Rail Tank Car Fleet Size Optimization at AKZO Nobel Base Chemicals

Final report

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Date: *4 November 2007*
Version: *Final*
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Public version

I. Executive summary

The motive to conduct this research project is that AKZO Nobel Base Chemicals (ANBC) suspects it has an overcapacity of rail tank cars (RTCs) and does not use them efficiently. ANBC uses RTCs to deliver Chlorine and Caustic to its customers in Northwestern Europe.

The objective of this research project is to:

Develop a tool that minimizes the RTC fleet size and:

1. ***meets market demand***
2. ***complies with safety requirements***
3. ***secures continuous production***

and

Use the tool to perform scenario analyses to determine the operational improvements that result in the largest savings.

The scope of this research project extends to the fleets of Chlorine and Caustic RTCs and to all customers these fleets deliver to.

The input factors to the model behind the tool are: customer demand, turnaround time of RTCs, loading time of RTCs, RTC maintenance and breakdowns, and RTCs for on-site storage purposes. The total fleet size and the service level achieved with this fleet size are the output factors or performance indicators of the model.

Example of an RTC (source: http://www.gatx.com)

In the course of this research project three fleet sizing models have been developed. However, after the validation of the models we conclude only the simulation model is valid. Table I.1 presents the three models developed and their key characteristics. It turns out that only the model that considers both demand and turnaround time as stochastic and at the level of the individual customer results in valid outcomes.

Model	*Kind of model*	*Demand*	*Turnaround time*	*Customer data*	*Validation result*
Simulation model	Simulation	Stochastic	Stochastic	Individual	Valid
Turnquist-Sherali	Analytical	Deterministic, dynamic	Stochastic	Individual	Invalid
Queueing model	Analytical	Stochastic	Stochastic	Aggregated	Invalid

Table I.1: Key characteristics and validation results of models developed in this research project

The only drawback of the simulation model is that limited availability of existing performance data makes it hard to fine-tune the model. Therefore scores on the output factor service level could be slightly pessimistic. However, this only has a minor impact on the final result of the model, if it has an impact at all.

The simulation model is built into a software tool, the *RTC Simulation Tool*. The RTC Simulation Tool determines the service levels achieved by a range of fleet sizes. It allows

ANBC to minimize its fleet size by choosing the minimum fleet size that results in an equal or higher service level than ANBC's desired service level.

The RTC Simulation Tool is the final tool that is implemented at ANBC. Recommendations regarding the implementation are:

1. Use the RTC Simulation Tool every time a significant change in the input factors occurs or when fleet size decisions have to be made.
2. Define the desired service level.
3. Start to measure the performance indicators service level and utilization. This allows a better validation of the simulation model against real data, as well as fine-tuning of the model. It could also solve the possible issue of slightly pessimistic scores on service level.

The RTC Simulation Tool is used to perform scenario analyses to obtain operational improvements. The scenario analyses result in two operational improvements that yield major savings:

- The reduction of the variability in customer demand
- The reduction of turnaround times

A 25% reduction of these factors results in yearly savings 16% of the total rental costs for the Chlorine RTC fleet and 8% for the Caustic RTC fleet.

To bring these operational improvements into effect, we recommend the following actions:

4. To reduce the variability of demand, educate the customer to order at more regular intervals or take over the responsibility of the daily delivery planning.
5. To reduce turnaround times, start to use Railion's tracking and tracing service to investigate who is responsible for excess turnaround time. When the responsible parties are identified, targeted follow-up actions can be taken to reduce turnaround times.

II. Preface

This report presents the final results of my graduation project at AKZO Nobel Base Chemicals (ANBC) in Amersfoort, The Netherlands. I conducted the project from October 2006 until November 2007 in order to finish my study and receive my Master's Degree in Industrial Engineering and Management at the University of Twente in Enschede, The Netherlands.

During my graduation project ANBC provided an interesting environment to work in. It has been very interesting to talk to many people in the organization and I very much appreciated their willingness to explain me all sorts of aspects of ANBC's logistics and its business in general. Therefore I thank all my colleagues at ANBC.

A few people at ANBC I thank in particular. First, I thank Rob de Leeuw and Rob Buitenhuis from the logistics department. From them I learned a lot of practical issues about logistics and especially Rob de Leeuw kept me focused on the practical issues of my project. Second, I thank my direct colleagues from the planning department: Koos Kuiper, Rene Essenius, Richard van Schaik, and Peter Schols. While working among them, they learned me a lot about the relations between different departments in an organization and about the fascinating practice of planning in a complex chemical industry. But above all I really enjoyed their company and the good atmosphere at our department. Last but not least, I thank Danny Dees, my supervisor at ANBC. Next to my gratitude for all his advice, guidance, and support during my project, I thank Danny for all our nice lunch conversations.

From the University of Twente, I thank Matthieu van der Heijden, Marco Schutten, and Erwin Hans. Although he has only been my supervisor for the first few months, I thank Matthieu for getting me on track during the first month of my research. I thank Marco for all his help with Delphi, for always making time available on a short notice, and for his critical remarks that kept me scientifically focused when I paid too much attention to the progress of my project. Finally, I thank Erwin because he took up the role of my second supervisor while already very busy with amongst others eighteen other graduate students to supervise.

Last but not least, I express many thanks to my parents and my girlfriend Juul. Juul is the one who had the most to suffer from my graduation project and I thank her for all her support and for reviewing this thesis. I thank my parents for their infinite support during my studies.

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III. Table of contents

IV. List of abbreviations

AGV: Automatic Guided Vehicle

ANBC: AKZO Nobel Base Chemicals, a business unit of AKZO Nobel. Unless otherwise stated, ANBC means only the sub business units Chlor-Alkali and Ecosystems.

CDF: Cumulative Distribution Function

CV: Coefficient of Variation

PVC: Poly Vinyl Chloride

RTC: Rail Tank Car

1 Introduction

This research project concerns the development of a tool to determine the optimal rail tank car fleet size at AKZO Nobel Base Chemicals. Before this report elaborates on this research project, this chapter presents the research introduction (Section 1.1) and the research design (Section 1.2). Section 1.3 contains a summary of this chapter and gives an outline of the remainder of this report.

1.1 Research introduction

To introduce the research project, this section introduces the context the research takes place, the motive to conduct the research, and the actual problem that is solved during this research project.

1.1.1 Research context

To provide a background to the research, this section gives a description of several relevant aspects of the research context. First, Section 1.1.1.1 describes the company where the research takes place, AKZO Nobel. Second, Section 1.1.1.2 describes the business context, Base Chemicals, which is a business unit of AKZO Nobel. And finally, Section 1.1.1.3 describes the functional context, rail transportation.

1.1.1.1 Company context: AKZO Nobel

AKZO Nobel is a multinational company based in The Netherlands, which services customers around the world with human and animal healthcare products, coatings, and chemicals.

For 2006, AKZO Nobel divides its activities in four segments: human health, animal health, coatings, and chemicals. The activities are subdivided into thirteen business units, with operating subsidiaries in more than 80 countries.

AKZO Nobel groups its activities in three groups: Pharma[1], Coatings, and Chemicals, and subdivides each group in business units and business units in sub business units. This research takes place within the sub business unit Chlor-Alkali, which is part of the business unit Base Chemicals. Figure 1.1 shows the relevant organizational structure for this research.

Key figures	*2005*	*2004*
Total revenues	€ 13,000 mln.	€ 12,833 mln.
Operating income (EBIT)	€ 1,486 mln.	€ 923 mln.
Number of employees	61,340	61,450

Table 1.1: AKZO Nobel key figures 2004-2005

[1] In the first half of 2007 AKZO Nobel sold its Pharma group to Schering-Plough, a U.S. based pharmaceutical company.

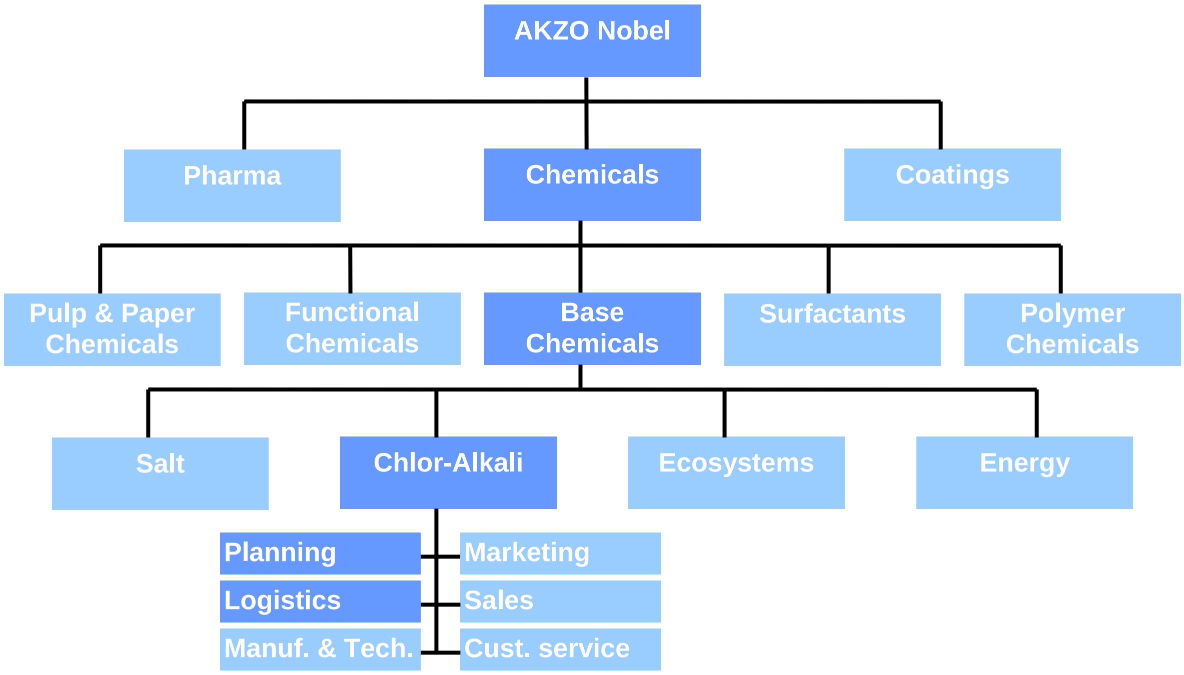

Figure 1.1: AKZO Nobel organizational structure - relevant parts for this research in dark blue

Section 1.1.1.2 further describes the business unit Base Chemicals and in particular its sub business unit Chlor-Alkali.

1.1.1.2 Business context: Base Chemicals

AKZO Nobel Base Chemicals (ANBC) has four sub business units, as shown in Figure 1.1, and this study concerns the sub business unit Chlor-Alkali. Figure 1.1 also shows the organizational structures within Chlor-Alkali. Within Chlor-Alkali, this study involves the planning department and logistics department. The planning department is responsible for the operational issues, for example the planning of transport movements, the call off of the carriers, and on-time delivery. The logistics department is responsible for more tactical issues like contracting logistic service providers and renting logistic equipment. Aside from the central planning department in Amersfoort (The Netherlands), there are also local planning departments at ANBC's plants in Ibbenbueren (Germany), Bitterfeld (Germany), and Skoghall (Sweden). The local planning departments are responsible for the daily planning of transport movements, but the local planning department in Ibbenbueren also has a coordinating role in rail transportation.

The products of ANBC[1] that are relevant for this study are produced through the electrolysis of salt. Electrolysis of salt results in two products: Chlorine and Caustic Soda Liquid (Caustic). Figure 1.2 shows the process of electrolysis.

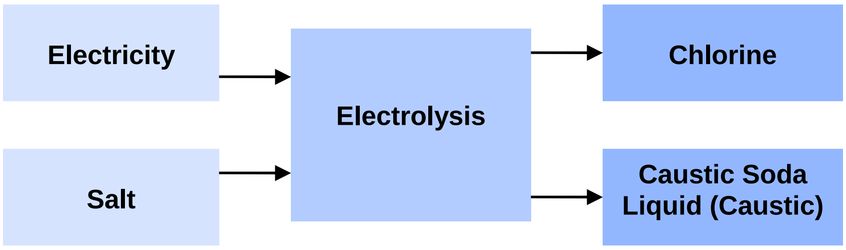

Figure 1.2: Electrolysis of salt

[1] From now on ANBC means the sub business unit Chlor-Alkali, unless otherwise stated.

Applications of the products can be found in PVC (Chlorine), bleaching of paper (Caustic), and industrial cleaning (Caustic).

In this industry safety is very important, because the industry works with very dangerous goods. For almost all customers, price is the leading differentiator because both Chlorine and Caustic are commodities.

1.1.1.3 Functional context: Rail transportation

Most transport of finished products to the customer is under ANBC's responsibility. ANBC transports the products by pipeline, truck, rail tank car (RTC), and ship. We focus on the rail transportation of ANBC.

1.1.2 Research motive: RTC overcapacity

The research motive concerns the problems ANBC has within the research context; the reasons for ANBC to conduct this research.

At the start of this research project ANBC suspected it had an overcapacity of RTCs. With significant yearly RTC rental costs and an industry focus on price, a reduction of the number of RTCs has a large potential for ANBC[1]. Although during the course of this research project RTCs already have been disposed, the drivers for the research motive are still in place. ANBC's presumption about the RTC overcapacity has a tactical and an operational driver:

- Tactical driver: the lack of a sophisticated tool to determine the need for RTCs;
- Operational driver: inefficient current operations.

The next sections explains both drivers.

1.1.2.1 Tactical driver: Lack of a sophisticated tool to determine RTC fleet size

Currently the need for RTCs is determined by a simple calculation. Due to time constraints nobody has ever developed a more sophisticated tool. Lately, when a lot of RTCs were replaced the question has risen how many RTCs ANBC really needs.

1.1.2.2 Operational driver: Inefficient current operations

ANBC suspects it does not make efficient use of its RTCs. This presumption is based on two issues: high turnaround times and a lot of idle time.

ANBC thinks the turnaround times of its RTCs are too high. Turnaround time is the time between an RTC leaving ANBC's site and returning again. ANBC suspects the main reason to be customers who keep the RTCs on their site longer than necessary.

The other issue concerns idle time. ANBC frequently mentions many empty RTCs at its sites. This could indicate unnecessary idle time and inefficient use of RTCs.

1.1.3 Management problem

The previous section describes ANBC's motivation to conduct this research project: ANBC's presumption it has an overcapacity of RTCs. The basic question behind this motivation is:

[1] This is also indicated in the *Logistics Excellence* project, a recent project at ANBC about improvements in logistics. This project has been conducted by Roland Berger Strategy Consultants.

How to determine the number of RTCs ANBC needs?

However, given the drivers of the research motive, this question could imply research in two directions. On the one hand, the tactical driver implies research to a sophisticated tool to determine the required number of RTCs given the current situation. On the other hand, the operational driver implies research directed on how to improve the current situation, i.e., the operational efficiency. In this case, the next step would be to determine the required number of RTC in this new situation.

ANBC has decided that its most important problem to solve is the tactical problem: the lack of a sophisticated tool to determine the RTC fleet size.

ANBC has chosen this problem because of two reasons:
1. ANBC itself lacks the knowledge to develop such a tool. In contrast to this problem, the operational problems could be solved by ANBC itself, when necessary.
2. The significance and priority of operational problems will follow from a tool to determine the fleet size. So the development of a tool should be the first step to take.

The full management problem can be formulated as follows:

ANBC lacks a sophisticated tool to determine the RTC fleet size. This tool should also help ANBC to determine the most interesting operational improvements.

The last part of this problem formulation aims at prioritization of the operational inefficiencies and the fleet size reductions that could result from improving them.

Based on this problem, Section 1.2 formulates the research objective and develops the research design.

1.2 Research design

Based on the management problem from Section 1.1.3, this section introduces the research objective and describes the design of the research. First, Section 1.2.1 presents the research objective. Second, Section 1.2.2 defines the scope of the research. Then Section 1.2.3 presents the research questions that have to be answered to reach the research objective. Finally, Section 1.2.4 presents the project framework, the research phases, and the research approach in these phases.

1.2.1 Research objective

This research aims at solving the management problem as stated in Section 1.1.3: the lack of a sophisticated method to determine the RTC fleet size and the need for an advice about the savings potential of possible fleet size reductions. The research objective or project assignment is therefore to:

Develop a tool that minimizes the RTC fleet size and:
1. ***meets market demand***
2. ***complies with safety requirements***
3. ***secures continuous production***

and

Use the tool to perform scenario analyses to determine the operational improvements that result in the largest savings.

The three constraints mean:
1. Meet market demand: achieve a predetermined minimum service level in the delivery of all customers.
2. Comply with safety requirements: meet all legal and internal maintenance and safety requirements.
3. Secure continuous production: provide enough RTCs for temporary storage of production overflow; to secure that storage capacity will not restrict the desired level of production of ANBC's plants.

We use the tool to perform scenario analyses on several scenarios for potential fleet size reductions. These scenarios concern operational improvements and are defined together with ANBC.

Although not in the research objective, ANBC has the practical requirements that the tool should be relatively easy to use and that ANBC should be able to run it on its current infrastructure or after little investment.

To reach the objective, several research questions have to be answered. Section 1.2.3 discusses these questions, but first we define the scope of the research in Section 1.2.2.

1.2.2 Research scope

We define the scope of this research on four aspects: products, markets, transport modalities, and supply and demand.

1.2.2.1 Products

Aside from Chlorine and Caustic, ANBC produces a few more products that it transports by rail, but only on a limited scale. Therefore, we focus on Chlorine and Caustic.

1.2.2.2 Markets

ANBC's markets could be divided in geographical areas around the plants, because in practice a customer is most often delivered from the same plant and most RTCs are used mainly for one plant. However there are quite some exceptions and the purchase and maintenance of RTCs is coordinated centrally from Amersfoort and Ibbenbueren. Therefore we take into account the whole market as one, with customers in the following countries in Northwestern Europe: Sweden, Germany, Austria, France, and Belgium. Customers buy Chlorine, Caustic, or both products.

1.2.2.3 Transport modalities

Regarding transport modalities, we focus on rail transportation. Although rail transportation sometimes interacts with transport by truck or ship, these cases are very rare and would create a very complex system. So for simplicity reasons we do not take them into account.

1.2.2.4 Supply and demand

The number of RTC deliveries depends on both the supply and the demand of product. Supply concerns the product quantities available for transport, i.e., the output of ANBC's plants and the quantities purchased. Demand concerns customer demand for product and thus demand for transport of product. This research only takes into account the demand, because demand is leading in determining the number of RTC deliveries. Supply can only limit the number of deliveries. This happens rarely and moreover it would create a very complex system because the supply of product for RTC delivery interacts with the supply for all other transport modalities. Because of these two reasons, we decide to leave the supply side out of scope.

1.2.3 Research questions

To reach the research objective, we answer the following research questions:

1. *What are the characteristics of ANBC's RTC transportation system and how does ANBC currently determine its fleet size?*
2. *Which input and output factors should be included in the fleet sizing model?*
3. *Which model should be used to determine the optimal fleet size?*
4. *How should this model be validated?*
5. *Which of the scenarios for operational improvements have the largest saving potential?*
6. *How could the fleet sizing model (as part of a tool) and the operational improvements with the largest savings potential be implemented at ANBC?*

The tool that has to be developed relies on a model of ANBC's RTC transportation system. Question 1 results in a description of the system that has to be modeled and gives insight to ANBC's current model to determine the size of its RTC fleet. Question 2 goes further and its answer results in the aspects of the system that have to be taken into account in the model: the input and output factors of a model. Question 3 concerns the way these factors can be combined to construct a model and how the optimal fleet size can be determined.

The answer on the fourth question provides ways to verify whether the model is a valid representation of reality. If the model is valid, Question 5 can be answered and its scenario analyses provide a prioritization of operational improvements according to their savings potential. Finally, Question 6 discusses how to implement the tool (and the model behind it) and how to implement the operational improvements that result from question 5.

Section 1.2.4 presents the approach used to answer the research questions.

1.2.4 Research approach and project framework

This research project is divided in four phases: an orientation phase, an analysis phase, a design phase, and an implementation phase. The project framework in Figure 1.3 represents these phases. The framework divides each phase in sub phases that roughly correspond with the research questions. The research approach describes which information is used to answer each research question.

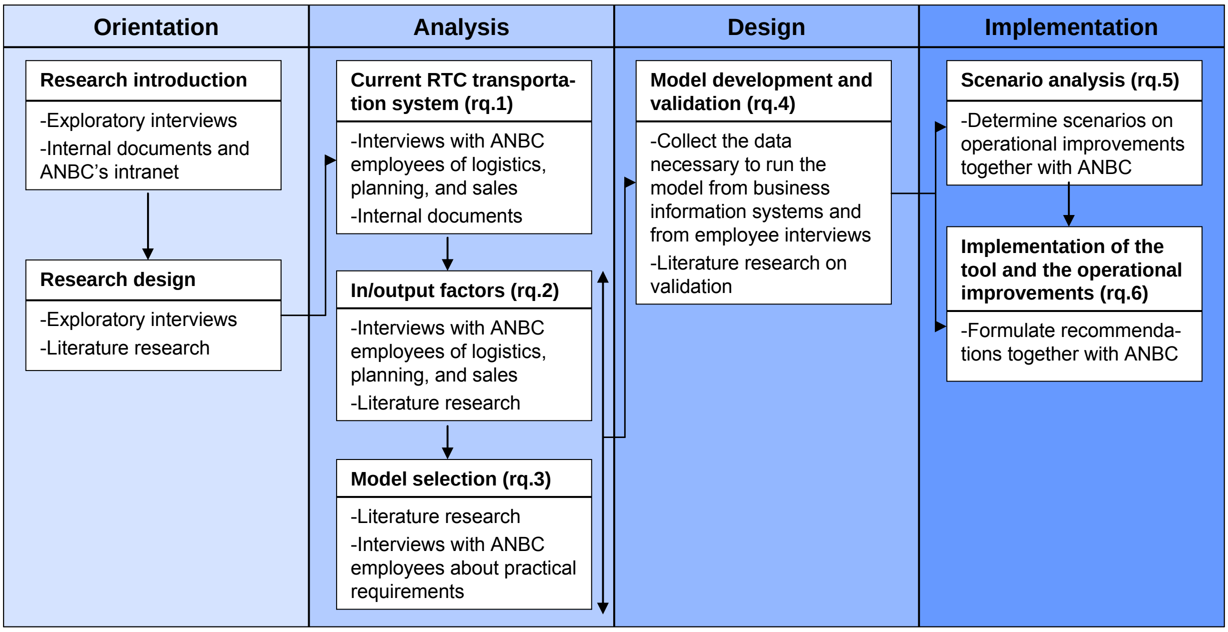

Figure 1.3: Project framework with the research approach (rq. = research question)

The orientation phase consists of the research introduction and the research design, i.e., the current and previous chapter. The analysis phase answers research questions 1, 2, and 3. It analyses the current RTC transportation system and the input and output factors of the fleet sizing model. Also this phase analyses what model should be used to model the system. The design phase contains the development and validation of the actual models. The implementation phase answers research question 5 by conducting scenario analyses. This phase also answers research question 6 by making recommendations on how to implement both the tool and the operational improvements with the largest savings potential.

1.3 Summary and report outline

This chapter starts with an introduction of the research context, the research motive, and the actual problem that is solved during this research project. The research takes place at AKZO Nobel Base Chemicals (ANBC) and focuses on ANBC's rail transportation. The research concerns the problem that ANBC lacks a sophisticated tool to determine the rail tank car (RTC) fleet size. This tool should also help ANBC to determine the operational improvements that results in the largest savings

Based on this problem, Section 1.2.1 defines the research objective: the design of a tool to minimize the RTC fleet size subject to demand, safety, and production constraints. Also part of the objective is the application of the tool to several scenarios for operational improvements to determine the scenarios with the largest saving potential. Subsequently, Section 1.2.2 narrows down the scope of the research to rail transportation of Chlorine and Caustic in Northwestern Europe.

Section 1.2.3 introduces the research questions. These questions that have to be answered to reach the research objective. The research questions concern ANBC's current RTC transportation system, the input and output factors of a fleet sizing model, the actual model, the validation of the model, the scenario analyses that have to be performed with the model, and the implementation of the model. The research approach in Section 1.2.4 presents the project framework and the information that is used to answer each research question.

The remainder of this report starts with a description of the practical background in Chapter 2. This chapter describes the RTC transportation system that is modeled later in this report. The model of this system functions as the model behind the tool that has to be developed according to the research objective.

Chapter 3 presents the theoretical background: a survey of the literature on fleet sizing models. Subsequent chapters use this literature research to decide on the input and output factors the model should have, to select a model, and to validate that model.

Chapter 4 presents the input and output factors that should be included in the model and Chapter 5 selects the final model that is applied at ANBC. Chapter 5 starts with a pre-selection of three models and subsequently develops and validates these models. Based on the validation, finally, it selects the final model.

Chapter 6 uses the final model to perform scenario analyses on scenarios for operational improvements. Chapter 7 discusses the implementation of the operational improvements and the implementation of the final model, incorporated in a tool. Finally, Chapter 8 contains the conclusions, recommendations, a discussion, and gives suggestions for further research.

2 Practical background: RTC transportation system

To explain the system that is modeled later in this report, this chapter describes the relevant aspects of ANBC's RTC transportation system and thereby answers the first research question:

> 1. *What are the characteristics of ANBC's RTC transportation system and how does ANBC currently determine its fleet size?*

The purpose of ANBC's RTC transportation system is to transport Chlorine and Caustic to its customers that require these products delivered by rail. Before this chapter elaborates on the characteristics of the system, Section 2.1 describes the decision to use rail transportation to deliver a certain customer. The subsequent sections describe the system's characteristics: first, Section 2.2 describes the system layout, second, Section 2.3 describes the system capacity, third, Section 2.4 discusses the system performance, and fourth, Section 2.5 describes the process within the system. To get an insight in the current fleet sizing practice, Section 2.6 contains a description of ANBC's current fleet sizing model. Finally, this chapter ends with a summary in Section 2.7.

2.1 Rail transportation versus alternative modalities

2.2 System layout: Locations of plants and customers

2.2.1 ANBC's plant locations

2.2.2 Customer locations

2.2.3 RTC allocation

2.3 System capacity

2.3.1 RTC fleets

2.3.1.1 Flexibility of capacity: RTC rental conditions

2.3.1.2 Customer dedicated RTCs

2.3.2 Factors that use RTC capacity

2.3.2.1 Chlorine and Caustic transport to customers

2.3.2.2 RTC inspection and maintenance

2.3.2.3 Special purposes for Chlorine RTCs: Temporary and safety storage

2.4 System performance

2.5 The process: From order to delivery

2.5.1 Receiving orders

2.5.2 Planning

2.5.3 The physical process: Product handling, transport, and delivery

2.6 ANBC's current fleet sizing model

2.7 Summary

3 Theoretical background: Survey of the literature on fleet sizing

This chapter presents a survey of the literature on fleet sizing with a focus on models that are used to represent and solve the fleet sizing problem. Together with the input and output factors, which are discussed in Chapter 4, the literature survey is the starting point of the model selection in Chapter 5. Besides a contribution to the model selection, the literature survey also contributes to the determination of the input and output factors in Chapter 4 and the validation of the model in Chapter 5.

The structure of this chapter is as follows: Section 3.1 discusses the fleet sizing problem, its application areas, and related problems. Section 3.2 describes the models that are used to model the fleet sizing problem and finally, Section 3.3 contains a summary of the chapter.

3.1 The fleet sizing problem

Du & Hall (1997) define the fleet sizing problem to determine the number of vehicles or containers that optimally balances service requirements against the cost of purchasing and maintaining the equipment. This section discusses the application areas of the fleet sizing problem and related problems.

3.1.1 Application areas

Applications of fleet sizing can be found in many areas. Key areas are amongst others: passenger transportation, trucking, rail freight transportation, automated guided vehicle (AGV) systems, and reusable resources, such as containers or military training equipment. Besides fleet sizing in rail freight transportation, in this literature research we focus on fleet sizing in the areas of AGV systems and reusable resources. Both areas show similarities because they consider individual transport requests and capacity is fixed on the short to medium term.

We pay limited attention to fleet sizing in passenger transportation and trucking, because both areas have an important difference with rail freight transportation. According to Ganesharajah et al. (1998) passenger transportation differs from rail freight transportation because it does not consider individual passenger transport request, while this is an important aspect in rail freight transportation. Sherali & Tuncbilek (1997) mention that opposed to fleet sizing models in rail freight transportation, those in trucking usually permit leasing in time of shortages and they track the cyclical tours for each individual truck.

3.1.2 Related problems

The fleet sizing problem relates to a number of other problems. Several authors discuss fleet sizing together with vehicle allocation, vehicle routing, vehicle dispatching or vehicle scheduling. For example, Beaujon & Turnquist (1991) discuss a model for fleet sizing and vehicle routing and Koo et al. (2004) discuss fleet sizing and vehicle routing for container transportation. Fleet sizing differs from these issues because it is a tactical issue. I.e., decisions about fleet sizing have a medium to long term impact, while issues such as allocation and routing are operational.

The next section discusses the fleet sizing models proposed in the literature in more detail.

3.2 Fleet sizing models

This section describes the different models that have been used to solve the fleet sizing problem. The literature survey by Ganesharajah et al. (1998) classifies the work on fleet sizing models into deterministic and stochastic studies. A deterministic system assumes all information to be known in advance. For example, a system is deterministic if it assumes information such as customer demand and travel times to be exactly known at the beginning of the planning horizon. In a stochastic system not all information is known in advance and variability has to be included in the system. The next two sections summarize deterministic studies (Section 3.2.1) and stochastic studies (Section 3.2.2). The papers discussed in both sections are in chronological order and all models described consider transports of full truck loads.

3.2.1 Deterministic models

This section discusses several deterministic models that are used to solve the fleet sizing problem. All factors in the models are deterministic.

According to a literature survey by Bojović (1999), in the early days of literature on fleet sizing the fleet sizing problem has been treated as a non dynamic problem. Bojović refers to Feeney (1957) and Leddon & Wrathall (1967) for examples of this approach. These authors formulate the problem as a linear programming problem with known supply and demand, the objective being to maximize revenue. They solve the linear programming using a standard simplex algorithm.

Powel et al. (1995) introduce a fleet sizing concept referred to as a logistic queueing network (LQN). Their approach is aimed at solving large scale fleet sizing problems with thousands, or even hundreds of thousands, of vehicles. The LQN substitutes large-scale linear programming by a series of very small-scale local network problems, which are solved iteratively. The main advantage of the method is that it is a much faster alternative to the simplex method used to solve LP problems. Numerical experiments show that results achieved by the LQN are very close to the results achieved by an LP model.

Sherali & Tuncbilek (1997) discuss a static and dynamic analytical model to determine the fleet size of railcars to ship automobiles. They also calibrate the static model to make it more accurate. The static model is time-independent and based on average yearly demand data and an expected turnaround time (including expected queue times). The dynamic model uses normalized historical data to derive a projected time-varying demand pattern for each origin-destination pair. This pattern is used in a time-space network to determine the smallest fleet size to satisfy all demands at various points in time. To solve this problem the authors propose a heuristic procedure that decomposes the planning horizon to reduce the computational requirements.

To make the static model more accurate, the authors calibrate it by using the average demand over a shorter time horizon. The total horizon is split up in shorter horizons (periods) and the period with the highest average demand is used in the static model. If properly calibrated the static model produces results within 0-1% of the outcome of the dynamic model. Together with the relatively small computational requirements, this makes the calibrated static model suitable to quickly evaluate various “what-if” scenarios. Sherali & Maguire (2000) demonstrate that these models show good results if applied in practice.

McGinnis (1997) proposes a heuristic methodology to size a large-scale system of constrained, reusable resources for military training purposes. McGinnis’ model minimizes the number of idle resources in a system of uniform resources. The system forecasts demand based on historical data. This forecast is the starting point of the system sizing methodology. The method consists of three major tasks: heuristic resource scheduling, system sizing, and policy improvement. Starting at system size zero, the method iterates the first two tasks until it finds a feasible fleet size and then a multi-pass heuristic policy further refines the solution.

Rajotia et al. (1998) formulate a mixed integer programming model to determine the optimal AGV fleet size for a flexible manufacturing system. They validate the results using the results of a simulation model. The model identifies three states of a vehicle journey: 1) Load handling, 2) Empty travel, and 3) Waiting. The latter two states depend on the randomness in the arrival pattern of load transport calls and for both empty travel time and waiting time approximations are made based on several models from literature. The objective of the model is to minimize empty travel. From the simulation study the authors conclude that the model they propose estimates the fleet size approximately the same as the simulation model and can act as a good initial estimate of the fleet size. This estimate could be fine-tuned in a follow-up simulation study, but this is more time consuming.

Koo et al. (2004) discuss fleet sizing in a static environment for container transportation between several container yards in a seaport. They propose a two phase approach where they use the optimization model proposed by Maxwell & Muckstadt (1982) to obtain a lower bound to the fleet size in phase 1. This model minimizes the empty travel time of the vehicles under the condition that demand is met. Phase 2 consists of an iterative process where a heuristic based on a tabu search algorithm is used to improve the vehicle routing, while the fleet size is increased by steps of one (starting at the lower bound from phase 1) until a feasible solution has been found.

3.2.2 Stochastic models

Next to the deterministic models discussed in the previous section, this section discusses stochastic models to solve the fleet sizing problem. In the models described below one or more factors are stochastic.

Turnquist & Jordan (1986) develop an analytical model for sizing a fleet of containers used to ship parts from a single manufacturing plant to a group of assembly plants. The manufacturing plant produces parts in a deterministic production cycle and the study starts with the assumption of deterministic travel times. The second part of the paper relaxes this assumption to investigate the impact of travel time uncertainty. The initial deterministic model takes into account the number of containers in each stage of the process: containers at the manufacturing plant, containers at the assembly plants, and containers in-transit. The number of containers in the first stage depends on the length of the production cycle, the number in the second stage depends on the required buffer capacity at the assembly plants, and the number in the last stage depends on the travel time.

In the second part of the paper, the authors recognize that travel times are uncertain and therefore that a deterministic model underestimates the number of containers needed. To take into account the uncertainty in travel times, the model formulation contain an average and standard deviation of the travel times to and from each assembly plant. The model formulation also contains a probability distribution function to determine the required buffer size at the assembly plant under a predetermined stock-out (i.e., vehicle shortage) probability. The paper ends with some empirical tests and concludes that travel time uncertainty does impact the required fleet size. The paper also concludes that pooling equipment reduces the effect of travel time uncertainty, i.e., using one pool of containers for all assembly plants, instead of a separate pool for each plant.

Beaujon & Turnquist (1991) recognize the importance of the interaction between decisions on the fleet size and decisions on vehicle allocations. They develop a general optimization model to optimize both sets of decisions simultaneously under dynamic and uncertain conditions. They present a network approximation to their model and propose a solution procedure. This iterative procedure includes the Frank-Wolfe algorithm and updates the variances, searching for a fixed-point solution in which a given set of variances used as input to the network model results in a set of network flows that reproduce those same variances.

Du & Hall (1997) apply inventory theory to empty equipment redistribution and fleet sizing for center-terminal transportation networks. The network considered consists of a center and a number of terminals (a hub and spoke system). Transportation demand and exchange of empty trucks only occur between the center and the terminals. However, flows are bidirectional, so that loads can be sent both from center tot terminal and terminal to center. In an environment of stochastic vehicle demand and deterministic travel times the objective is to minimize the fleet size, subject to meeting a given allowed long-run stock-out probability. The authors decompose the problem and determine stock-out probabilities for the center and the individual terminals. Based on the stock-out probabilities, from inventory theory they develop decentralized stock control policies for empty equipment. With this information they calculate the number of vehicles that has to be committed to each terminal. They use queueing theory to determine the number of vehicles needed at the center.

Lesyna (1999) uses discrete-event simulation to size the rail car fleets of DuPont, a U.S. based chemical company. He addresses the advantages and disadvantages of simulation. Simulation can take into account the complexity, the dynamics, and the randomness of a system. However, simulation does require a lot of input data and is more time consuming to implement and maintain, compared to analytical models.

Bojović (1999) determines the optimal number of rail freight cars using a general system theory approach. He presents a comprehensive analytical model, which includes many cost parameters. The paper demonstrates how the problem can be solved from the standpoint of general system theory. Numerical experiments have shown the model to be very good in terms of computational efficiency.

Koo et al. (2005) present a fleet sizing procedure that uses a queueing model to estimate part waiting time in an AGV system. The fleet sizing procedure estimates the minimum number of vehicles needed to ensure a predefined part waiting time limit. The paper considers stochastic demand, but deterministic travel times. Simulation experiments confirmed the accuracy of the new model, although if the model considers stochastic travel times, the estimation accuracy decreases. Another example of the application of a queueing model can be found in Mantel & Landeweerd (1995), who propose a two level hierarchical queueing network approach to determine a rough fleet size.

3.3 Summary

This chapter describes the fleet sizing problem in general in Section 3.1 and presents an overview of the fleet sizing models proposed in literature in Section 3.2. The fleet sizing problem is defined as the problem to determine the number of vehicles or containers that optimally balances service requirements against the cost of purchasing and maintaining the equipment. Key areas of applications of fleet sizing model are passenger transportation, trucking, rail freight transportation, automated guided vehicle (AGV) systems, and reusable resources. Besides rail freight transportation, the literature survey also focuses on AGVs and reusable resources, because of their similarities with rail freight transportation. Related problems such as vehicle allocation and vehicle routing differ from fleet sizing because they are operational issues, while fleet sizing is a tactical issues.

Section 3.2 gives an overview of the fleet sizing models proposed in the literature. Table 3.1 presents several key elements from this overview. The second column of Table 3.1 lists the characteristic feature of every paper. Except Lesyna's simulation model, all models proposed are analytical models. For these papers the characteristic features concern the kind of analytical model, the field of the theory used, or the technique to solve the model. Some papers propose models that are solved by exact calculation, others use a heuristic procedure. Furthermore, for every paper, Table 3.1 lists an important characteristic of demand and turnaround time in the model: whether the model considers them as deterministic or stochastic. From the survey we conclude that demand and turnaround time are the most important input factors in the fleet sizing models. Section 2.3.2, about the factor that use RTC capacity, supports this conclusion.

Author	*Characteristic feature*	*Demand*	*Turnaround time*
Feeney (1957) Leddon & Wrathall (1967)	Linear Programming	Deterministic	Deterministic
Powel et al. (1995)	Logistic Queueing Network	Deterministic	Deterministic
Sherali & Tuncbilek (1997)	Dynamic approach to demand	Deterministic	Deterministic
McGinnis (1997)	A heuristic methodology	Deterministic	Deterministic
Rajotia et al. (1998)	Mixed Integer Programming	Deterministic	Deterministic
Koo et al. (2004)	Tabu search	Deterministic	Deterministic
Turnquist & Jordan (1986)	Probability function	Deterministic	Stochastic
Beaujon & Turnquist (1991)	Network approximation	Stochastic	Stochastic
Du & Hall (1997)	Inventory theory	Stochastic	Deterministic
Lesyna (1999)	Simulation model	Stochastic	Stochastic
Bojović (1999)	System theory	Stochastic	Stochastic
Koo et al. (2005)	Queueing model	Stochastic	Deterministic

Table 3.1: Overview of key elements of the fleet sizing models proposed in literature

4 Input and output factors of the model

Based on the information from the practical and theoretical background, this chapter answers the second research question:

2. *Which input and output factors should be included in the fleet sizing model?*

Input factors are factors that influence the fleet size and therefore they are input to the fleet sizing model. Together all input factors determine the total fleet size and the performance that is achieved with that fleet size. Output factors are the output of the model and they say something about the fleet size or the performance that is achieved with that fleet size.

The structure of this chapter is as follows: Section 4.1 concerns the input factors, Section 4.2 concerns the output factors, and the chapter ends with a summary in Section 4.3.

4.1 Input factors

To define the final input factors, this section starts with list of the factors that are relevant to include in the model in Section 4.1.1. Subsequently Section 4.1.2. describes the characteristics and available data of these factors. Based on the available data, Section 4.1.3 presents the final list of input factors.

4.1.1 Relevant input factors

To determine the input factors both information from practice and information from the literature is used. Appendix B lists all input factors derived from the practice and the literature and reduces this list to a list of the relevant factors, which is presented below. The list is grouped by demand factors, transport factors, maintenance factors, and storage factors. An explanation of each factor can be found in Appendix B.

Demand factors

1. Customer demand
2. Interruptions in production at the customer
3. Customer dedicated RTCs

Transport factors

4. Transit times between ANBC plants and customers and the return trip.
5. Waiting times at country borders
6. Unloading times at customer
7. Unnecessary holding times at customer
8. Loading times at ANBC
9. The possibilities of alternative transport modalities (relevant only for Caustic)

Maintenance factors

10. RTC inspection and maintenance
11. RTC breakdowns

Storage factors

12. RTCs as safety storage (relevant only for Chlorine)

13. RTCs as temporary storage (relevant only for Chlorine)

Section 4.1.2 further describes the characteristics of these input factors and the availability of data for each factor.

4.1.2 Factor characteristics and available data

For each of the input factors from the previous section, this section describes the important characteristics and the availability of data. Based on the information from this section the complete list of final factors is presented in Section 4.3.

Because ANBC measures all of its data in no shorter time unit than days, unless stated otherwise, the time units used are days.

4.1.2.1 Demand factors

4.1.2.2 Transport factors

4.1.2.3 Maintenance factors

4.1.2.4 Storage factors

4.1.3 Final input factors

Based on the relevance of the factors and on the available data, the following factors are the final input factors to be included in the model to determine the optimal RTC fleet size:

1. Customer demand (with the sub factors average and variability)
2. Turnaround time (with the sub factors average and variability)
3. Loading time at ANBC
4. RTC inspection and maintenance
5. RTC breakdowns
6. RTCs as safety storage
7. RTCs as temporary storage

4.2 Output factors

4.3 Summary

The aim of this chapter is to answer the research question: *Which input and output factors should be included in the fleet sizing model?*

Section 4.1 concerns the input factors and based on the relevance of each factor and on the available data it concludes the final list of input factors:

1. Customer demand (with the sub factors average and variability)
2. Turnaround time (with the sub factors average and variability)
3. Loading time at ANBC

4. RTC inspection and maintenance
5. RTC breakdowns
6. RTCs as safety storage
7. RTCs as temporary storage

Section 4.2 discusses the output factors or performance indicators of the model and determines two performance indicators:

- Total fleet size
- Service level

Because both performance indicators relate to each other, for one of them a desired value has to be set to determine the optimal value of the other.

Figure 4.1 presents a schematic view of the final input and output factors.

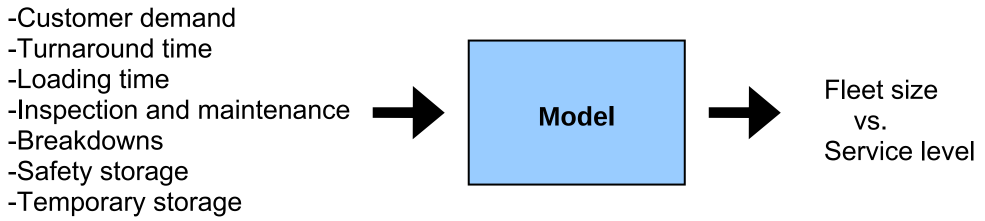

Figure 4.1: Schematic view of the final input and output factors

5 Model selection

This chapter answers two research questions:

3. Which model should be used to determine the optimal fleet size?

and

4. How should this model be validated?

To answer Research question 3, Section 5.1 pre-selects three models that are each developed and applied to ANBC's fleet sizing problem in Section 5.2 to Section 5.4. Section 5.5 selects the final model. To be able to make a final selection, the three models have to be validated and therefore Research question 4 has to be answered. Starting in Section 5.1.4, in the course of this chapter this question is addressed and answered.

5.1 Introduction

This introduction section discusses four issues. First, Section 5.1.1 discusses the pre-selection of the three models that are further developed. Second, Section 5.1.2 briefly lists the underlying assumptions to the three models selected. Third, Section 5.1.3 gives a brief overview of the input data that is used to obtain the results presented later on in this chapter. Finally, Section 5.1.4 introduces the validation methods that are used to validate the models.

5.1.1 Pre-selection: Three fleet sizing models

This section describes how we pre-select three models to apply at ANBC's fleet sizing problem. These three models are a pre-selection based on the requirements described in this section. Based on the validations and results of the three models, in Section 5.5 we select the final model.

The selection's starting point are the model requirements. Based on the previous chapters, we formulate the following requirements:

1. The model should be able to deal with variability in both demand and turnaround times.
2. The model should only consider the fleet size, fleet allocation is out of scope.
3. The model should not require detailed information.
4. The model is kept as easy to understand and to use as possible.

The reason behind the first requirement is the large variability in turnaround times and especially in demand. The second requirement is inserted because fleet allocation seldom causes problems to ANBC, as described in Section 2.2.3, and ANBC is primary interested in the tactical problem of fleet sizing. The reason behind the third requirement is that only limited information is available about the breakup of turnaround times and RTC costs.

Based on these requirements deterministic models are not suitable because they cannot deal with the variability. From the stochastic models that Chapter 3 discusses, queueing models and simulation models seem to be the most suitable because they can include variability in both demand and turnaround times[1]. Other reasons we select them are that they can be used to consider only fleet size (as opposed to Beaujon & Turnquist's (1991) network approximation), and that they do not need detailed information (as opposed to Bojović's (2002) system theory approach).

Because queueing models and simulation models are not the easiest models to understand or to use, we decide to include one other model in the selection. This model is a combination of the models proposed by Turnquist & Jordan (1986) and Sherali & Tuncbilek (1997) and from now on to this model is referred as the Turnquist-Sherali model. The model combines Turnquist & Jordan's stochastic approach of turnaround times and Sherali & Tuncbilek's approach to demand, where they consider demand as deterministic, but dynamic.

In the literature simulation models are quite often used to validate results of other models, amongst others by Rajotia et al. (1998) and Koo et al. (2005). One of the reasons we choose to apply a simulation model, next to a queueing model that is also stochastic, is to validate the results of the other models. In case of ANBC, an equally performing analytical model would outrank a simulation model because of its ease of use.

Section 5.2 to Section 5.4 successively discuss the simulation model, the Turnquist-Sherali model, and the queueing model. But first, Section 5.1.2 to Section 5.1.4 present some prerequisite information.

5.1.2 Model assumptions

Before the three models that are pre-selected in Section 5.1.1 are further explained, this section gives a brief review of the most important underlying assumptions to these models.

These assumptions are:

1. Customer demand is considered stochastic (except for the Turnquist-Sherali model)
2. Turnaround times are considered stochastic
3. Loading time is considered deterministic
4. The proportion of the fleet size that is required to cover for maintenance and breakdowns is considered deterministic
5. The number of RTC required for storage purposes is considered deterministic
6. ANBC's different plant locations are not taken into account and only turnaround times from a customer's default plant are considered.

5.1.3 Input data

This section briefly describes the data that is used as input to the models to produce the results this chapter presents. Most data has been described earlier in this report, so this section mainly functions as an overview.

[1] Although Koo et al. (2005) propose a queueing model that considers deterministic turnaround times, queueing model, queueing models in general take into account variability in both demand and turnaround time. See also Section 5.4.

5.1.4 Validation methods

Because three models have to be validated, there is no single answer to the question on how to validate the model. A distinction is made between the analytical models (the Turnquist & Sherali model and the queueing model) and the simulation model.

Regarding the analytical models, from the literature review in Chapter 3 we conclude that these models are most often validated in a comparison with a simulation model. Amongst others Rajotia et al. (1998) and Koo et al. (2005) use simulation models to validate their analytical models. Therefore, the simulation model, that is proposed in Section 5.2, is used to validate the two analytical models. Furthermore, the validation of the analytical models involves a theoretical validation. A theoretical validation tests the model for input data for which the outcomes can be calculated exactly. In this way the validation checks whether the model works correctly.

To determine whether the simulation model is valid and thus if it can be used to validate the analytical models, the validation of the simulation models contains three different validations. Section 5.2.2 explains these validations in more detail.

Because a valid simulation model is required to validate the other two model, the simulation model is the first model that is discussed. Section 5.2 gives a description of the simulation model and discusses its validation and results.

5.2 Simulation model

This section considers the first model applied at ANBC's fleet sizing problem, a simulation model. The section starts with a description of the model in Section 5.2.1, subsequently Section 5.2.2 discusses the validation of the model, and finally, Section 5.2.3 presents the results of the simulation model.

5.2.1 Description of the simulation model

A simulation model differs from the other two models that are pre-selected, because it is not an analytical model; it is not possible to work out the relationships of the model for the input data to get an exact analytical solution. Instead of calculating the exact solution, a simulation model performs numerical exercises for a set of input data to see how they affect the output measures.

The idea to use a simulation model to determine ANBC's required fleet size comes from Lesyna (1999), who uses a simulation model to determine the rail tank car fleet size in a similar system to ANBC's. The theory about simulation modeling and analysis used in this section comes from Law & Kelton (2000).

We have used Borland Delphi to build the simulation model and Microsoft Excel to prepare the input data and to process the output data.

5.2.1.1 Model description

The simulation model proposed here simulates ANBC's RTC transportation system and Figure 5.1 shows the process within the simulation model.

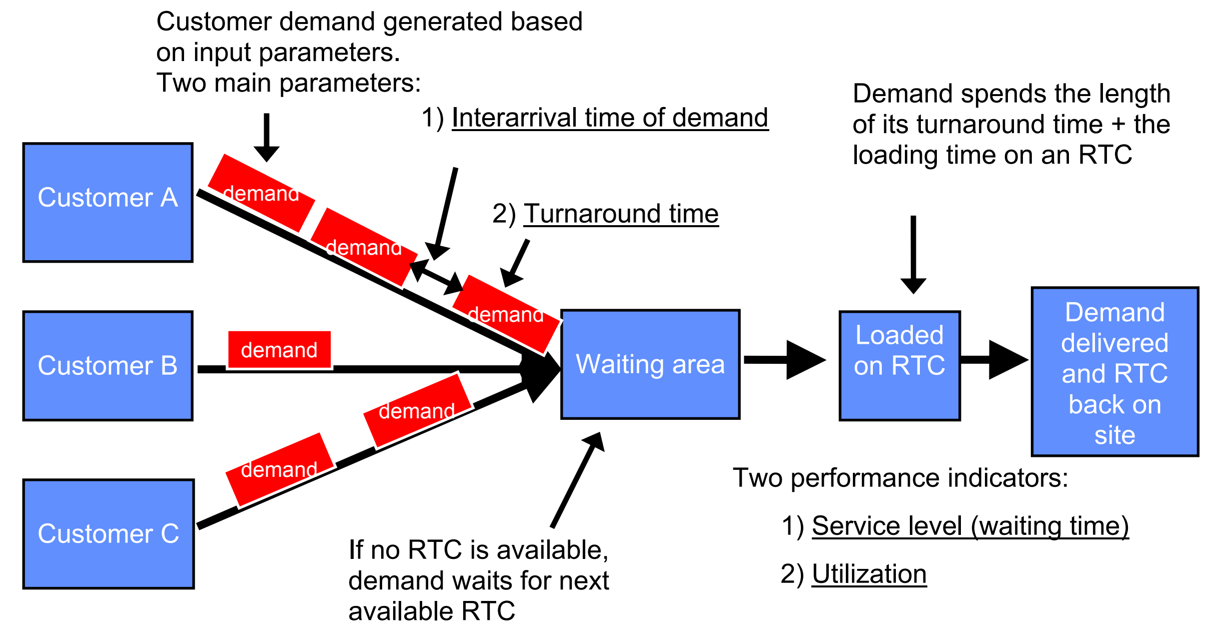

Figure 5.1: Graphical representation of the simulation model of ANBC's RTC transportation system

For every customer, the simulation model generates demand (one piece of demand is one RTC) on a variable interval and as it generates a piece of demand the model also generates a turnaround time for this piece of demand. Both demand and turnaround time are generated from a gamma distribution[1]. As proven in Appendix C, both the actual distributions of customer demand and turnaround time can be fairly well approximated with a gamma distribution.

Once the demand for an RTC is generated, it is loaded on an RTC or placed in the waiting area if no RTC is available. If demand is loaded on an RTC, it occupies the RTC for the length of its turnaround time plus its loading time. When this time period has passed the RTC gets available again.

During the simulation process, two performance indicators are measured: the utilization of the RTC fleet and the waiting time for each piece of demand. At the end of the simulation from all waiting times the average waiting time and the service level is calculated; the fraction of demand that spent a certain period of time or less in the waiting area.

5.2.1.2 Simulation settings

To obtain reliable results from a simulation, several settings have to be set: the simulation length, the number of runs, and the warm-up period.

Because demand and turnaround times are generated through a random process the output of the performance indicators varies for each simulation. However if simulations are done for longer periods of time and many simulation runs are performed, the average values of the performance indicators get quite stable. Appendix D describes the methods on how to determine the simulation length and the number of runs. Appendix D also determines the actual values of these settings for the ANBC situation. Figure 5.2 shows the high level steps in a simulation exercise.

[1] Law & Kelton (2000) describe the pseudo code to generate general gamma random variates (pp 461-464).

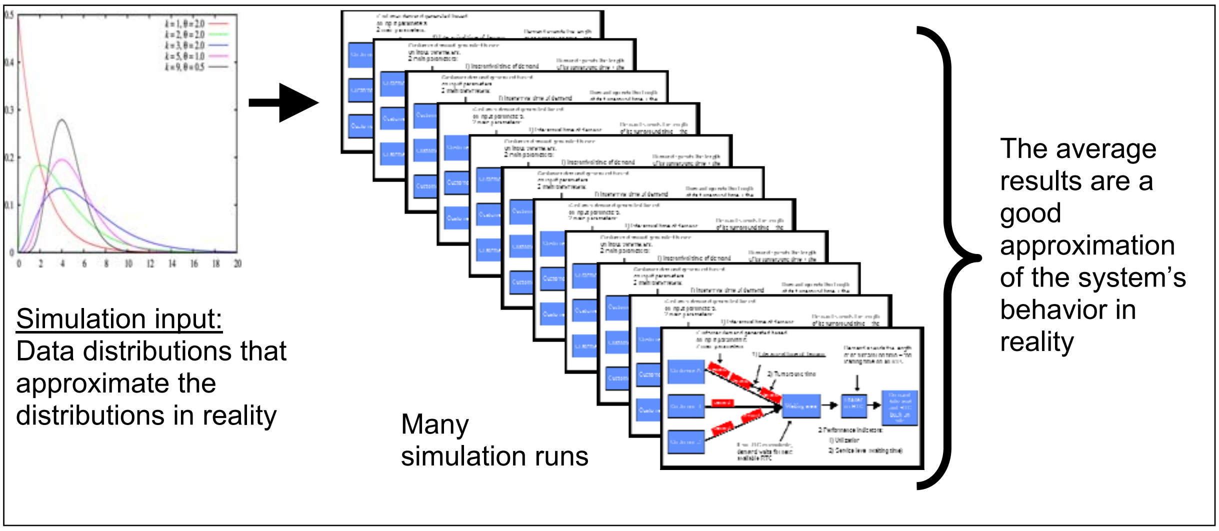

Figure 5.2: High level steps in a simulation exercise

Another problem regarding simulations of continuous processes is the state of the system the simulation starts with: an empty system. In ANBC's case an empty system means there is no demand in the system at the start of the simulation, i.e., all RTCs are empty. For the first period of the simulation this results in lower waiting times and a lower utilization than there would be in reality. A solution to this is to determine the warm-up period, the period the simulation needs to get to a steady state, and only start to measure the performance indicators when the warm-up period is over. Appendix D describes how the warm-up period is determined and determines the length of the warm-up period for the ANBC situation.

5.2.1.3 Input and output factors

Besides the input factors already mentioned all other input factors are also included in the model. The application of the simulation model itself results in the number of RTCs needed for transportation. Added to this "intermediate" fleet size are the RTCs needed for safety and temporary storage and the average percentage of RTCs needed to cover for maintenance and breakdowns.

The final output of the simulation model is a range of fleet sizes for which the average waiting time, service level, and utilization are approximated. With this data and the desired service level set by ANBC, the required fleet size can be determined.

5.2.2 Validation of the simulation model

This section discusses the validation of the simulation model. Law & Kelton (2000) describe several ways to verify and validate a simulation model. Verification concerns the determination whether the computer program works correctly and validation is the process of determining whether the simulation model is an accurate representation of the real system, i.e., whether the results of the simulation model correspond with those of the real system.

To decide whether the simulation model is a valid representation of reality, the model is validated in three ways. First, Section 5.2.2.1 verifies whether the distribution of data generated by the simulation model matches the desired distribution. Second, Section 5.2.2.2 compares the results of the simulation model with observations from reality and finally, Section 5.2.2.3 tests the simulation model with input data for which the exact results are known.

Unless otherwise stated, all simulation results in this section and subsequent sections and chapters are from simulations with the settings as determined in Appendix D: a warm-up period of 2 years, a simulation length of 20 years, and 100 simulation runs.

5.2.2.1 Verification of the generation of data

5.2.2.2 Validation with observations from reality

5.2.2.3 Theoretical validation

Aside from validating the simulation model trough a comparison with observations of reality, a theoretical validation is another way to check whether the system performs well. A theoretical validation uses input data with a certain distribution of which the output data can be computed exactly.

Two examples of similar systems with a distribution for which the system output can be exactly computed are the M/M/1 and M/M/c queueing systems. Both queues have exponentially distributed (*M*) arrival rates and process times (turnaround times). The M/M/1 system has 1 process station, while M/M/c system has *c* process stations. Zijm (2003) presents the equations to compute their average waiting time and utilization exactly. The results of a comparison between the simulation model (ran for exponentially distributed data and 1 or *c* RTCs) and the exact calculations for the M/M/1 and M/M/c queues are presented in Table 5.1 and Table 5.2 and show good results.

Turnaround time (days)	*Interarrival time (days)*	*Average waiting time*			*Utilization*	
		M/M/1	*Simulation*	*Difference*	*M/M/1*	*Simulation*
4	10	2.6667	2.6600	0%	40.00%	40.05%
4	5	16.000	16.1004	1%	80.00%	80.18%
2	5	1.3333	1.3372	0%	40.00%	40.07%
2	2.5	8.0000	7.9643	0%	80.00%	80.01%
1	1.25	4.0000	3.9845	0%	80.00%	79.99%
1	1.111	9.0000	8.9632	0%	90.00%	89.96%
0.5	0.667	1.5000	1.4977	0%	75.00%	75.00%
0.5	0.526	9.5000	9.4730	0%	95.00%	94.99%

Table 5.1: Comparison between results of simulation model (1,000 runs) and M/M/1 queue

Turnar. time	*Interarr. time*	*Fleet size*	*Average waiting time*			*Utilization*	
			M/M/c	*Simulation*	*Difference*	*M/M/c*	*Simulation*
10	0.2	52	3.4981	3.4982	0%	96.15%	96.16%
10	0.2	55	0.7691	0.7687	0%	90.91%	90.92%
10	0.2	62	0.0565	0.0565	0%	80.65%	80.65%
10	0.2	67	0.0083	0.0083	0%	74.63%	74.63%
15	0.4	39	7.3664	7.2616	1%	96.15%	96.14%
15	0.4	42	1.2382	1.2329	0%	89.29%	89.29%
15	0.4	47	0.1462	0.1455	0%	79.79%	79.79%
15	0.4	50	0.0409	0.0405	1%	75.00%	75.00%

Table 5.2: Comparison between results of simulation model (10,000 runs) and M/M/c queue

5.2.2.4 Validation summary

From this section we conclude the simulation model is valid with perhaps slightly pessimistic scores on the performance indicator service level. The model is valid because of three reasons. First, the generated data is verified with the desired data and the averages and the distributions match well. Second, a theoretical validation proves the system works well and third, the simulation model performs well compared to observations from reality.

However only limited observations of reality are available and the first impression of the performance of the current fleets indicates that the service level resulting from the simulation could be slightly pessimistic. An explanation for this could be the operational flexibility that is not incorporated in the simulation model.

5.2.3 Results of the simulation model

5.3 Turnquist-Sherali model

This section concerns the Turnquist-Sherali model. Section 5.3.1 gives a description of the model and Section 5.3.2 discusses the validation and results of the model.

5.3.1 Description of the Turnquist-Sherali model

The Turnquist-Sherali model combines features of the models from Turnquist & Jordan (1986) and Sherali & Tuncbilek (1997) into a new analytical model. From Turnquist & Jordan the model uses their approach to deal with uncertain travel times and from Sherali & Tuncbilek the model uses their approach that recognizes demand as dynamic over time. Sherali & Tuncbilek's model is deterministic, but instead of basing the fleet size on the average demand during a year, they determine the period with the highest demand and base the fleet size on the average demand in this period. This approach results in a higher service level during times of high demand.

Aside from demand and turnaround time, the other input factors are included in the model as well. The performance indicator fill rate (a special kind of service level) is set to a certain level and thereby used as an input factor in this model. The model uses the desired fill rate to determine how much margin should be added to the turnaround time. Loading time is simply added to the turnaround time. With the factors discussed so far, the model calculates the fleet size needed to transport goods to customers. Added to this "intermediate" fleet size are the RTCs needed for safety and temporary storage and to the total fleet size at this point a percentage is added to cover the average number of RTCs that will be in maintenance or suffer from breakdowns.

Section 5.3.1.1 and Section 5.3.1.2 discuss the approaches to uncertain turnaround times and dynamic demand in more detail. These sections give model formulations of important parts of the model and Appendix F presents the full model formulation. We have used Microsoft Excel to develop the Turnquist-Sherali model.

5.3.1.1 Turnquist & Jordan's approach to uncertain turnaround times

Next to the average turnaround time, Turnquist & Jordan also incorporate a probability function in their model to compensate for vehicles that do not return in time. Their model uses the desired fill rate[1] and the standard deviation of the turnaround time to calculate the number

[1] The fill rate is a variant of the service level and concerns the percentage of orders that is delivered at the required time and no later. In case of ANBC the fill rate concerns the percentage of RTCs that were issued on their planned good issue date.

of vehicles that has to be added to bring the probability of running out of vehicles to an acceptable level (1 minus the required fill rate[1]). This results in Equation 5.1:

$$X_i = (1/R_i)\cdot\left[2\cdot\left(D_i\cdot\frac{1}{2}(T_i+L)-\Phi^{-1}(P_i)\cdot\frac{1}{\sqrt[4]{\pi}}\cdot D_i\cdot\sqrt{\frac{1}{2}}\sigma_i\right)\right] \qquad \text{Equation 5.1}$$

Where X_i is the number of RTCs needed to deliver customer i, R_i is the RTC volume (in Kton) of the RTCs used for customer i, D_i is the demand (in Kton/day) of customer i, T_i is the turnaround time for customer i, L is the loading time of an RTC, and $\Phi^{-1}(P)$ is the inverse of the cumulative distribution function of a standard normal[1] random variable for a probability or chance P_i of running out of RTCs for customer i. P_i is equal to 1 minus the required fill rate[1] for customer i. Finally σ_i is the standard deviation of the turnaround time for customer i. Turnquist & Jordan's actual model does not work with turnaround time, but with the travel time to the customer, the travel time back from the customer, and a non variable holding time at the customer. To use their model for ANBC's situation, where only the total turnaround time is known, the turnaround time and its standard deviation are split in two equal parts to represent the travel time to and from the customer.

5.3.1.2 Sherali & Tuncbilek's approach to dynamic demand

In Turnquist & Jordan's approach and the equation derived from it (Equation 5.1), demand is treated as deterministic, which is not the case for ANBC. However, with Sherali & Tuncbilek's approach it is still possible to use Equation 5.1, but not with an average daily demand averaged over the whole year. Their approach determines the period of the year with the highest average demand and uses this demand to determine the required fleet size. The highest average period demand substitutes the yearly average demand in Equation 5.1.

Sherali & Tuncbilek's approach needs two things to be determined: the time window of the periods that are taken into account and the horizon shift. The time window concerns the length of the period about which demand is averaged. For example a short period length will give a lot of weight to that one day with extremely high demand and a period length of one year will result in the demand averaged over the whole year. The horizon shift concerns the overlap between the periods. A horizon shift equal to the period length means there is no overlap and the year is divided in consecutive periods. A horizon shift of one day means the year is divided in many periods, each differing only one day from its preceding and succeeding periods. A shorter horizon shift gives a more accurate result, but costs more in terms of computational time.

Figure 5.3 gives an example of Sherali & Tuncbilek's approach to dynamic demand. The time window is 2 days to both sides, so a period takes up 5 days, and the horizon shift is 2 days.

[1] Turnquist & Jordan assume that turnaround times are normally distributed or at least close to a normal distribution, e.g., skewed to the right.

Day	1	2	3	4	5	6	7	8	9	*Total*
Demand	50	30	75	55	20	10	25	35	60	*360*

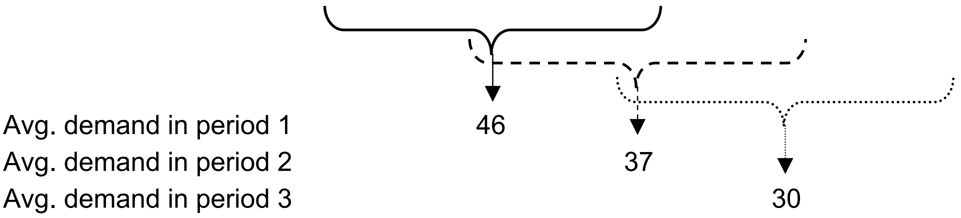

Figure 5.3: Example of Sherali & Tuncbilek's approach to dynamic demand

As Figure 5.3 shows, taking into account the whole 9 days would result in an average demand of 40 per day, while recognizing the time dynamics of demand and looking at shorter periods results in an average demand of 46 per day.

To determine the period length the model has to be calibrated towards a (valid) base situation. We use the current situation at ANBC and the results of a validated simulation model to do this. Section 5.3.2 discusses the calibration together with the results and validation of the model. Regarding the horizon shift a shift of one day is applied, as this gives the most accurate results and the computational time required for it is negligible these days.

In practice, detailed demand data, as in the example above, is often not available about future demand. But if previous years show equal demand patterns, this approach can still be used by applying historical relative demand patterns on future demand, according to Sherali & Tuncbilek.

5.3.1.3 Model summary

In summary the Turnquist-Sherali model combines a stochastic approach to turnaround times with a deterministic but dynamic approach to demand. Based on a desired fill rate and the input data the model calculates the required fleet size. Before this can be done, the model has to be calibrated to determine the period length of the periods of which the model considers the average demand.

5.3.2 Validation and results of the Turnquist-Sherali model

5.4 Queueing model

This section describes the third model applied at ANBC's fleet sizing problem. First, Section 5.4.1 gives a description of the queueing model and second, Section 5.4.2 discusses the validation and results of the model.

5.4.1 Description of the queueing model

The original application of queueing theory is in manufacturing systems, where (un)finished goods or production jobs move through production lines and queue for each process station. The waiting time in such a queue depends on several aspects: the capacity of the (parallel) process station(s), the arrival rate of jobs, the required process time of the jobs, and the variability in both the arrival rate of jobs and their required process time. In such a system, waiting time is the performance indicator on how much capacity is needed.

Queueing theory is applicable at ANBC's fleet sizing problem because of the analogy between the manufacturing system described above and ANBC's RTC transportation system. If RTCs are seen as process stations and demand as production jobs with a demand rate as the arrival rate and a turnaround time as the process time, both systems are very similar. In this case waiting time can be seen as the delay of an RTC delivery and the probability of a certain waiting time translates to a service level.

The idea to use this analogy and apply a queueing model to ANBC's fleet sizing problem comes from Koo et al. (2005). However the theory used in this section is based on other authors, namely: Hopp & Spearman (2000), Tijms (2003), and Whitt (1993).

We have developed the queueing model in Microsoft Excel.

5.4.1.1 Input factors

The queueing model we propose in this section takes into account all input factors concluded in Chapter 4 and works similar as the models in the two previous sections with an "intermediate" fleet size and a total fleet size. The "intermediate" fleet size concerns the RTCs needed to transport goods to customers and includes the factors customer demand, turnaround time, and loading time. The total fleet size adds the factors maintenance and breakdowns, safety storage, and temporary storage to the "intermediate" fleet size.

Unlike the Turnquist-Sherali model, the queueing model does not take into account individual customer data, but aggregated data. Because all customers use the same RTCs, the individual customer demand for RTCs interacts with the demand of other customers and the standard deviation of the total demand is the only way to take into account the variability of demand correctly. With demand on an aggregated level it is of no use to take into account turnaround time on a customer level, so turnaround times are taken into account on an aggregated level as well.

5.4.1.2 The queueing model

The queueing model described in this section is based on three literature sources, as mentioned above. The basic model is the VUT equation from Hopp & Spearman (2000) and this model is extended using theory from Whitt (1993) and Tijms (2003). This section explains the model and presents the different parts of the model formulation. Appendix G presents the full model formulation.

The VUT equation

Hopp & Spearman (2000) describe the VUT equation, which stands for Variability, Utilization, and Time, the three elements the equation can be separated in. The VUT equation is aimed at queueing systems with generally distributed interarrival times (of demand) and process times and approximates the average waiting time in such a system. Generally distributed data means that only the average and the standard deviation (the first and second moments) of the data have to be known.

Equation 5.2 shows the VUT equation for G/G/c queues. The notation G/G/c indicates a queue with generally distributed interarrival and process times and *c* parallel processing stations (RTCs in ANBC's case). The notation in Equation 5.2 and further equations is already adapted to ANBC's situation.

$$\bar{W} = \left(\frac{c_d^2 + c_t^2}{2}\right) \cdot \left(\frac{u^{\sqrt{2\cdot(X+1)}-1}}{X \cdot (1-u)}\right) \cdot (T + L)$$ *Equation 5.2*

Where $\bar{W}$ approximates the average waiting time[1] of a customer request (demand) before an RTC is available to transport it. c_d and c_t are the coefficients of variation of respectively demand and turnaround time. X represents the number of RTCs in the system (the c from G/G/c), T is the average turnaround time for the whole customer population, L is the loading time of an RTC, and u is the utilization which is calculated by Equation 5.3:

$$u = \frac{D \cdot (T + L)}{X}$$ *Equation 5.3*

Where D is the total demand rate of all customers.

Waiting time probability

With the VUT equation it is possible to approximate the average waiting time for a range of fleet sizes and pick the fleet size that results in the preferred average waiting time. However, the average waiting time is of limited use to ANBC, as it only concerns an average and says nothing about the distribution of the waiting time. To create a useful model for ANBC, the model is extended with the probability of a waiting time equal or less than a certain value (x): $P(W \leq x)$. This probability can be directly translated into a service level, i.e., the percentage of RTCs that are issued within x days of their planned good issue date.

Whitt (1993) argues that the waiting time probability can be approximated from the probability distribution function or cumulative distribution function (CDF) of the waiting time. Because it is not clear how the waiting time is distributed, we apply a gamma distribution. The gamma distribution can approximate the waiting time distributions in situations of low and high utilization. In situations of low utilization, we assume the waiting time to be approximately exponentially distributed and in situations of high utilization, we assume the waiting time to be approximately normally distributed.

The CDF for a gamma distribution is easily calculated in Microsoft's Excel and requires the average and standard deviation of waiting time as input. Whitt (1993) makes an approximation of the coefficient of variation of the waiting time, which can be used to calculate the standard deviation. Appendix G presents the full model formulation that includes Whitt's approximation of the coefficient of variation of the waiting time. The appendix also presents Whitt's approximations and calculations needed to calculate the coefficient of variation of the waiting time. The probability of delay for a queue with exponentially (M) distributed arrival and process times ($P(W(M/M/X) > 0)$) presented in Appendix G, is derived from Tijms (2003).

5.4.1.3 Model summary and model accuracy

This section describes the VUT queueing model to approximate the average waiting time resulting from a certain fleet size. In addition to the average waiting time, the waiting time

[1] Waiting time is defined as the actual time an RTC (i.e., a piece of demand) is issued from an ANBC plant minus its planned good issue time. This time difference is caused by unavailability of RTCs. Waiting time cannot be negative.

probability is introduced. This allows the approximation of the fraction of RTCs that has a waiting time equal or less than a certain value and can be directly translated into a service level. So this model can be used to approximate the service levels of a range of fleet sizes, which allows the user to determine the required fleet size by picking the smallest fleet size resulting in a service level equal or higher than the desired service level.

Concerning the accuracy of the model the authors make two important comments. Hopp & Spearman state that the VUT equation is valid for most cases except those with c_d and c_t much larger than one, or u larger than 0.95 or smaller than 0.1. Whitt states that concerning his approximations c_d and c_t (especially c_d) should not be too large and u should not be too small.

5.4.2 Validation and results of the queueing model

5.5 Summary and conclusions

This chapter answers the third and fourth research question:

3. *Which model should be used to determine the optimal fleet size?*
4. *How should this model be validated?*

This section gives a summary of this chapter and selects the final fleet sizing model to apply at ANBC's fleet sizing problem.

In Section 5.1 the chapter starts with a pre-selection of three fleet sizing models from the literature. The selection criteria concern the variability in two important input factors: demand and turnaround time, the fact that only fleet size should be considered, the limited information that is available, and ANBC's preference that the model should be kept as easy as possible.

The pre-selection results in a simulation model and two analytical models: the Turnquist Sherali model and a queueing model. One of the reasons of the selection of the simulation model is that it can be used to validate the two analytical models.

Section 5.2 discusses the simulation model, its validation, and its results. A simulation model does not lead to an analytical solution, but simulates the actual RTC transportation system of ANBC. The simulation model results in the approximation of the service levels that result from a range of fleet sizes. If a required fleet size is set, from the simulation results its is easy to determine the minimum fleet size that results in an equal or higher service level than required.

The validation of the simulation model involves three methods of validation and all three methods prove the validity of the model. First, a verification of the generated data shows that the distributions of the data generated by the simulation model match the desired distributions. Second, a theoretical validation proves that the model itself works correctly and third, a comparison with (a limited number of) observations from reality indicates that the simulation model performs well.

The only drawback of the simulation model is the fact that the validation towards observation from reality is based on a limited number of observations and that the first impression of the performance of the current fleet indicates that the service level resulting from the simulation could be slightly pessimistic. An explanation for this could be the operational flexibility that is not incorporated in the simulation model. Nonetheless the results of the simulation model gives a clear insight in the relation between fleet size and service level, an insight very useful in fleet size decisions.

Section 5.3 discusses the Turnquist-Sherali model, its validation, and its results. The Turnquist-Sherali model combines theory from two papers: the stochastic approach to turnaround time of one paper and the deterministic, but dynamic approach to demand of the other. The model is named after the leading authors of the two papers. Before the model can be used, it needs to be calibrated. Simulation results are used to perform the calibration.

The validation of the Turnquist-Sherali model concerns two methods of validation. A theoretical validation proves that the model works correctly. However, the practical validation already fails in the calibration phase. It turns out that, based on the simulation results, the model can not be calibrated.

Section 5.4 concerns the queueing model. The queueing model takes into account the variability in demand and turnaround time. The model calculates the average waiting time or delay of a delivery as well as the probability of a waiting time equal or less than a certain threshold. This probability is in fact the same as a service level and so this model allows the user to determine the required fleet size by picking the smallest fleet size resulting in a service level equal or higher than the required service level.

Although the theoretical validation of the queueing model proves that the model works correctly, the comparison of its results with the results of the simulation model show a significant deviation.

Table 5.3 presents a brief overview of the model developed in this chapter. The overview contains the key characteristics of the models and the results of their validation.

Model	*Kind of model*	*Demand*	*Turnaround time*	*Customer data*	*Validation result*
Simulation model	Simulation	Stochastic	Stochastic	Individual	Valid
Turnquist-Sherali	Analytical	Deterministic, dynamic	Stochastic	Individual	Invalid
Queueing model	Analytical	Stochastic	Stochastic	Aggregated	Invalid

Table 5.3: Key characteristics and validation results of models developed in this chapter

From the validations of the three models developed in this chapter, we conclude that only the simulation model is valid. At least for ANBC's fleet sizing problem, it turns out that a fleet sizing model needs to consider stochastic demand, stochastic turnaround times, and customer data on the level of the individual customer. Because the simulation model is the only valid model, we select the simulation model as the final model to be applied at ANBC's fleet sizing problem. Chapter 6 uses the simulation model to conduct scenario analyses and Chapter 7 answers the question how the simulation model could be implemented at ANBC.

6 Scenario analyses

This chapter describes the scenario analyses conducted with the simulation model as proposed in Chapter 5. The scenario analyses consider several scenario for operational improvements and are performed because ANBC wants to know in which areas measures to save on fleet size rental costs are most effective. In the end, this chapter answers Research question 5:

> 5. *Which of the scenarios for operational improvements have the largest saving potential?*

To answer this question, Section 6.1 defines the scenarios for operational improvements that are analyzed and Section 6.2 presents the results of the scenario analyses. Finally, Section 6.3 gives a summary of this chapter.

6.1 Scenarios for operational improvements

6.2 Scenario results

6.2.1 Scenario results for the individual scenarios

6.2.2 Results of cumulative scenarios

6.2.3 Results for individual customers

6.3 Summary

This chapter answers Research question 5: *Which of the scenarios for operational improvements have the largest saving potential?*

Section 6.1 defines the scenarios about reduction of demand variability, reduction of turnaround time, and reduction of turnaround time variability to be the scenarios to analyze.

In the scenario analyses performed in Section 6.2 the scenarios about reduction of demand variability and reduction of turnaround times turn out to be the scenarios with the largest savings potential. Only a 25% reduction of the factors concerned results in yearly savings of 16% for Chlorine and 8% for Caustic.

The next chapter, Chapter 7, proposes actions to bring in effect the scenarios about reduction of demand variability and reduction of turnaround times. Chapter 7 also discusses the implementation of the simulation model.

7 Implementation

Chapter 5 and Chapter 6 result in two issues that have to be implemented at ANBC:

1. The simulation model, proposed in Chapter 5
2. The scenarios with the largest savings potential, determined in Chapter 6

The next two sections discuss these issues and thereby answer the last research question:

> *6. How could the fleet sizing model (as part of a tool) and the operational improvements with the largest savings potential be implemented at ANBC?*

7.1 Implementation of the RTC Simulation Tool

7.1.1 How to use the tool

7.1.2 Who should use the tool

7.1.3 When to use the tool

7.1.4 Recommendations to improve the effect of the tool

7.2 Implementation of operational improvements

7.2.1 Actions to reduce the variability in demand

7.2.2 Actions to reduce turnaround times

7.3 Summary

8 Conclusions and recommendations

This chapter presents the conclusions and recommendations of this research project in respectively Section 8.1 and Section 8.2. Furthermore Section 8.3 contains a discussion and gives suggestions for further research.

8.1 Conclusions

The research objective of this study is to:

Develop a tool that minimizes the RTC fleet size and:

1. ***meets market demand***
2. ***complies with safety requirements***
3. ***secures continuous production***

and

Use the tool to perform scenario analyses to determine the operational improvements that result in the largest savings.

To reach the objective, we develop three fleet sizing models and apply these models at ANBC's RTC transportation system. These models concern a simulation model, a model that combines a stochastic approach of turnaround times with a deterministic, but dynamic approach to demand (named the *Turnquist-Sherali model*), and a queueing model. Based on the validation of the models, we conclude only the simulation model to be valid. An explanation for this is that the simulation model is the only model that considers demand and turnaround times as stochastic and considers data on the level of the individual customer. Table 8.1 presents the key characteristics of each model:

Model	Kind of model	Demand	Turnaround time	Customer data	Validation result
Simulation model	Simulation	Stochastic	Stochastic	Individual	Valid
Turnquist-Sherali	Analytical	Deterministic, dynamic	Stochastic	Individual	Invalid
Queueing model	Analytical	Stochastic	Stochastic	Aggregated	Invalid

Table 8.1: Key characteristics and validation results of models developed in this research project

The simulation model is incorporated in the *RTC Simulation Tool*. This software tool determines the service levels achieved by a range of fleet sizes. The tool allows ANBC to minimize its fleet size by choosing the minimum fleet size that results in an equal or higher service level than the minimum service level ANBC wants to achieve. The minimum service level assures that market demand is met.

The RTC Simulation Tool takes into account the interarrival time and variability of demand, the length and variability of turnaround time, and the loading time of an RTC. Furthermore the tool adds the RTCs required for storage and the RTCs required to cover for breakdowns and maintenance. These latter factors take care the final result complies with safety requirements and secures continuous production.

The results of the scenario analyses show that the largest savings can be gained by reduction of variability in demand and reduction of excess turnaround time. A 25% reduction of these factors results in yearly savings of 16% of the total rental costs for the Chlorine RTC fleet and 8% for the Caustic RTC fleet. Recommendations on how to gain these savings can be found in Section 8.2.

One critical remark has to be made about the simulation model. For one of the three ways in which the simulation model is validated, the validation toward observations from reality, the most recent observations indicate a small deviation between reality and the results of the simulation model. Although limited observation from 2006 prove the model to be valid, observations of the service level achieved with the new fleet size (the RTC fleets have been resized in Q2 2007) indicate the service level resulting from the simulation could be slightly pessimistic. An explanation for this could be the operational flexibility that is not incorporated in the simulation model. Nonetheless the results of the simulation model gives a clear insight in the relation between fleet size and service level, an insight very useful in fleet size decisions.

8.2 Recommendations

We recommend ANBC to take the following actions:

Regarding the implementation of the RTC Simulation Tool:

1. Use the RTC Simulation Tool every time a significant change in the input factors occurs or when fleet size decisions have to be made.

2. Define the desired service level.

3. Start to measure the performance indicators service level and utilization. This allows a better validation of the simulation model against real data, as well as fine-tuning of the model. It could also solve the possible issue of slightly pessimistic service levels mentioned in the last paragraph of the previous section.

Regarding the reduction of the fleet size (based on the scenario analyses):

4. To reduce the variability of demand, educate the customer to order at more regular intervals or take over the responsibility of the daily delivery planning.

5. To reduce turnaround times, start to use Railion's tracking and tracing service to investigate who is responsible for excess turnaround time. When the responsible parties are identified, targeted follow-up actions can be taken to reduce turnaround times.

8.3 Discussion and suggestions for further research

This section discusses several issues of this research project that could be improved and based on these issues the section gives suggestions for further research. The issues are:

- Data distribution
- Variability in the input factors other than customer demand and turnaround time
- Operational flexibility and data about performance indicators

The choice for the gamma distribution might not be the optimal choice. Although visual tests prove the gamma distribution as an acceptable distribution and the majority of the distributions of customer demand and turnaround time fit the gamma distribution. Also quite some distributions do not pass the goodness of fit test. Further research should involve more in-depth tests of the actual distributions against other theoretical distributions such as the Weibull distribution and the log-normal distribution.

Also the test method is subject to further research. A preferred test method takes into account how far a deviation of the observed and expected probabilities is located from the average. Besides another test method a chi-square test with fewer degrees of freedom could already be an improvement. This means that the observations has to be grouped in classes of variable length that contain approximately equal numbers of observations. Apart from the preceding issues, the tests of observed distributions against theoretical distributions could also be improved by using a larger base of observations. For some customers the current tests are done on quite a small number of observations.

The second issue is the variability in the input factors that are, because of a lack of data, currently considered as deterministic. A suggestion for further research is to collect more data about these factors and investigate if they are really deterministic. Most likely, factors such as maintenance and breakdowns involve some uncertainty and are stochastic.

The last issue involves the operational flexibility in the system and the lack of data about the performance indicators. The indication that the simulation model is slightly pessimistic in its scores on service levels could basically have two reasons: 1) The fact that the simulation model has no build-in procedures to simulate measures of operational control, in this way operational flexibility could be build into the model. 2) The indication that the service levels are slightly pessimistic comes from a first impressions of the practice. The indication is not based on real data and is neither based on a whole year yet. Collection of at least one year of data about the performance indicators and the subsequent decision whether to build measures of operational control into the model are suggestions for further research.

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Glossary

Caustic: Caustic Soda Liquid or Caustic Lye.

Coefficient of Variation (CV): The standard deviation divided by the average.

Demand rate: The quantity a customer orders per unit of time. In this report the demand rate is expressed as the number of RTC ordered per day or the volume ordered per day.

Deterministic: A factor is deterministic if all information is assumed to be known in advance. For example, the factor turnaround times is deterministic if all turnaround times are exactly known at the beginning of the planning horizon.

Fill rate: The probability that an RTC can be issued at its *planned good issue date*. Actually this is a special case of *service level* where the *service level threshold* is set at 0 days.

Holding time: The time a customer holds an RTC on his site. Holding time includes the time needed to receive, unload, and dispatch an RTC. The sum of these factors subtracted from the total holding time results in the unnecessary holding time.

Interarrival time: The time between the issue dates of two customer orders (the time between the *planned good issue dates* of the RTCs). The interarrival time of demand is the inverse of the demand rate (in RTCs per day).

LIFO principle: LIFO stands for Last In First Out, the customer (or RTC) that arrived last is serviced (or unloaded and returned) first.

Planned Good Issue date: The date an RTC (carrying a customer order) is planned to be dispatched from one of ANBC's plants.

Rail Tank Car (RTC): Rail car for transport of liquid material in bulk.

Service level: The probability that an RTC can be issued within *X* days of its *planned good issue date*. Where *X* is the *service level threshold*.

Service level threshold: A parameter of the *service level* that defines how much time later than the *planned good issue date* an RTC can be dispatched before it effects the *service level*.

Steady state: The normal state of a system. This is an important issue in simulation models. At the start of a simulation the system is empty and the system will not behave normal (for example in ANBC's case no RTCs are in use at the beginning of a simulation and therefore utilization will be low and the service level 100%). A system has reached a steady state when its behavior is no longer influenced by the empty state from the beginning.

Stochastic: A factor is stochastic if not all information is known in advance. Therefore in a stochastic factor variability has to be included. For example, the factor turnaround times is stochastic if not all turnaround times are known at the beginning of the planning horizon. In such a case an average and a standard deviation from historical turnaround times could be used to estimate the future turnaround times.

Transit time: The travel time of an RTC between an ANBC plant and a customer or between a customer and an ANBC plant.

Turnaround time: The time span between the moment an RTC leaves ANBC's plant and the moment that the RTC returns, after delivering the customer. The turnaround time consists of the *transit time* to and back from a customer plus the holding time of the RTC at the customer. In this report turnaround time is usually measured in days.

Utilization: The average percentage of the system capacity that has been used during a certain period. The average number of RTCs that has been used divided by the total fleet size.

Waiting time: Waiting time is defined as the actual time an RTC is issued from an ANBC plant minus its *planned good issue time*. This time difference is caused by unavailability of RTCs. Waiting time cannot be negative.