077	140.5027
Asbestos	26.69583	55.5782
C_gradeWood	195.7248	198.7477
CarTires	49.24074	49.42029
ChemicalWaste	52.51167	52.64852
CrudeGardenWaste	355.0629	356.192
CrudeHomeWaste	91.90635	96.0734
CrudeWaste	61.61024	62.80429
Debris	138.7823	137.9814
E_Waste	93.98068	94.09989
GasConcrete	214.6515	216.4443
GlassBottles	91.02743	91.2218
GlassPlates	78.4382	77.73553
Gravel	69.52585	172.6252
HardPlastics	116.2547	109.4592
Mattresses	100.5646	104.5504
OldMetal	102.4804	102.6736
PaperNCarton	132.9041	133.0208
Plaster	246.7861	246.7023
RoofingWaste	208.227	208.2294
SoftPlastics	92.70992	92.76352
Styrofoam	83.52897	83.48485
Textile	104.7642	104.7097
Total Sojourn Time	376.0549	377.0911
Total Sojourn Time 2	487.474	490.1286

Appendix I Complete overview waiting times after concentrating waste streams

	base case	Concentration of waste streams
	Mean	mean
EntranceWDS	6.27949	6.292356
SmallChemicalDepot	4.07E-11	4.06E-11
WeighingScale	5.725627	5.748912
SubStationPlatform	182.204	184.4331
OtherSubStation	14.33408	15.94381
ExitWDS	2.526811	2.527549
AnBGradeWood	0.579757	2.679012
C_gradeWood	8.317828	11.37117
CarTires	1.9E-11	0.123026
ChemicalWaste	0	NA
CrudeGardenWaste	182.204	184.4331
CrudeHomeWaste	1.51509	5.710973
CrudeWaste	1.889473	3.285631
Debris	22.77584	22.10693
E_Waste	0	NA
GasConcrete	0.028874	1.612506
GlassBottles	0	NA
GlassPlates	0	NA
Gravel	1E-11	1.017728
HardPlastics	20.3443	13.47372
Mattresses	9.876012	13.25961
OldMetal	0	NA
PaperNCarton	0	NA
Plaster	7.772703	5.464884
RoofingWaste	1.428669	0.752616
SoftPlastics	0	NA
Styrofoam	0	NA
Textile	0	NA
Total Waiting Time	72.93386	73.99623