The potential of unmanned cargo aircraft for a logistics service provider

A simulation study

Bachelor Thesis Industrial Engineering and Management

Pim Eerden

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Preface

This report shows the result of the bachelor thesis “The potential of unmanned cargo aircraft for a logistics service provider” that I have conducted for the bachelor Industrial Engineering & Management at the University of Twente.

The completion of this thesis could not be achieved without the support of several people. First of all, I would like to thank my first supervisor, Martijn Mes, for always providing me with useful feedback in the countless meetings we had. Secondly I would like to thank my second supervisor, Eduardo Lalla for providing me with a lot of useful feedback in the final stage of finishing this thesis.

I would also like to thank Ipek. She was always able to talk about my progress and give me helpful advice on how to get further with the thesis. This can also be said about all of my friends and family. In particular, I would like to thank Matthijs, Florian and Casper for the many conversations and study sessions that definitely helped me in finishing this bachelor thesis.

Pim Eerden, 2020

Management Summary

Introduction
The logistics service provider considered in this study, provides a feeder transport system in the Netherlands from seven regional locations towards a warehouse at Schiphol Airport. This transport is currently done by trucks; however, they see great potential in the use of unmanned cargo aircraft (UCA). The core problem is defined as follows: *The company has no insight in the potential of unmanned cargo aircraft for their business in comparison to their current feeder system.* With this study, they want to gain insight in the potential of unmanned cargo aircraft in comparison to their current feeder system. Therefore, this research is a simulation study about the potential of unmanned cargo aircraft for the company.

Approach
The approach in giving the company an answer, consists of 5 phases.

1: Collecting information about the current activities of the company
2: Literature research about the performance of trucks and unmanned cargo aircraft
3: The design of a simulation model
4: Experiments with the simulation model
5: Analysis of the experimental results and conclusions based on this analysis

Current activities of the company
The company uses a hub and spoke system in the Netherlands with 7 regional warehouses, from which everyday trucks with a capacity of 25 tonnes drive towards Schiphol.

Findings in the literature research
Literature research provided an introduction to UCA and its potential. It also provided the input parameters used in the simulation model, which are the CO_2 emissions, operating costs, speeds and capacities of unmanned cargo aircraft and trucks. Also, the effect of different parts of an unmanned cargo aircraft and the design of it are researched.

The simulation model
The simulation model is designed in such a way, that it could simulate the current activities of the company with trucks, as well as with the use of UCA. Per experiment, five replications are run in which the simulation is run for 100 days.

Experiments with the simulation model
To run experiments with the simulation model to study the performance of trucks and UCA, various settings in the simulation model are varied: the capacity of UCA, the number of UCA and trucks, the average time between orders, the minimal utilisation, the maximal permissible waiting time of the freight and the decision whether to use only unmanned cargo aircraft or not. Also the decision whether to use a home base scenario or not is taken into account. In the home base scenario, each location is assigned its own vehicle that only travels between this location and Schiphol and is never used to pick up freight at other locations. The number of UCA and trucks that would be roughly needed is calculated and experiments are done by varying around these numbers.

Results and conclusion
The results of the run experiments show that trucks perform much better than UCA in terms of CO_2 emissions and total operating costs. One reason for this is that the CO_2 emission factors and the operating costs in dollars per hour are much higher for UCA than for trucks. All vehicles perform better in terms of CO_2 emissions when a higher utilization is used, due to a decreased number of

trips. An increase in interarrival time between the freight decreases the operating costs when a scenario without home bases is simulated. An increase in utilization level also leads to a decrease in operating costs due to an increase in waiting time. However, when looking at the total waiting times of the freight, it seems not to matter which system is used when orders arrive not too often.

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Readers guide

In this readers guide, an overview of the chapters of this bachelor thesis can be found.

Chapter 1 Introduction

This chapter provides an introduction to the company, the research motivation, the problem statement of the company and a problem solving approach. It also describes the research questions.

Chapter 2 Context analysis

This chapter covers information about the current logistic system of the company.

Chapter 3 Literature study

This chapter gives an introduction to UCA and its potential. It gives answers to all research questions, based on the literature about unmanned cargo aircraft. The answers to these questions are useful for the design and implementation of the simulation model.

Chapter 4 Design of a solution

This chapter covers the conceptual model of the simulation model.

Chapter 5 Experiments, results and analysis

This chapter explains the design and settings of the simulation model. The results of the experiments are shown and analysed in this chapter.

Chapter 6 Conclusions and recommendations

This chapter draws the conclusions based on the experimental results. Also, recommendations for further research are given.

Definitions and abbreviations

UCA	Unmanned Cargo Aircraft.
PUCA	The Platform for Unmanned Cargo Aircraft
IATA	International Air Transport Association.
ICAO	International Civil Aviation Organization.

1 Introduction

This chapter describes the introduction to this bachelor assignment. It introduces the company as well as the research motivation to conduct this research. The problem statement is elaborated, together with the problem solving approach. Also, a clarification of the differences between unmanned cargo aircraft, unmanned aerial vehicles and drones is given.

1.1 Introduction to the company

The logistics service provider of this study provides logistics services at 660 locations in more than 40 countries and has an annual turnover of 5.1 billion euros. This company employs 31,000 people and works in three areas of logistics: contract logistics, freight logistics and port logistics. This thesis is focused on freight logistics. The company provides solutions for the following industries: events, fashion, fresh products, offshore and pharma. They also provide logistic services in terms of general cargo and e-cargo. They are specialized in the export and import of general goods as well as goods that require special attention during transport. At their location at Amsterdam Airport Schiphol, airfreight is transported to many locations in Europe. This location also consolidates airfreight shipments delivered from seven regional offices in the Netherlands. The ocean freight forwarding activities of the company are based in the port of Rotterdam.

1.2 Research motivation

In the Netherlands, the company provides a so-called feeder transport system from seven regional locations in the Netherlands to their warehouse at Schiphol Airport. This transport is done by means of trailers. Often, these trailers are stuck in traffic jams and are not always fully loaded. This way of transport is not efficient and not sustainable. The project and product manager of the company sees great potential in the use of unmanned cargo aircraft. However, he is not sure about the advantages of the use of unmanned cargo aircraft in comparison to their current feeder transport system, in terms of CO_2 emissions, costs and travel durations. This research is a simulation study for the company, about the potential of unmanned cargo aircraft.

1.3 Problem statement

In the problem cluster in Figure 1 below, the coherence between the problems of the company can be seen. It can be seen that there are several causes for the current feeder system not being efficient. First, trucks are often stuck in traffic jams. This leads to the fact that it takes long for cargo to be delivered, which in turn leads to an inefficient way of transporting. The fact that the trailers of the company are not always fully loaded for some orders, leads to an inefficient transport system as well. This also holds for the loading and unloading of the freight, which sometimes takes too long.

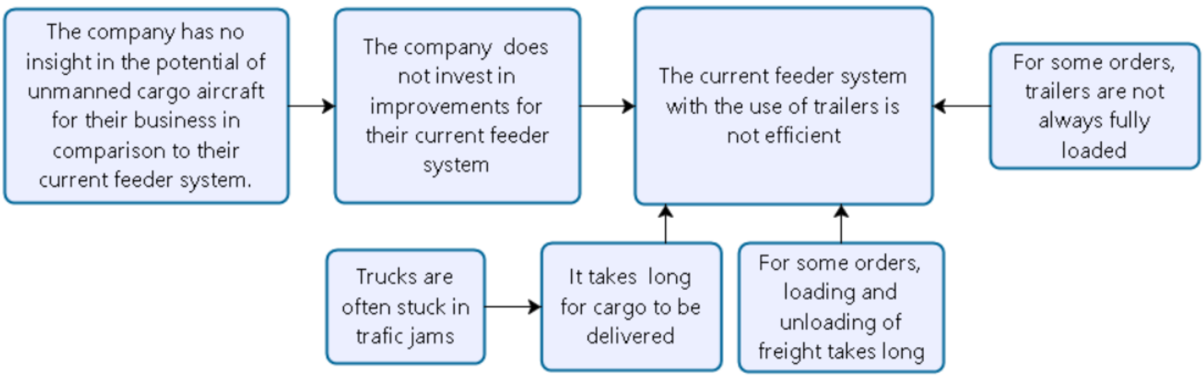

Figure 1. Problem cluster

All of the causes of the current feeder system not being efficient can be traced back to one major cause. This cause is placed at the end of the problem cluster, and is denoted by the core problem. This core problem can be defined as follows:

The company has no insight in the potential of unmanned cargo aircraft for their business in comparison to their current feeder system.

Since the company has no insight in the potential of unmanned cargo aircraft, they do not know, whether it could be more beneficial to use unmanned cargo aircraft compared to using their current feeder system. For that reason, they do not invest in improvements for the current feeder system, which is another cause of the inefficiency of the current feeder system. The above mentioned core problem, is definitely the most important problem in the problem cluster. The company has initially not asked me to tackle the other causes of the inefficient transport system, but requested a study about the potential of unmanned cargo aircraft for their company.

1.4 Problem solving approach

This section consists of the steps that need to be carried out to give the company an insight in the potential of unmanned cargo aircraft in comparison to their current feeder system. This approach consists of several phases. Each phase is described by a research question and is explained below.

Phase 1: What are the current activities of the company?
In this phase, information is gathered by doing interviews with the project and product manager about how the activities of the company are arranged in the Netherlands. This phase shows how the companies logistic system works and is addressed in Chapter 2. This information is important because it can be used in the eventual comparison between a system with unmanned cargo aircraft and trucks.

Phase 2: What is known in literature about the performance of trucks and unmanned cargo aircraft?
In this phase, literature research is done about the current and estimated future performance of both trucks and unmanned cargo aircraft in terms of CO_2 emissions, operating costs and travel durations. The research questions that will be answered in this section are denoted below. To get a better understanding of these performances is useful for the eventual comparison between a system with unmanned cargo aircraft and trucks.

1. What is the potential of unmanned cargo aircraft?
2. What is the CO_2 emission of unmanned cargo aircraft?
3. What is the CO_2 emission of trucks ?
4. What are the operating costs of unmanned cargo aircraft?
5. What are the operating costs of trucks?
6. What are the cruising speeds for future unmanned cargo aircraft?

This phase is addressed in Chapter 3.

Phase 3: How will the simulation model be designed?
In this phase, a simulation model will be designed in the simulation software Plant Simulation, that is able to simulate the current activities of the company with the use of trucks as well as a new scenario with unmanned cargo aircraft. Doing a simulation study is useful, since no real experiments can be done with unmanned cargo aircraft yet, and if this was possible, it would be too costly and time consuming. This also hold for experimenting with real trucks: experimenting in a simulation model saves time and costs. Furthermore, experimenting with a real system would be too difficult, since

arrival rates of customers could not be easily controlled. In a simulation model, this is possible. Also, in a simulation model, experiments can be repeated many times under the same conditions, whereas this would be very hard to do in a real system. The conceptual model of the simulation can be seen in Chapter 4, whereas the explanation of all the components of the simulation model is given in Appendix 1.

Phase 4: Which experiments could be run in the simulation model?
In the fourth phase, experiments will be designed, which will be run with the simulation model to see the effects of several combinations of variables on the performance in terms of CO_2 emissions, operating costs and travel durations when transporting freight with either trucks or unmanned cargo aircraft. Elaboration on the design and settings of these experiments can be seen in Chapter 5.

Phase 5: What are the results of the experiments and what can be concluded out of these results?
In this phase, the results of the experiments will be analysed and conclusions will be drawn about how unmanned cargo aircraft and trucks perform in terms of CO_2 emissions, operating costs and travel durations. This phase is also addressed in Chapter 5 as well as in Chapter 6.

1.5 Unmanned cargo aircraft, unmanned aerial vehicle or drone?

This research is specifically about unmanned cargo aircraft. Sometimes, confusion arises between several definitions like unmanned cargo aircraft, unmanned aerial vehicles or drones. UAV stands for unmanned aerial vehicle and UCA stands for unmanned cargo aircraft. Drones and UCA are a type of UAV. Drones are much smaller than UCA and UCA can be seen as the unmanned counterpart of manned cargo aircraft, which means that they look more like an actual airplane, than drones do. In the rest of this research, the abbreviation UCA is used. In Figure 2, an example of an unmanned cargo aircraft can be seen. In Figure 3, a drone can be seen.

Figure 2. An unmanned cargo aircraft

Figure 3. A drone

2 Context analysis

This chapter describes the current activities of the company in the Netherlands in detail. It gives an insight in how the different offices work together.

2.1 Current system analysis

This subsection describes the current activities of the company.

The company uses a hub and spoke system in the Netherlands. Their warehouse located at Schiphol Airport can be seen as the so-called master-hub. Furthermore, there are seven other locations in the Netherlands, located all across the country in the following places: Aalsmeer, Rotterdam, Vaassen, Drachten, Tilburg, Eindhoven and Maastricht. These locations can be seen as hubs as well. In each of the regions corresponding to the regional offices, freight gets picked-up at local customers and is brought back to the regional office, after which it is transported to Schiphol. This happens every workday at every location. The local customers can be seen as the spokes in the hub-and-spoke network. The original pick-up times at the local customers are known to the company. It is important to mention that the company does not take care of the transport of this freight themselves, but instead outsource it to another transporting company.

At Schiphol, the airfreight shipments are consolidated and handed over to a handling agency. An important part of this consolidation is the labelling of the freight. The handling agency makes sure that freight gets onboard the aircraft. This system of transporting freight from local customers to regional offices to a master-hub is not everywhere the same in Europe. However, in the end, all freight is handed over to a handling agent at an airport, regardless of the route it travelled towards the airport.

2.2 Transport volumes

This section gives information about the volumes transported by the company.

Every day, at least one truck drives from each regional office to the warehouse at Schiphol and back. The volumes that are transported between these locations vary every day and are not fixed. Trailers are not per definition fully loaded. However, the trailers that are used can contain a fixed amount of two types of pallets. These types are the so-called block pallets and euro pallets. There are several differences between these types of pallets, which can be found in Table 1 below.

Table 1. Characteristics of block pallets and euro pallets

	Block pallet	Euro pallet
Length x width (cm)	120 x 100	120 x 80
Max Height (m)	2.8	2.2
Max weight (kg)	2000	1500

The trucks used are 13.6 meters long and can carry a maximum of 25 tonnes, which is equal to a maximum of 26 block pallets or 33 euro pallets.

In conclusion, the company uses a hub and spoke system in the Netherlands. Between the seven regional locations and Schiphol, varying volumes are transported on a daily basis.

3 Literature study

This chapter gives an introduction to UCA and its potential. It also gives answers to the several research questions mentioned in phase 2 in Section 1.4, which are useful for the design and implementation of the simulation model.

3.1 The potential of unmanned cargo aircraft

This section gives an introduction into the usefulness of UCA. The effect of a blended wing body is discussed in more detail and UCA are compared to traditional modes of transport. Also, information about the potential market of UCA and the potential of UCA according to shippers is given. This section also describes which types of UCA could be distinguished and which existing aircraft could be used as a reference.

3.1.1 The usefulness of unmanned cargo aircraft

The American Federal Aviation Administration predicts that in forty years, 40% of air cargo will be transported by UCA. According to the platform for unmanned cargo aircraft (PUCA) , UCA can be more productive and cheaper to operate in comparison to manned cargo aircraft. They state that taking into account the duty lengths of on-board crew does not have to be done anymore when flying with UCA. Therefore, UCA can fly with low cruising speeds to consume little amounts of fuel. According to Koopman (2017), the UCA with the best potential for the near future are expected to have a range of 1000 to 10000 kilometres and will fly with a cruising speed of approximately 450 kilometres per hour. Prent mentioned in 2013, that UCA can already be efficient from ranges of 300 kilometres. According to PUCA, the decreased fuel consumption of UCA leads to bigger ranges than comparable manned aircraft. Also, lower speeds require shorter runways. Another advantage of UCA is the fact that one person on the ground could possibly control between 10 and 30 UCA at the same time according to PUCA, which would result in big savings in personnel costs when comparing UCA to trucks or manned aircraft. PUCA mentions that UCA do not require pressurized cabins, since no personnel will be inside the aircraft. This means that the cross-section of the fuselage of UCA does not need to be circular, which means it can be shaped more efficiently to make sure that certain types of freight could fit in the aircraft. One example of this would be the blended wing body.

3.1.2 The effect of a blended wing body compared to a ‘normal’ designed aircraft

Liebeck (2004) states that cabin pressure loads are most efficiently taken in hoop tension. He also mentions that the concept of a blended wing body arose when this constraint got abandoned in a small study about transporting 800 people over a distance of 7000 miles. A blended wing body can be seen as an aircraft in which no clear distinction can be seen between the wing and the body of the aircraft since these are blended together. The blended wing body implied an improvement in aerodynamical efficiency. Liebeck stated that testing results with a blended wing body showed an improvement of 15 percent reduction in take-off weight and a 27 percent reduction in burned fuel per seat mile. PUCA states that a blended wing body would be 15 to 20 percent more aerodynamically efficient than a usual aircraft shape.

3.1.3 Unmanned cargo aircraft versus traditional modes of transport

According to Prent (2013), the limit for which goods can be better transported by trucks instead of by aircraft is around 570 kilometres in developed countries. When UCA would be operating as flexible as trucks, only small amounts of new infrastructure are needed, according to Lugtig and Prent (2012). They also mention that UCA could deliver freight much faster, since UCA can fly faster than trucks can drive. Furthermore, trucks are sensitive to external circumstances such as traffic jams, whereas UCA are not. When comparing UCA to trains, trains have a huge capacity and can carry big and heavy amounts of freight. Another advantage of trains, is that they can transport a big amount of freight with low operating costs. UCA could be beneficial in comparison to trains, because they do not require the big amount of infrastructure that trains do. Also, trains cannot deliver directly at companies, since rail networks are often not built close to them, whereas UCA can. Also, capacity of the rail network could be a problem, whereas capacity of the sky would be much bigger, since no obstacles block the way for UCA in the sky. The problems that trains have, also hold for existing manned cargo aircraft. They do require another mode of transport to get freight to companies, since existing aircraft cannot deliver directly to companies.

UCA can also be compared to transport by water. Inland vessels often have big capacities, low costs and a high reliability and are often used for the transport of heavy goods (Inland shipping information agency, 2011). However, according to Lugtig and Prent (2012), the delivery of goods with inland vessels can never be fast due to the big masses transported and the limited spaces on rivers, whereas UCA can deliver much faster. When comparing UCA to big shipping containers that are used on big container ships, container ships can carry huge amounts of freight for low costs per tonne-kilometre. However, freight takes very long to be delivered on these ships, which excludes the transport of perishable goods. Just as with inland vessels, container ships are very reliable.

3.1.4 The potential market for unmanned cargo aircraft

In a research of Prent in 2013 about the potential market for UCA, several things became clear. Markets for UCA are advantageous when they are new markets, in which there is no space for traditional freight transport. These markets should be markets in which goods are offered in small quantities in volumes small and light enough to be carried by UCA. In less developed countries, the limit for which goods can be better transported by trucks is lower than in developed countries, which means that UCA have more potential to be successful in less developed countries. Also UCA should have more advantage as traditional infrastructure for other transport modes becomes worse, since UCA can fly over it. In the research of Prent (2013), as well as in the research from Hoeben (2014), it becomes clear that the market in which UCA should be operating, should be a market in which valuable and time-bound goods are transported.

3.1.5. The potential of unmanned cargo aircraft according to shippers

The project and product manager of the company sees potential in UCA, but other shippers do so too, according to the research of Koopman (2017), 76.6 percent of shippers have stated that they have one or more transportable goods that could be transported by UCA. 64 percent of shippers think UCA have good potential and have loads that they would like to have transported with UCA. When looking at who should take the lead in the development of UCA, logistic service providers are set on the first place in Koopmans research with 28%. Aircraft manufacturers come second with 24%.

3.1.6 Types of unmanned cargo aircraft

According to Koopman, unmanned cargo aircraft with the best potential for the near future will have a freight capacity between 2 and 20 tonnes. Therefore, 3 types of unmanned cargo aircraft will be distinguished in this research: light, medium and heavy aircraft, as can be seen in Table 2 below. Each type of aircraft has its own range of freight capacity.

Table 2. Freight capacities of unmanned cargo aircraft

Type of unmanned cargo aircraft	Freight capacity in tonnes
Light	2 – 7
Medium	7 – 14
Heavy	14 - 20

3.1.7 Reference types of existing cargo aircraft

For each type of aircraft in Table 2, existing cargo aircraft will be used as a reference. The names of these aircraft and their payloads in kilograms are listed in Table 3 below. Reference aircraft will be useful later in calculating the CO_2 emissions and operating costs of future UCA, since for UCA, not every cost factor can already be determined and CO_2 emissions are unknown yet.

Table 3. Reference aircraft and their payloads

Type of aircraft	Payload (kg)
Light	
Casa C-212-300	2770
Cessna 208B Grand Caravan	1484
Fairchild Swearingen Metroliner	2614
Short 330-200	3707
Medium	
Alenia C027J Spartan	11500
ATR 72-600	7500
BAE ATP Cargo	8200
Heavy	
Boeing 737-700C	18200
Antonov AN 178	18000
Lockheed L-188A	15311

3.2 CO_2

This section describes which types of aircraft engines could be relevant for the use of UCA. It also elaborates on how emissions are related to the size of an aircraft and the type of engine used. Furthermore, the emissions of UCA and trucks are given in this section.

3.2.1 Types of aircraft engines and their relevance

According to a guide about engines from the National Aeronautics and Space Administration (NASA), 4 major types of engines can be distinguished. Their relevance for the further development of unmanned cargo aircraft will be discussed.

1. Internal combustion engine
   This type of engine was used for 40 years after the first ever flight with an aircraft. How this engines works is irrelevant for the further development of unmanned cargo aircraft.
2. Turbine engine
   In this type of engine, air is compressed after it is sucked in the engine. Fuel is added and burned, which results in hot gases leaving the back of the engine with high speed. As a result of that, the aircraft moves forward.
   Several types of turbine engines can be distinguished
    a. Turbojet engine
       This type of engine is also called jet engine. All of the thrust that this engine delivers is generated in the turbine and the core of the engine.
    b. Turbofan engine
       This type of turbine engine is more fuel efficient, since it generates more thrust per pound of fuel burned in comparison to a turbojet engine. According to NASA, this type of engine is used most on commercial passenger aircraft.
    c. Turboprop engine
       This type of engine makes use of the energy of the exhaust gas stream. According to

NASA, this engine can be found often on helicopters or slower cargo aircraft. This means that this type of engine is very relevant for unmanned cargo aircraft. Turboprop engines can often be found at low altitudes. This type of engine runs on jet fuel.

   d. Afterburning turbojet engine
   This type of engine gets only shortly used on fighter jets that fly with supersonic speed, which is, based on the estimated speed of Koopman, irrelevant for the further development of unmanned cargo aircraft.

3. Ramjet engine
   Ramjet engines are types of engines that do not make use of a compressor, but instead let air come into the engine with very high speed. The shape of the engine makes the air slowing down which creates pressure that is needed for the engine to work. However, this air can only come in with very high speed when an aircraft is flying supersonic. So this engine is, just like the afterburning turbojet engine, irrelevant for the further development of unmanned cargo aircraft.
4. Scramjet engine
   A scramjet engine is designed to overcome heat problems in a ramjet engine when speeds get too high. A ramjet engine would get damaged when flying faster than 5 times the speed of sound. Therefore, this type of engine is irrelevant for the further development of unmanned cargo aircraft as well.

According to Bejan, Charles and Lorent (2014), the two largest types of engines that are in use nowadays are the gas turbine engine and steam turbine engine. They state that gas turbine engines are perfect for aircraft propulsion. Both of these engines run on jet fuel as well as the relevant turboprop engine. Therefore, it can be said that future unmanned cargo aircraft will most probably run on jet fuel, which will be taken into account in the rest of this research.

3.2.2 Emissions of aircraft and engines

According to Bejan, Charles and Lorent (2014), the mass of the engine is proportional with the mass of a whole aircraft. Bigger aircraft carry bigger engines and bigger fuel loads. They also state that larger aircraft are more efficient and can travel relatively further than smaller aircraft.

In a research about commercial aircraft propulsion and energy systems of the national academies press of the United States of America, it is mentioned that engine fuel consumption decreases over the years and emissions from flights with jet engines are higher than from flights with turboprop engines. This is very useful for unmanned cargo aircraft, when considering that turboprop engines are already used often in helicopters or slower cargo aircraft.

3.2.3 The influence of aircraft parts on CO_2 emissions

According to a model that the company has developed for calculating the CO_2 emissions of a flight in kilograms per tonne-kilometre, the following five factors are relevant. The fifth factor is dependent on the second and third factor.

1. Maximum take-off weight (MTOW)
2. Max design zero fuel weight (MZFW)
3. Operational empty weight (OEW)
4. Max range at full payload at typical seating per kilograms
5. Freighter payload 100% (MZFW-OEW)

3.2.4 The effect of the design and use of an unmanned cargo aircraft on emissions.

Goodchild and Toy (2017) evaluated the technology of unmanned aerial vehicles in reducing the CO_2 emissions in the delivery industry. They stated that the use of drones in service zones that are close to a depot or have small numbers of recipients, is advantageous in terms of CO_2 emissions. However, trucks seem to be more advantageous over drones when the distance between a depot and service zone is large, with much recipients. Their research suggests, when looking at CO_2 emissions, that a mixed system would be the best when drones would serve nearby customers and trucks would serve customers that are located further away.

According to van Groningen (2017), the airframe of unmanned cargo aircraft is assumed to be 20 percent more light weight than a similar size manned aircraft. And, again, according to Bejan, Charles and Lorente, the carried fuel of an aircraft is proportional to its weight. Therefore, according to these claims, it is logical to assume that an unmanned cargo aircraft would use 20% less fuel and therefore emit 20% less CO_2.

3.2.5 CO_2 emissions of unmanned cargo aircraft

For each of the reference cargo aircraft, the data from the International Civil Aviation Organization is used to denote the fuel consumption in kilograms per flight distance in kilometres, which can be seen in Table 4 below.

Table 4 Fuel consumption of reference cargo aircraft

	Flight distance (km)					
	125	**250**	**500**	**750**	**1000**	**1500**
Fuel consumption (l)						
Light						
Casa C-212-300	244	488	733	991	1234	1695
Cessna 208B Grand Caravan	No data					
Fairchild Swearingen Metroliner	219	438	659	890	1109	1523
Short 330-200	293	586	882	1191		
Medium						
Alenia C027J Spartan	No data					
ATR 72-600	426	878	1397	1993	2612	3942
BAE ATP Cargo	No data					
Heavy						
Boeing 737-700C	1586	3202	4173	5570	6895	9410
Antonov AN 178	No data					
Lockheed L-188A	No data					

The emission factor of jet fuel is 9.75 kg CO_2 per gallon. 1 US gallon corresponds to 3.78541178 litres. 9.75/3.78541178 = 2.57677513. So per litre, the emission factor is 2.575677513 kg CO_2.

The maximum distance between the several locations of the company is approximately 250 kilometres and the average of all distances between the locations of the company is approximately 100 kilometres. Assuming that an aircraft would never fly more than 500 kilometres before refuelling and would not refuel at every stop, the fuel consumption that corresponds with a distance flown of 250 kilometres is taken.

Per type of reference aircraft, the fuel consumption of UCA per 250 kilometres can be taken as the average of all reference aircraft of the same class, multiplied by 0.8, when taking into account the earlier mentioned 20% reduction. This is denoted in Table 5 below. In the right-most column of this table, the CO_2 emission is calculated by using the earlier mentioned emission factor per litre. These calculated CO_2 emissions for UCA will be used in the simulation model.

Table 5. CO_2 emissions of unmanned cargo aircraft

Type of aircraft	Fuel consumption per 250 km (kg)	CO_2 emission (kg)
Small	504	1038.512
Medium	878	1809.152
Heavy	3202	6597.856

3.2.6 CO_2 emissions of trucks

In a report of the Netherlands Organisation for Applied Scientific Research about Dutch CO_2 emission factors for road vehicles, the CO_2 emission for trucks can be found. In this research, trucks are classified as heavy duty when they weigh more than 20 tons. The maximum capacity of the trucks of the company is 25 tons, but when assuming that the trucks are not always fully loaded it would be better to use the emission factor of medium duty. Trucks are classified as medium duty when they weigh between 10 and 20 tons. The emission factor for these trucks is 728 grams CO_2 per kilometre. This number will be used in the simulation model for the emission of trucks.

3.3 Costs

This section describes the several factors that make up the operating costs of flying UCA. Values for these factors are given based on an existing costs model for UCA of Lugtig and Prent (2012).

3.3.1 Aircraft operating costs

Horder (2003) presented on a conference about the management of aircraft maintenance costs, that the operating costs of an aircraft can be divided into direct and indirect operating costs. This statement is supported by Tsai and Kuo, who stated in 2004 in the journal of air transport management that operating costs can be divided into direct and indirect operating costs. According to Horder, the direct operating costs can be divided into the following costs.

- Airport fees
- Navigation fees
- Handling and Dispatch fees
- Commissions
- Insurances
- Lease charges
- Flight crew
- Maintenance
- Passenger service costs
- Fuel and oil

Horder divides indirect operating costs into the following

- Depreciation and interest
- Staff costs
- Marketing costs

- Administration costs
- Other costs

According to Lappas (2018), a reliable estimate of the operating costs of an aircraft platform can always be offered, provided that it has been in operation and has reached it's so called 'fleet maturity stage'. This is also mentioned by Wu and Caves in 2000 in the journal of air transport management. They also state that the fleet structure of an airline has an influence on the operating cost. According to Zuidberg (2014), the size of an aircraft has no significant effect on the operating costs of an aircraft. He also mentions that the total number of operations and the number of destinations have an effect on the operating costs and an increase in load factor has no effect on operating costs.

The operating costs found for the reference cargo aircraft are noted in Table 6 below in dollars per hour. These give an insight when comparing them with the operating costs of future unmanned cargo aircraft.

Table 6. Operating costs for reference cargo aircraft

Type of aircraft	**Operating costs (dollars per hour)**
Light	
Casa C-212-300	928
Cessna 208B Grand Caravan	579
Fairchild Swearingen Metroliner	1389
Short 330-200	1270
Medium	
Alenia C-27J Spartan	Not found
ATR 72-600	2084
BAE ATP Cargo	Not found
Heavy	
Boeing 737-700C	Not found
Antonov AN178	Not found
Lockheed L-188A	Not found

3.3.2 Aircraft acquisition costs

According to the International Air Transport Association (IATA), manufacturers make list prices when selling their aircraft, but these prices are usually not the prices for which an aircraft will be sold. Additional costs could include payments for the rights to purchase the aircraft or purchase options.

The fair value of the aircraft usually consists of the following main components:

- Airframe
- Engines
- Modifications
- Rotable assets
- Repairables
- Embedded Maintenance

The acquisition costs found for the reference cargo aircraft are noted in Table 7 in millions of dollars.

Table 7. Acquisition costs for reference cargo aircraft

Type of aircraft	Acquisition costs (million dollars)
Light	
Casa C-212-300	5.2-8
Cessna 208B Grand Caravan	2.685
Fairchild Swearingen Metroliner	0.442
Short 330-200	Not found
Medium	
Alenia C-27J Spartan	32
ATR 72-600	19
BAE ATP Cargo	13.25
Heavy	
Boeing 737-700C	26.7
Antonov AN178	40-70
Lockheed L-188A	Not found

Using the chosen aircraft as a reference, the acquisition costs for future UCA are assumed to be the average of the acquisition costs of the chosen aircraft. They are noted in Table 8 in millions of dollars and are useful later in the calculation of the operating costs of UCA.

Table 8. Acquisition costs for unmanned cargo aircraft

Type of aircraft	Acquisition cost (million dollars)
Light	3.24
Medium	21.42
Heavy	40.85

3.3.3 Aircraft depreciation costs

According to the airline disclosure guide of IATA, each aircraft component should be depreciated separately by using the residual value and useful life that is specific for this component.

The report mentions that determining a depreciation rate depends on the following factors:

- Intended life of the fleet type being operated by the airline
- Estimate of the economic life from the manufacturer
- Fleet deployment plans including timing of fleet replacements
- Changes in technology
- Repairs and maintenance policies
- Aircraft operating cycles
- Prevailing market prices and the trend in price of second hand and replacement aircraft
- Aircraft-related fixed asset depreciation rates, for example, rotables and repairables may reflect the airline’s ability to use common components across different aircraft type
- Treatment of idle assets
- Distinction between fleet types

According to a costs model of Lugtig and Prent (2012) about unmanned cargo aircraft, the depreciation costs for future unmanned cargo aircraft can be calculated by assuming the rest value on 5% of the acquisition value and assuming the percentage of costs for components on 22.5%. Also, the number of years before depreciation is assumed to be 12.5 and the number of cycles flown with the aircraft is assumed to be 60000. With this model, the depreciation costs for future unmanned cargo aircraft can be calculated by using the acquisition values of the reference cargo aircraft, as can be seen in Table 9 below. So this table shows the depreciation costs as if these cargo aircraft were unmanned.

Table 9. Depreciation costs of unmanned cargo aircraft

Type of aircraft	**Depreciation costs (dollars per flight cycle)**
Light	
Casa C-212-300	10.34
Cessna 208B Grand Caravan	4.2065
Fairchild Swearingen Metroliner	0.6925
Short 330-200	Not found
Medium	
Alenia C-27J Spartan	50.13
ATR 72-600	29.77
BAE ATP Cargo	20.76
Heavy	
Boeing 737-700C	41.83
Antonov AN178	86.17
Lockheed L-188A	Not found

3.3.4 The operating costs for future unmanned cargo aircraft

Based on the costs model for unmanned cargo aircraft from Lugtig and Prent (2012), the operating costs per flight of each of the reference cargo are calculated, in dollars per hour, as if they would be unmanned cargo aircraft. This is done since operating costs of unmanned cargo aircraft are unknown yet. Assumptions for unmanned cargo aircraft were made according to the model. In the costs model, the estimated acquisition prices for UCA as found in Section 3.3.2 are the only input from outside the model on which the calculations are based. The rest of the calculations is based on a list of assumptions for UCA, which can be seen in Table 10. When comparing manned to unmanned aircraft, obviously, no pilots will control UCA in the aircraft. However, aircraft controllers need to control the UCA from the ground. This job would be comparable to the job of air traffic controllers who are controlling manned aircraft. Therefore, the assumption for the hourly wage of the aircraft controller is based on the hourly wage of present air traffic controllers.

Table 10. Assumptions for calculating the operating costs of unmanned cargo aircraft

Name	Assumption
Acquisition price	3.24-40.85 million (see section 3.3.2)
Restvalue	5%
Number of cycles an aircraft flies	60,000
Hourly wage, maintenance personnel	$35
Number of tons of goods to be handled	3 tons
Costs per ton of handling	0.073
Engine thrust	28,5 kN
Number of years before depreciation	12.5
Number of engines	1
Percentage paid from business treasury	25%
Percentage insurance	0.6% per year
Percentage costs for components	22.5%
Price of 1 kilogram jet fuel in US dollars	$0.7
Interest rate investment	2%
Investment rate loan	11%
Specific fuel consumption in kilogram per power * time unit	0.00005783 kg/pk*sec
Weight of the airframe	9.5 tonnes
Landing fee	$71.58
Starting fee	$46.45
Parking fee	$6.56
Government taxes	$112.62
Other costs	$0
Hourly wage aircraft controller	$74
Hours flown with cruising speed	0.94
Average power	2062,5 hp

So based on the above assumptions and the costs model of Lugtig and Prent (2012), the operating costs per aircraft would be the following, when they were unmanned.

Table 11. Operating costs for unmanned cargo aircraft

Type of aircraft	Future Operating Costs (dollars per hour)
Light	
Casa C-212-300	2070.34
Cessna 208B Grand Caravan	2060.29
Fairchild Swearingen Metroliner	2054.53
Short 330-200	Not found
Medium	
Alenia C-27J Spartan	2135.67
ATR 72-600	2102.30
BAE ATP Cargo	2087.54
Heavy	
Boeing 737-700C	2122.21
Antonov AN178	2194.85
Lockheed L-188A	Not found

Based on these operating costs, the operating costs of future unmanned cargo aircraft are assumed to be the average of the operating costs of the reference cargo aircraft. This can be seen in Table 12 below.

Table 12. Operating costs for future unmanned cargo aircraft

Type of Aircraft	Operating Costs (dollars per hour)
Light	2061.72
Medium	2108.50
Heavy	2158.53

3.3.5 The operating costs of trucks

The American Transportation Research Institute has made an analysis in 2018 about the operational costs of trucking. This research showed that the operating costs are 1.86 dollars per mile. The components of these costs consist of vehicle-based and driver-based costs. The vehicle-based costs are the following:

- Fuel costs
- Truck/trailer lease or purchase payments
- Repair and maintenance
- Truck insurance premiums
- Permits and licenses
- Tires
- Tolls

The driver-based costs are the following:

- Driver wages
- Driver benefits

One mile corresponds to 1.609344 kilometres. Therefore the operating costs per kilometre are 1.16 dollars rounded. On average a truck drives 90 kilometres per hour, which makes the operating costs of a truck per hour 104.02 dollars.

3.4 Aircraft speeds

This section gives the values for the cruise speeds of the reference aircraft as well as for the future UCA.

The cruise speeds found for the reference cargo aircraft can be find in Table 13 below.

Table 13. Cruise speeds for reference cargo aircraft

Type of aircraft	Cruise speed (km/h)
Light	
Casa C-212-300	275
Cessna 208B Grand Caravan	344
Fairchild Swearingen Metroliner	515
Short 330-200	300
Medium	
Alenia C-27J Spartan	583

ATR 72-600	510
BAE ATP Cargo	436
Heavy	
Boeing 737-700C	938
Antonov AN178	800
Lockheed L-188A	620

The cruise speeds of the reference cargo aircraft are taken as a reference for calculating the cruise speeds of future unmanned cargo aircraft. This can be done by taking the average per category, which is denoted in Table 14 in kilometres per hour.

Table 14. Cruise speeds of unmanned cargo aircraft

Type of aircraft	Cruise speed (km/h)
Light	358.5
Medium	509.67
Heavy	786

Since the potential of UCA is described in this chapter and a lot of information is collected about the costs, CO_2 emissions and speeds of aircraft, a conceptual model can be made and a simulation model can be designed. The values given in this chapter can be used as the input for the simulation model.

Chapter 4: Solution Design

In this chapter, the conceptual model of the simulation model is shown. It can be seen as an abstraction of the part of the real world that it is representing, as says the definition of Robinson (2015). That means it is a simplified representation of reality.

The conceptual model

This conceptual model is described in such a way, that it could be used by anyone who would want to perform the same simulation study. The approach of Robinson (2015) for making a conceptual model is followed.

Modelling objective.

The modelling objective describes the purpose for which the simulation model is made and can be described as follows: The objective of the simulation model is to give the company a better understanding of the performance of UCA in comparison to trucks in terms of CO_2 emissions, operating costs and travel durations. Quantitative comparisons need to be possible.

Project objectives

The project objectives are the more general objectives that relate to the feasibility and utility of the model and are the following.

- Time scale: No time restriction
- Flexibility: Flexible (changes during study likeable)
- Run-speed: Many experiment scenario's to be run
- Visual Display: 2D-animation of UCA and Trucks moving in the model
- Ease-of-use: Use by modeller only, results used to give company the better understanding

In Figure 4, a snapshot of the visualisation of trucks moving in the model can be seen.

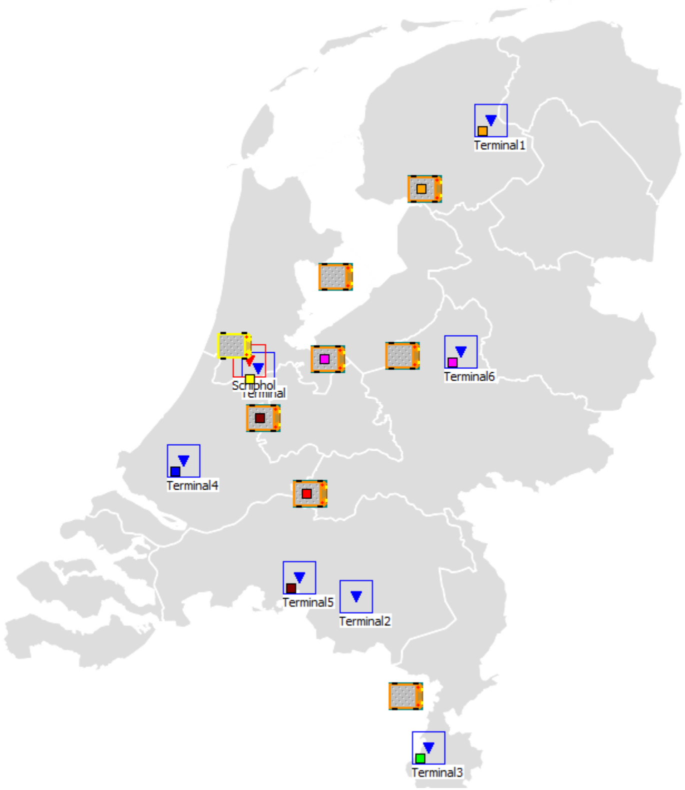

Figure 4 A snapshot of trucks moving in the simulation model

Outputs

The outputs of the model determine whether the objective is achieved. When the company can get a better understanding in terms of CO_2 emission, operating costs and travel durations while looking at the outputs, then the objective is achieved. The outputs of the model are the following.

- Total CO_2 emissions of UCA and trucks in kilograms
- Total operating costs of UCA and trucks in dollars
- The total waiting time of the freight in seconds

In the model, more statistics are kept, but these are not considered as outputs that determine whether the modelling objective is achieved.

Inputs

The inputs of the model can be seen as the means that could be changed when one wants to see a change in the outputs. These inputs, including their range or values are the following. Some inputs do not vary between a range of values but have one default value. However, changing these inputs would have an effect on the outputs. Not every input necessarily has an effect on all three outputs.

- The number of orders that arrive per time unit. There are three possible arrival rates: one order per 30 minutes, one order per 60 minutes or one order per 90 minutes.
- The distribution of the order size. The order size varies between 1 and 5, all with an equal probability of occurrence.
- The total number of locations. There are 8 locations.
- The distances as the crow flies between all locations for UCA. These distances vary between 4 kilometres and 250 kilometres.
- The distances using the road network between all locations for trucks. These distances vary between 6 kilometres and 310 kilometres.
- The kilograms of CO_2 an UCA emits when flying 250 kilometres. This number can be either 1038.512, 1809.152 or 6597.856, depending on the type of UCA, as can also be read in Section 3.2.5.
- The operating costs of an UCA in dollars per hour. This number can be either 2061.72, 2108.50 or 2158.53 depending on the type of UCA, as can also be read in Section 3.3.4.
- The grams of CO_2 a truck emits when driving one kilometre. This corresponds to 728 grams per kilometre.
- The operating costs of a truck in dollars per hour. This corresponds to 104.02 dollars per hour.
- The speed of an unmanned cargo aircraft in metres per second. This speed is 125 metres per second.
- The speed of a truck in metres per second. This speed is 25 metres per second.
- The capacity of an UCA in tonnes. This capacity can be either 7, 14 or 20 tonnes, depending on the type of UCA, as can also be read in Section 3.1.6.
- The capacity of a truck in tonnes. This capacity is 25 tonnes.
- The total number of UCA. This number varies between 3 and 15 and is calculated in Chapter 5.
- The total number of trucks. This number varies between 4 and 16 and is calculated in Chapter 5.
- The use of a home base scenario in which each location has its own vehicle, or the use of a scenario without home bases.
- The minimal utilization of a vehicle before it starts travelling. This value is set to be 0.5 or 0.3

- The maximal permissible waiting time of the freight. This is 3 hours or 10800 seconds.

Content
The content of the model consists of the scope and the level of detail. This respectively describes what is modelled and how it is modelled.

Scope
The entities that are modelled are the UCA, the trucks and the freight. These entities move around in the model between the several locations. All of them are always in one of the three stages: parking, waiting or handling. The parking and handling stage are queues in which multiple entities can be waiting. Also, each terminal has its own colour of freight.

Level of detail
Each UCA and truck represent one vehicle. Each freight represents one piece of freight. The shape of the freight is not included in the model, although the volume of the freight is. UCA and Trucks drive straight towards their destinations, without stopping in between.

Assumptions
Most of the assumptions made in the model are made due to a lack of data or knowledge of the company. These are the following:

- The minimal size of freight is 1 tonne and the maximal is 5 tonnes.
- Every order size occurs equally often.
- The company uses an utilization level before letting their vehicles travel.
- Orders arrive on average every 0.5 hour, 1 hour or 1.5 hour.

Simplifications

- UCA travel with average speeds equal to their cruising speeds, without taking into account take-off and landing speeds.
- Trucks travel with average speeds equal to the speeds they drive on highways, without taking into account slower speeds at the beginning and end of their routes.
- When the needed number of vehicles per scenario is calculated, then the number of vehicles gets varied with 1 less and 1 more than this calculated number.

List of events + actions taken
In the simulation, five possible events can happen. For each of these events, the list of actions taken is denoted below. For the third and fourth event, the same actions are taken. Also, one logic flow diagram is provided for the first two events and the corresponding actions taken. For the third and fourth event, also another logic flow diagram is provided as well for the fifth event.

<u>1. A vehicle arrives in the parking of Schiphol in a home base scenario</u>

- Select the first vehicle in the parking
- Set this vehicle as unavailable
- Determine the destination of the vehicle as its home base
- Determine the origin of the vehicle as Schiphol
- Set the volume loaded in the vehicle as zero
- Start the vehicle

<u>2. A vehicle arrives in the parking of Schiphol in a scenario without home bases</u>

- Select the first vehicle in the parking
- Create a table with candidate terminals
    - Scan all terminals
    - Check whether the terminals are waiting for a resource
    - If a terminal is waiting for a resource, check whether the volume available at the terminal is bigger than or equal to the minimal utilization times the capacity of the vehicle or whether the volume available at the terminal is waiting longer than the maximal permissible waiting time.
    - If one of these is the case for one or more of the terminals, add them to the table with candidate terminals.
- Randomly select one of the candidate terminals
- Set the destination of the vehicle as this selected terminal
- Set Schiphol as the origin of the vehicle
- Set the vehicle as unavailable
- Start the vehicle

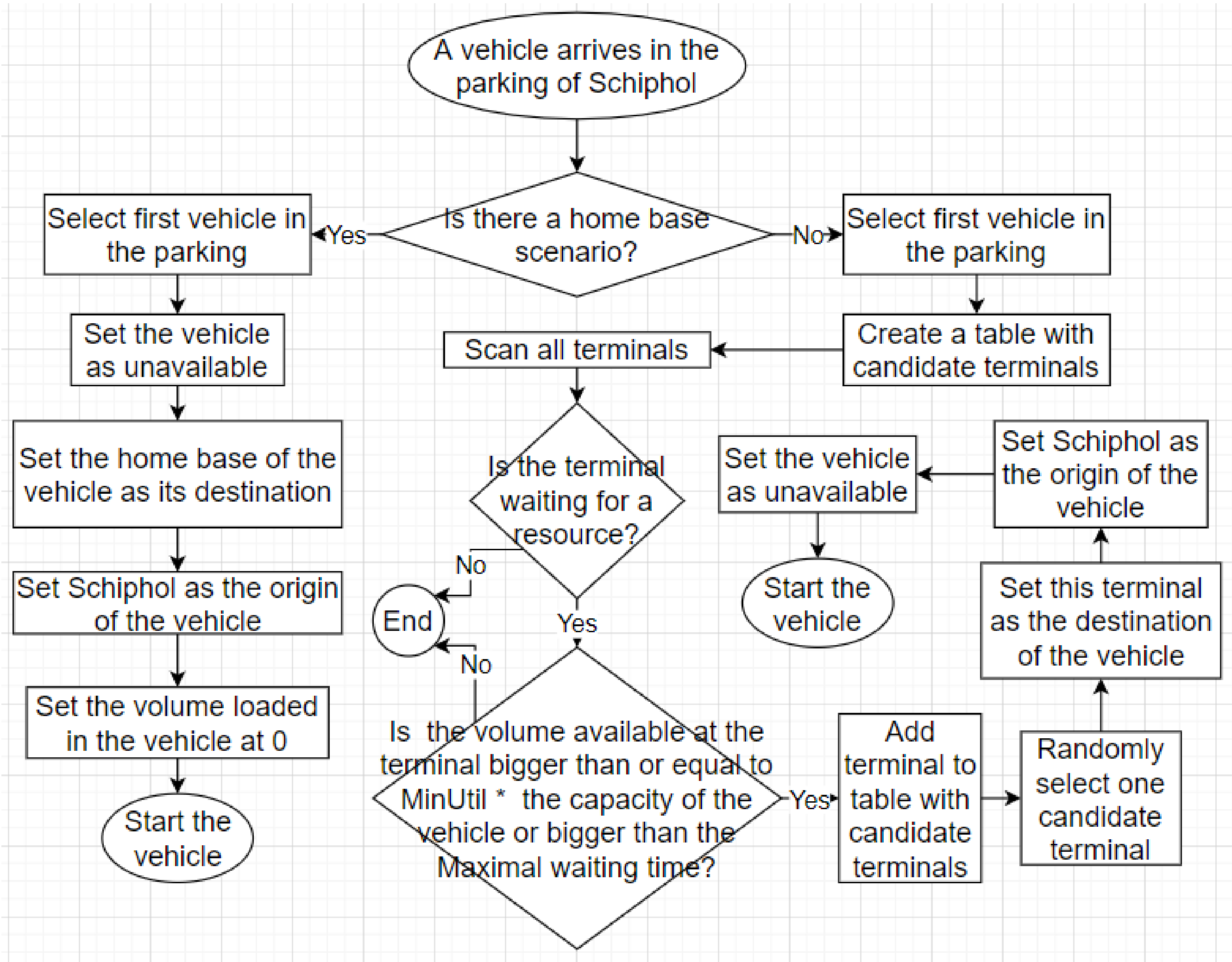

Figure 5. Logic flow diagram of the first two events

<u>3. An order arrives at a terminal or 4. A vehicle arrives in the parking of a terminal</u>

- Check whether the handling is empty
- When the handling is empty, check whether the parking is empty.

When the parking is empty, the following list of actions is executed.

- Check whether the terminal is waiting for a resource and check if there is no home base scenario in order to make sure the following actions can be executed.
- If this is the case: scan all vehicles on their availability
- Scan first available vehicle on whether the volume available at the terminal where the order arrives is bigger than or equal to the minimal utilization times the capacity of the vehicle or whether the volume available at the terminal is waiting longer than the maximal permissible waiting time.
- When this is the case, make the terminal where the order arrived the destination of the vehicle
- Set the vehicle as unavailable
- Check whether the current location of the vehicle is Schiphol
- When this is the case, set the current location of the vehicle as its origin.
- Start the vehicle

When the parking is not empty, the following list of actions is executed.

- Select the first vehicle in the parking
- Check whether the volume available at the terminal is bigger than or equal to the minimal utilization times the capacity of the vehicle or whether the volume available at the terminal is waiting longer than the maximal permissible waiting time.
- Set remaining capacity of the vehicle as its volume capacity.
- Scan all orders at a terminal
- Check whether the volume of an order is smaller than the remaining capacity of a vehicle.
- If the volume of an order is not smaller than the remaining capacity, check the same for the next order.
- If the volume of an order is smaller than the remaining capacity, set the waiting time of the order as the current simulation time minus the last updated time of the order.
- Update the volume loaded in the vehicle with the volume of the order.
- Subtract the volume of the order from the remaining capacity of the vehicle.
- Delete the order from the list of orders at the terminal.
- Set the terminal as not waiting for a resource.
- Set the destination of the vehicle as Schiphol.
- Set the vehicle as unavailable.
- Set the terminal as the origin of the vehicle.
- Set the volume available at the terminal as the previous volume available minus the volume loaded in the vehicle.
- Move the vehicle to the handling.

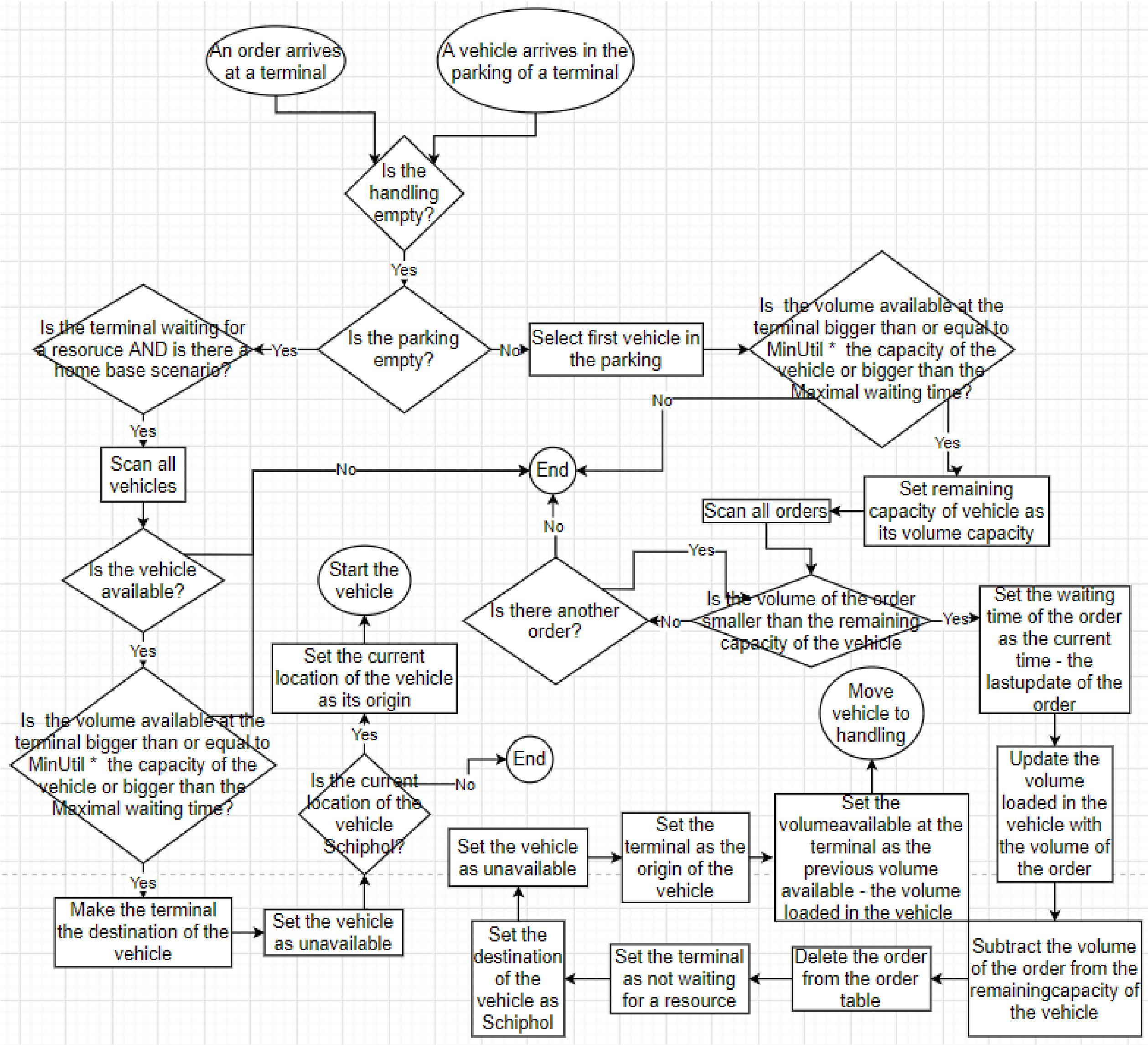

Figure 6. Logic flow diagram of the third and fourth event

5. A vehicle arrives at a location

- Set the location of the terminal as the current location of the vehicle
- Clear the destination of the vehicle
- Check whether the vehicle did both arrive at Schiphol and brought freight
- If this is the case, move the vehicle to the handling.
- If this is not the case, check whether a home base scenario is used.
- If this is the case, move the vehicle to the parking.

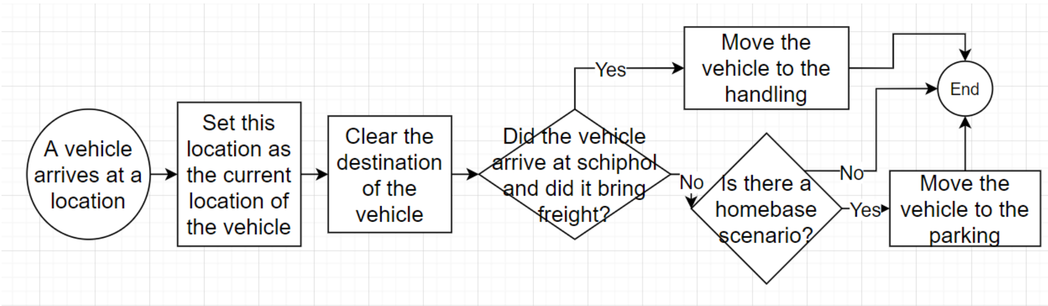

Figure 7. Logic flow diagram of the fifth event

This chapter described the level of abstraction at which should be worked when implementing the simulation model in any kind of simulation programming tool. The modelling objective, outputs, inputs, scope, level of detail, assumptions, simplifications and list of events are described and visualized in such a way that anyone could perform the same simulation study. In Appendix 1, the implementation of the simulation model can be seen in detail. All components of the model and their usefulness are described in this Appendix 1.

5 Experimental design, results and analysis

This chapter covers the design and settings of the experiments that we are going to run. Also the results of these experiments are shown and analysed in this chapter.

In the simulation model, various settings are varied. Varying with these settings results in different experiments. However, not every setting will be varied. The settings that will be varied are the following. Behind each setting is in brackets what these settings are called in the simulation model.

- The capacity of an UCA (UCACapacity)
- The total number of UCA (NrUCA)
- The total number of trucks (NrTrucks)
- The average time between orders (AvgTimeBetweenOrders)
- The use of a Home Base scenario or not (HomeBase)
- The minimal utilization of a vehicle (MinUtil)
- The maximal permissible waiting time of the freight (MaxTime)
- The type of vehicle (UCAOnly)

The capacity of the UCA will be varied, since there are three types of UCA: light, medium and heavy. The average time between orders will be varied in three ways as well. There are seven terminals. The average time between orders will be varied in such a way that orders will arrive at a terminal every half an hour, every hour and every one and a half hour on average. This means that in the settings of the model, the average time between orders will be 4 minutes and 17 seconds, 8 minutes and 34 seconds and 12 minutes and 51 seconds. The home base scenario can be either false or true, resulting in a home base scenario or a scenario without home bases. The minimal utilization will be either 0.3 or 0.5 times the capacity of a vehicle to experiment with a low and a normal utilisation. The variable MaxTime will be set on either infinite or 10800 seconds. This means that in some of the experiments, this variable will not be used as a restriction, but in the experiments where vehicles have to wait longer than three hours to reach the minimum utilization, the maximal permissible waiting time will be used to make sure a vehicle does start moving. The type of vehicle can be false or true as well, resulting in a scenario with respectively trucks or UCA. Each of the options for each setting can be seen below in Table 15.

Table 15. The possible options for each setting in the simulation model

UCACapacity (tonnes)	NrUCA	NrTrucks	AvgTimeBetweenOrders (minutes)	HomeBase	MinUtil	MaxTime (seconds)	UCAOnly
7	3	4	4:17.00	True	0.3	0	True
14	4	5	8:34.00	False	0.5	10800	False
20	5	6	12:51.00				
	6	8					
	7	9					
	8	10					
	9	11					
	10	12					
	11	13					
	12	14					
	13	15					
	14	16					
	15						

In a simulation study, interventions and scenarios can be distinguished. Interventions are the type of variables in the settings that are chosen and could be varied by the company as well. The scenarios are the ones you have no control over. In this case, the scenarios are the average time between orders, the capacity of UCA, the use of a home base scenario and the use of UCA or truck only. This would result in 24 possible scenarios. These scenarios can be seen in Appendix 2 in Table A2.1. Not every possible combination of settings in Table 15 will be evaluated. The configuration of all settings can be found in Appendix 3. This results in 75 experiments. The purpose of doing these experiments is to be later able to filter out the experiments that are of little use. The calculation of the number of UCA and trucks follows in the next sections.

5.1 Calculation of the number of unmanned cargo aircraft and trucks.

The number of UCA and trucks that will be used in a scenario without home bases, is dependent on several factors. In the following sections, the calculation of those numbers will be explained. Each step of the calculation will be explained.

5.1.1 Calculation of the number of unmanned cargo aircraft in a scenario without home bases

The calculation of the number of UCA follows 11 steps, which are described below.

1. Determination of the total volume of freight generated with each interarrival time of the freight.
2. Determination of the average load size per type of UCA and per value for the minimal utilization.
3. Determination of the average number of loads needed per type of UCA and per value for the minimal utilization. This number tells how many loads an UCA needs on average before it can start flying.
4. Determination of the average time before an UCA starts flying towards its destination. This is useful for the eventual calculation of the time it takes for UCA to deliver all freight.
5. Correction for the maximal permissible waiting time. This is done when the average time before an UCA starts flying calculated in step four is bigger than 180 minutes, which is set as the maximal permissible waiting time of the freight.
6. Determination of the average time it takes for an UCA to fly back and forth to its destination. This is useful for the calculation of the total number of minutes it would take for a certain number of UCA to deliver all freight.
7. Determination of the actual average load sizes per type of UCA and per value for the minimal utilization. Determining this again is useful since an utilization of zero is taken into account.
8. Determination of the number of loads needed to carry all freight per type of UCA and per value for the minimal utilization. This is useful for the calculation of the total number of minutes it would take for a certain number of UCA to deliver all freight.
9. Determination of the number of loads that can be transported when using a certain number of UCA. This is useful as well for the calculation of the total numbers of minutes it would take for a certain number of UCA to deliver all freight.
10. Determination of the number of minutes needed to transport all loads, by a certain number of UCA and by certain values of the minimal utilization.
11. Determination of the minimal number of UCA needed to be able to transport all loads in the determined simulation time.

How each step is exactly executed, will be explained below. Also, figures of the Excel file in which the calculation was executed are added in Appendix 4.

1. Determination of the total volume of freight generated
Orders arrive on average every half an hour, hour and one and a half hour at a terminal. Simulating for 100 days means that 4800, 2400 or 1600 times, freight will be generated at a terminal on average, since 100 days contain 4800 times 30 minutes, 2400 times 60 minutes and 1600 times 90 minutes. Multiplying these numbers by 7, shows the total number of freight that will be generated with each interarrival time of the freight, since there are seven terminals. This results in 33600, 16800 or 11200 pieces of freight. Multiplying these numbers by 3, which is the average size of a piece of freight, gives the total volume of freight per interarrival time of the freight. This results in the three total volumes of 100800, 50400 and 33600.

2. Determination of the average load size
For each type of UCA, the average load size is calculated, by multiplying its capacity by the minimal utilization (MinUtil). Three values are taken for the minimal utilization 0.5, 0.3 and 0.0. However, 0.0 is only used for the smallest type of UCA. This results in the average load sizes that can be seen in Figure A4.1 in Appendix 4.

3. Determination of the average number of loads needed
Dividing the average load sizes by the average size of a piece of freight, results in the average number of loads that are needed. These numbers can also be seen in Figure A4.1 in Appendix 4.

4. Determination of the average time before an UCA starts flying towards its destination
Multiplying these number of loads needed per minimal utilization by the average time between an order arrival per terminal, results in the average time before an UCA starts flying towards a terminal per UCA type and per value for the minimal utilization, which can also be seen in Figure A4.1 in Appendix 4.

5. Correction for the maximal permissible waiting time
When the average time before an UCA starts flying is bigger than 180 minutes, a correction is needed. In this case, the average time should be set at 180 minutes, since when UCA are waiting longer than 180 minutes, the maximal permissible waiting time would be exceeded. This correction can be seen in Appendix 4, Figure A4.2.

6. Determination of the average time it takes for an UCA to fly back and forth to its destination
As mentioned in the conceptual model, the distances as the crow flies between all locations hold as one of the inputs for the simulation model. Taking the average distance between Schiphol and the other locations and dividing it by the average speed of an UCA in metres per second results in the average number of seconds it would take for an UCA to fly this average distance. Dividing the found number by 60 and multiplying it by two, results in the average number of minutes it would take for an UCA to fly back and forth between Schiphol and a location. Adding the handling time of 15 minutes gives the total time it would take for an UCA to get back and forth, as can be seen in Figure A4.3 in Appendix 4. Adding these times to the average times it takes before an UCA starts flying, results in the average time between the take-off of an UCA and the arrival of the freight, which can be seen in Figure A4.4 in Appendix 4.

7. Determination of the actual average load sizes
A new table with the average load sizes is made, in which the actual average load size with an utilisation of 0.0 is denoted, since the average load size cannot be zero. In this case, the average load size will be the average size of the freight, which is 3. This can be seen in Figure A4.5 in Appendix 4.

8. Determination of the number of loads needed to carry all freight
Per aircraft type and value for MinUtil, the average total number of needed loads is calculated by

dividing the total number of loads by the actual average size of a load, which can be seen in Figure A4.5 in Appendix 4 as well.

9. Determination of the number of loads that can be transported
Per type of UCA and value for MinUtil, the total loads that can be transported by a certain number of UCA are denoted in the Figures A4.6, A4.7 and A4.8 in Appendix 4. This is done for each interarrival time of the freight.

10. Determination of the number of minutes needed to transport all loads,
Multiplying these total loads by the average time between the take-off of an UCA and the arrival of the freight, results in the average numbers of minutes needed to transport all loads.

11. Determination of the minimal number of UCA needed
The first number of UCA that corresponds to a number of minutes that is smaller than the total number of minutes which are simulated, is the minimal number of UCA that is needed. These numbers are made green, as can be seen in the figures A4.9, A4.10 and A4.11 in Appendix 4 . For each combination of UCA type, Minimal utilization and interarrival times of the freight, the minimal number of UCA needed is denoted in Table 16 below.

Table 16. The minimal number of unmanned cargo aircraft needed in a scenario without home bases

	30 min between freight	60 min between freight	90 min between freight
UCA capacity 7	10	5	4
UCA capacity 14, MinUtil 0.5	11	9	8
UCA capacity 14, MinUtil 0.3	14	11	10
UCA capacity 20, MinUtil 0.5	10	8	6
UCA capacity 20, MinUtil 0.3	12	10	9

During the simulation, these numbers of UCA will be used, as well as one UCA less and more, to see the effect and have some margin, since the calculations are based on averages. This declares the numbers of UCA as stated in Table 15.

5.1.2 Calculation of the number of Trucks in a scenario without home bases
The calculation of the number of trucks goes approximately along the same steps as the calculation of the number of UCA in a scenario without home bases. However, for trucks, other distances between the locations and Schiphol are used. Also, the capacity and speed of a truck are used.

For each combination of MinUtil and interarrival times of the freight, the minimal number of trucks needed is denoted in Table 17 below.

Table 17. The minimal number of trucks needed in a scenario without home bases

	30 min between freight	60 min between freight	90 min between freight
MinUtil 0.5	12	10	5
MinUtil 0.3	15	11	9

During the simulation, these numbers of trucks will be used, as well as one truck less and more, just as with the UCA.

5.2 Results and analysis

In this section, the results of the 74 experiments will be presented and analysed. Especially the performance of UCA in comparison to trucks in terms of duration, CO2 emission and operating costs will be analysed. All 24 scenarios will be compared, which is useful to write off experiments that do not show good performance when certain interventions are chosen.

5.2.1 Duration

When looking at the total waiting time of the freight, two scenarios are standing out above the rest, which are the scenarios 1 and 10 as can be seen in Figure 8 below. The red bars include the scenarios with trucks, whereas the blue include the scenarios with UCA only. For each scenario, the lowest waiting time of the freight is depicted when a scenario includes more than 1 experiment.

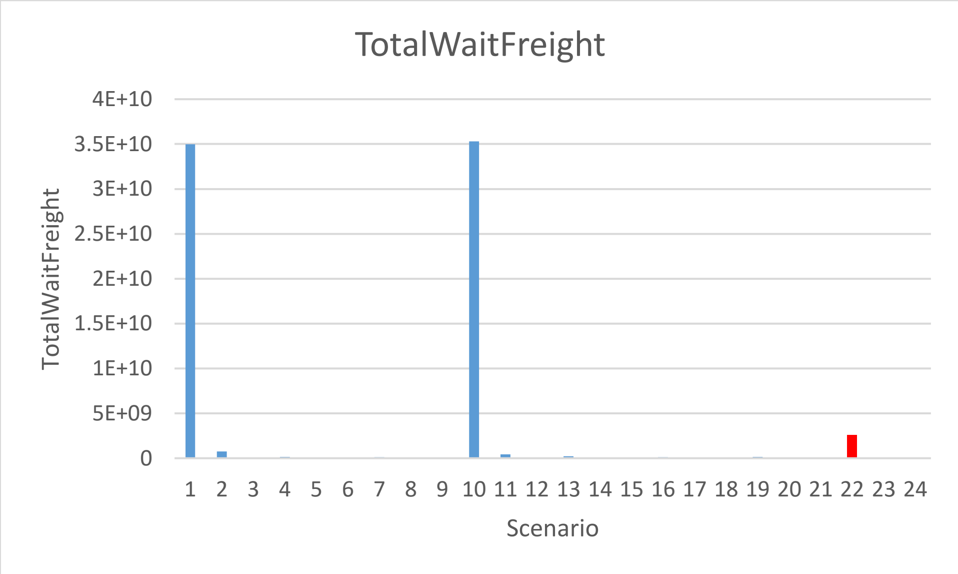

Figure 8. The total waiting time of the freight per scenario

In scenario 1 and 10, the following experiment settings were used.

Table 18. The experiment settings of scenario 1 and 10

Scenario	Exp	NrTrucks	NrUCA	AvgTime BetweenOrders (min)	HomeBase	MinUtil	MaxTime (sec)	UCACapacity (tonnes)
1	12	0	9	4.29	FALSE	0	0	7
1	13	0	10	4.29	FALSE	0	0	7
1	14	0	11	4.29	FALSE	0	0	7
10	0	0	7	4.29	TRUE	-	-	7

In scenario 1, the experiments 12, 13 and 14 were run. In these experiments the capacity of the UCA was the lowest, in combination with the shortest interarrival time of the freight. Apparently, the number of UCA used in combination with a value of zero for the minimal utilization, was not enough to result in short waiting times of the freight. This can be said because no other interventions are used in these experiments. The waiting time of a single piece of freight in all three experiments is approximately 12 days. However, there was no stationary behaviour during the experiments. The waiting times increased during the run.

Experiment zero is the first experiment in which UCA were run in a home base scenario. This UCA has a capacity of 7 tonnes and, in comparison to the other home base scenario's, this experiment was run with an interarrival time of the freight of 4:17 minutes. An explanation for this can be found in the fact that an UCA can carry a very low amount of freight, with on average not more than 2 pieces, although the amount of freight generated was very high. The number of seven UCA used in a scenario with home bases could apparently not cope with the high numbers of freight generated. No interventions were used, but this is not even possible in this scenario, since the number of UCA is fixed in a home base scenario and a minimal utilization level or maximum permissible waiting time is not taken into account.

As can also be seen in Figure 8, there is one scenario with trucks that stands out a bit above the rest, which is scenario 22. This scenario covers experiment 9 in which the following experiment settings were used.

Table 19. The experiment settings of scenario 22

Scenario	Exp	NrTrucks	NrUCA	AvgTime BetweenOrders (min)	HomeBase	UCACapacity (tonnes)
22	9	7	0	4.29	TRUE	0

In this experiment, trucks were run in a home base scenario with an interarrival time of the freight of 4:17 minutes. This resulted in considerably more waiting time of the freight, than in the home base scenarios in which the average time between orders was bigger. Just as with UCA, the fixed number of seven vehicles in a home base scenario could apparently not cope with the high numbers of freight generated. However, when comparing experiment 0 and 9, the total waiting time of the freight is much lower for trucks, since trucks can carry much more pieces of freight on average than the smallest type of UCA can.

5.2.2 CO_2

When looking at CO_2 emissions, 6 scenarios are standing out above the rest, which are the scenarios 7,8,9,16,17 and 18 as can be seen in Figure 9. The scenarios 19 until 24 are the scenarios in which trucks are used, but their CO_2 emissions are so small in comparison to the CO_2 emissions of UCA, that they are not even shown in the figure. Just as for the total waiting time of the freight, the lowest CO_2 emission is depicted when a scenario includes more than 1 experiment.

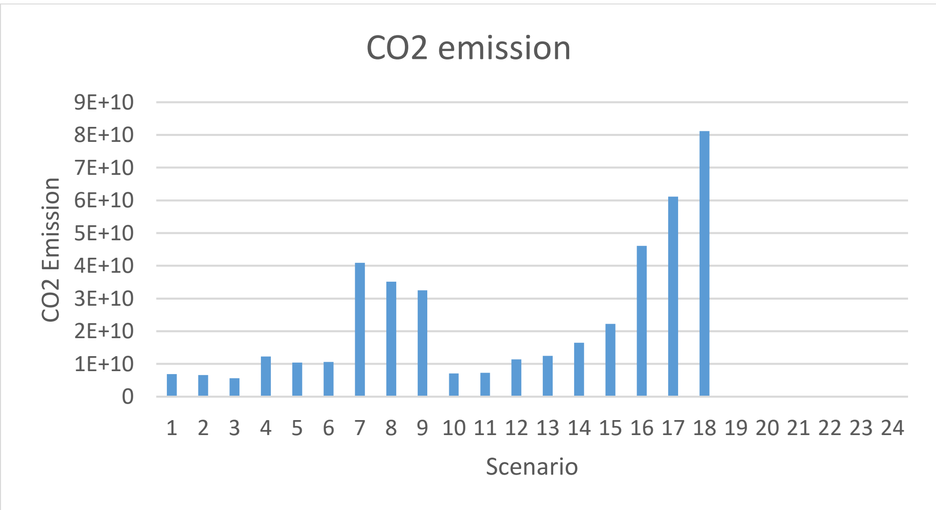

Figure 9. The CO2 emission per scenario

In scenario 16,17 and 18, the following experiment settings were used.

Table 20. The experiment settings of the scenarios 16,17 and 18

Scenario	Exp	NrTrucks	NrUCA	AvgTime BetweenOrders (min)	HomeBase	UCACapacity (tonnes)
16	6	0	7	4.29	TRUE	20
17	7	0	7	8.57	TRUE	20
18	8	0	7	12.86	TRUE	20

In these experiments, a home base scenario was used in combination with the biggest type of UCA. It can be seen that the CO_2 emission increases when the interarrival time between the freight becomes bigger. As a result of the increasing interarrival time, the total flying time of an UCA increases, which is the cause of the increasing CO_2 emission. Also, in a home base scenario, an UCA keeps flying without looking at load factors or time schedules. This means that the number of trips is relatively high in comparison to a scenario without home bases, which results in a lot of flying time, which results in a lot of CO_2 emission when using the largest UCA type.

In scenario 7,8 and 9, the experiments 39 until 56 were run. The settings used in these experiments were the following.

Table 21. The experiment settings of experiments 39 until 56

Exp	NrTrucks	NrUCA	AvgTimeBetweenOrders (min)	HomeBase	MinUtil	MaxTime (sec)	UCACapacity
39	0	11	4.29	FALSE	0.3	10800	20
40	0	9	4.29	FALSE	0.5	10800	20
41	0	12	4.29	FALSE	0.3	10800	20
42	0	10	4.29	FALSE	0.5	10800	20
43	0	13	4.29	FALSE	0.3	10800	20
44	0	11	4.29	FALSE	0.5	10800	20
45	0	9	8.57	FALSE	0.3	10800	20
46	0	7	8.57	FALSE	0.5	10800	20
47	0	10	8.57	FALSE	0.3	10800	20
48	0	8	8.57	FALSE	0.5	10800	20
49	0	11	8.57	FALSE	0.3	10800	20
50	0	9	8.57	FALSE	0.5	10800	20
51	0	8	12.86	FALSE	0.3	10800	20
52	0	5	12.86	FALSE	0.5	10800	20
53	0	9	12.86	FALSE	0.3	10800	20
54	0	6	12.86	FALSE	0.5	10800	20
55	0	10	12.86	FALSE	0.3	10800	20
56	0	7	12.86	FALSE	0.5	10800	20

Several interventions were used in these experiments, but regardless of the intervention chosen, the CO_2 emissions are still considerably higher than in the other experiments with UCA in a scenario without home bases. An explanation for this can be found in the fact that the CO_2 emission factor of the largest type of UCA is approximately 3.65 times higher than for the medium UCA type and 6.35 higher than for the small UCA type. So when this largest UCA would fly just as much as the other UCA types, it would already emit considerably more CO_2.

The scenario with UCA that comes closest to the low CO_2 emissions of trucks, is scenario 3. In this scenario, experiment 18 shows the lowest CO_2 emission. In this experiment, 3 small UCA were used together with the highest interarrival time of the freight. However, the CO_2 emission in this experiment is still 5121 times as high as the experiment with trucks with the highest amount of CO_2 emission.

5.2.3 Operating costs

When looking at the total operating costs of all scenarios, a few scenarios stand out above the rest. These are the scenarios 1,4 and 10 until 18 as can be seen in Figure 10. The scenarios in which trucks are used are made red.

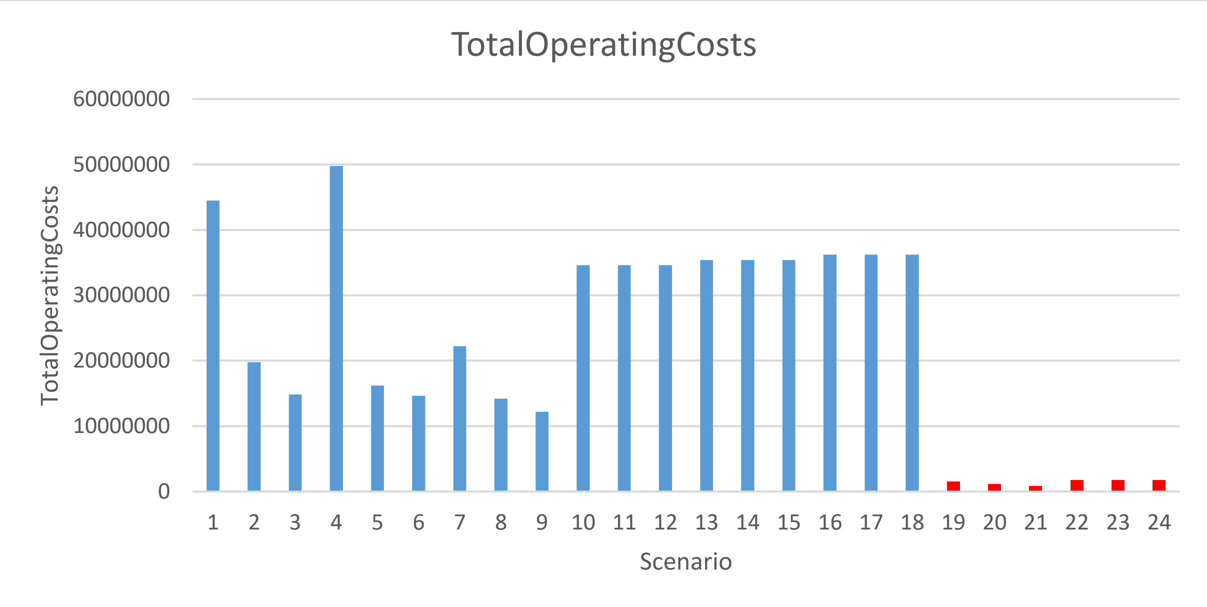

Figure 10. The total operating costs per scenario

It stands out, that the operating costs are clearly the lowest when trucks are used. In the scenarios 1 and 4, the interarrival time of the freight is the lowest. For the scenarios with UCA without home bases, it can be seen that for each type of UCA, the operating costs decrease as soon as the interarrival time between the freight increases. In the scenarios with UCA and home bases, constant high operating costs can be seen for the scenarios 10 until 18. This is due to the fact that aircraft cannot make use of utilization levels or a maximum waiting time and are bound to a fixed number of aircraft.

When looking at the scenarios 1 to 9, in which UCA were used without home bases, peaks in the operating costs of UCA can be found in experiment 14, 21, 23, 25, 39, 41 and 43 as can be seen in figure 11.

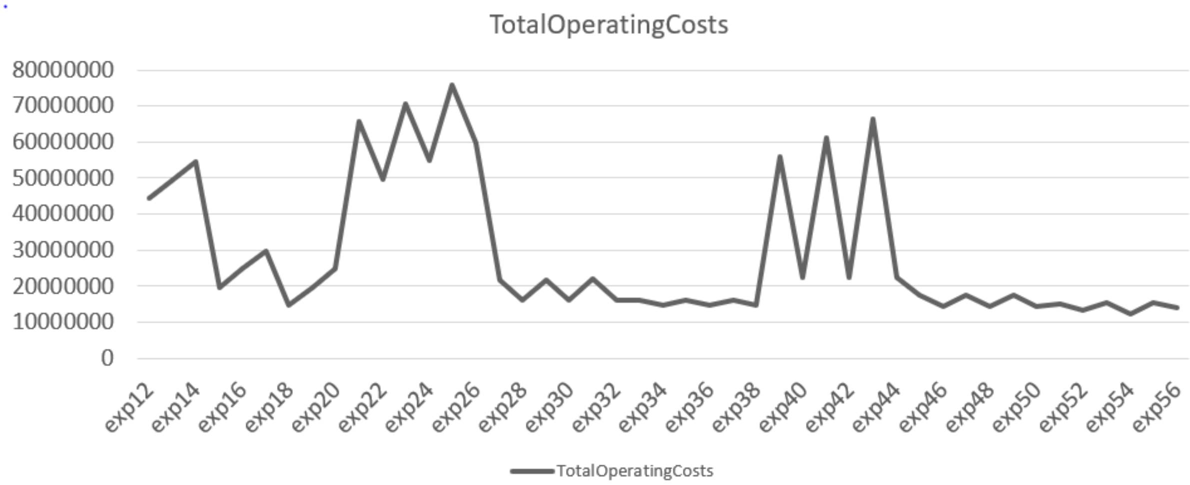

Figure 11. Operating costs for unmanned cargo aircraft in the scnearios without home bases

The settings used in the experiments 14, 21, 23, 25, 39, 41 and 43 can be seen in Table 22.

Table 22. Experiment settings used in experiments 14, 21, 24, 25, 39, 41 and 43

Exp	NrTrucks	NrUCA	AvgTimeBetweenOrders (min)	HomeBase	MinUtil	MaxTime (sec)	UCACapacity (tonnes)
14	0	11	4.29	FALSE	0.3	0	7
21	0	13	4.29	FALSE	0.3	10800	14
23	0	14	4.29	FALSE	0.3	10800	14
25	0	15	4.29	FALSE	0.3	10800	14
39	0	11	4.29	FALSE	0.3	10800	20
41	0	12	4.29	FALSE	0.3	10800	20
43	0	13	4.29	FALSE	0.3	10800	20

Experiment 14 is an experiment with 11 UCA in a scenario without home bases and the shortest interarrival time between the freight of 4:17 minutes. Among the experiments with an UCA capacity of 7 in a scenario without home bases, experiment 14 is the experiment in which the most UCA were used. Therefore it is logical to say that this experiment has the highest operating costs. In all of these experiments with a capacity of 7 in a scenario without home bases, it can be seen that with every possible interarrival time of the freight, the experiment with the highest number of UCA has the highest operating costs.

Experiment 21, 23 and 25 are experiments with the medium UCA type and a value of 0.3 was used here as the minimal utilization. The experiments 22, 24, 26 are the experiments with a medium type of UCA as well, but then with a minimal utilization of 0.5. Increasing this value results in a lower total operating costs, which is mainly due to an increase in waiting time, since UCA have to wait longer before they are allowed to start flying. In the other experiments with the medium UCA type but with other interarrival times between the freight, the same effect can be seen when looking at the experiments with different values for MinUtil. However, the change in interarrival time has a huge effect on the total operating costs as can be seen in the big decrease in total operating costs after experiment 26. Experiment 21 to 26 cover the shortest interarrival times, whereas experiments 27 to 32 and 33 to 38 cover the larger interarrival times between the freight.

For the peaks in experiments 39, 41 and 43, the same thing holds. In these experiments the value for MinUtil is 0.3 whereas for the subsequent experiments 40, 42 and 44, the value for MinUtil is 0.5. However, when the capacity is bigger, the same percentual difference for the value of MinUtil has an even bigger effect, since absolutely seen, more freight is needed when increasing the minimal utilisation before driving. Again the change in interarrival time has a big effect for the experiments with the large UCA as well. Experiments 39 to 56 cover these experiments with large UCA, in which experiment 45 to 56 are the experiments with the highest interarrival times between the freight.

In conclusion, this chapter provided a calculation of the number of UCA and trucks that were used in many experiments. The performance in these experiments in terms of CO_2 emissions, travel durations and operating costs were analysed, based on the several scenarios and interventions that were used. From these results, it can be learned that trucks do outperform UCA in terms of CO_2 emissions and operating costs, but not necessarily in terms of waiting times of the freight. For each of the 24 scenarios, the best performing experiment can be chosen. When the performance in terms of CO_2 emissions, operating costs and waiting time of the freight is valued equally important. The average value of those three could be taken per experiment. Per scenario, the best performing experiment would then be the experiment with the lowest average value. The best performing experiments per scenario can be seen below in Table 23.

Table 23. Best performing experiments per scenario

Scenario	Best performing experiment
1	12
2	16
3	18
4	21
5	32
6	34
7	40
8	46
9	54
10	0
11	1
12	2
13	3
14	4
15	5
16	6
17	7
18	8
19	59
20	67
21	71
22	9
23	10
24	11

The settings used in these experiments are the following and can be seen in Table 24.

Table 24. Settings of the best performing experiments

Exp	NrTrucks	NrUCA	AvgTimeBetweenOrders (min)	HomeBase	MinUtil	MaxTime (sec)	UCACapacity (tonnes)
12	0	9	4.29	FALSE	0	0	7

16	0	5	8.57	FALSE	0	0	7
18	0	3	12.86	FALSE	0	0	7
21	0	13	4.29	FALSE	0.3	10800	14
32	0	10	8.57	FALSE	0.5	10800	14
34	0	7	12.86	FALSE	0.5	10800	14
40	0	9	4.29	FALSE	0.5	10800	20
46	0	7	8.57	FALSE	0.5	10800	20
54	0	6	12.86	FALSE	0.5	10800	20
0	0	7	4.29	TRUE	X	X	7
1	0	7	8.57	TRUE	X	X	7
2	0	7	12.86	TRUE	X	X	7
3	0	7	4.29	TRUE	X	X	14
4	0	7	8.57	TRUE	X	X	14
5	0	7	12.86	TRUE	X	X	14
6	0	7	4.29	TRUE	X	X	20
7	0	7	8.57	TRUE	X	X	20
8	0	7	12.86	TRUE	X	X	20
59	15	0	4.29	FALSE	0.3	10800	X
67	12	0	8.57	FALSE	0.3	10800	X
71	9	0	12.86	FALSE	0.3	10800	X
9	7	0	4.29	TRUE	X	X	X
10	7	0	8.57	TRUE	X	X	X
11	7	0	12.86	TRUE	X	X	X

From this table of settings, it can be concluded that in the scenarios with UCA and without home bases, the use of a normal utilization almost always performs best. However, in the experiment with trucks and without home bases, the use of a low utilization always performs best. However, it need to be taken into account that those results would be different when the three performance measurements are not valued equally important.

6. Conclusion and recommendations

In this chapter, conclusions are drawn about the findings in the previous chapters. The performance of UCA is compared with the performance of trucks.

6.1 Conclusion

The company uses a hub and spoke system in the Netherlands in which they transport freight from seven locations towards Schiphol on a daily basis. At Schiphol, this freight is consolidated and handed over to a handling agency. Every day, at least one truck drives from each regional location to Schiphol and back. The volumes transported are not fixed and trailers are not per definition fully loaded.

UCA can be more productive and cheaper to operate than manned cargo aircraft and have advantages over other existing modes of transport. UCA have the highest potential in less developed countries and would be best performing in a market in which valuable and time-bound goods are transported. 76.6 percent of shippers have stated that they have one or more transportable goods that could be transported by UCA and 64 percent of shippers think UCA have good potential and have loads that they would like to have transported with UCA. The assumption is made that UCA would use 20% less fuel and emit 20% less CO_2, since van Groningen (2017) mentioned that the airframe of UCA would be 20% more light weight than a similar size manned aircraft and Bejan, Charles and Lorente mentioned that carried fuel of an aircraft is proportional to its weight. With this information and the emission factor of jet fuel, the CO_2 emissions for small, medium and heavy UCA are calculated to be respectively 1038.512, 1809.152 and 6597.856 kilograms per 250 kilometres. The CO_2 emission of trucks is 728 grams per kilometre. The operating costs for future UCA are calculated to be 2061.72, 2108.50 and 2158.53 dollars per hour for respectively light, medium and heavy UCA. The cruise speeds of future UCA are 358.5, 509.67 and 786 kilometres per hour for respectively light, medium and heavy UCA.

In terms of CO_2 emissions and operating costs, it can be concluded that trucks perform much better than UCA. First of all, this could be explained by the fact that the CO_2 emission factors and the operating costs in dollars per hour are much higher for UCA than for trucks. Although in many experiments, less UCA than trucks were used, they could not operate that efficiently to perform better in terms of CO_2 emissions and operating costs. For CO_2 emissions, it holds that all vehicles perform better when a higher utilization is used, due to a decreased number of trips. For the operating costs, it can be concluded that an increase in interarrival time between the freight has a big effect on the total operating costs when a scenario without home bases is simulated. Also, a higher value for the minimal utilization also leads to a decrease in operating costs due to an increase in waiting time. UCA and trucks do not deviate from each other too much, when looking at the time that freight needs to wait before getting picked up. However, it is not recommended to use a low number of UCA with low capacity when a lot of orders are arriving per time unit, because this does result in long waiting times for the freight. That also holds for using a low number of trucks.

The company could benefit from this experiment, since they could decide whether they would like to keep using their current feeder transport system or whether they would like to implement a new system with UCA, based on this research. If they would, their choice for the type and number of UCA should at least be based on the arrival rate of the freight, since this can affect waiting times of the freight a lot. One advise that would have a positive impact on operating costs and CO_2 emissions, is to use high utilizations.

6.2 Recommendations for further research

When more research would be done about the potential of unmanned cargo aircraft in comparison to trucks, it could be worth looking into the distances from which UCA are researched to become efficient. For this research, the estimated ranges from Prent and Koopman could be used. Also it could be an idea to look at a mixed system in which UCA and trucks are operating simultaneously. In such a system priority rules could be used, which would state when a truck would get priority over using an UCA, or the other way around.

With respect to the costs of using UCA, this research only emphasized on the UCA being in operation. It did not take into account the costs of infrastructure that would be needed to make UCA operational. This could be taken into account in further research.

The simulation model does not make use of data provided by the company, which results in the fact that the simulation results are not per definition the perfect fit for the company. This could be beneficial when it would be used in further research. Also, it could be taken into account that UCA would never travel with 125 kilometres per hour on average, since they have to deal with lower speeds while taking off and landing. This also holds for trucks, since they have to deal with slower speeds at the begin and end of their routes.

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Appendix 1

This appendix explains how all the different components of the simulation model work, together with their usefulness.

First, several definitions of terms used in this appendix are given.

- Moving Unit: A Moving Unit is an entity that moves around in the simulation model. In our model, this unit could represent freight, trucks or UCA.
- Tablefile: A two-dimensional table in which data can be stored in our simulation model.
- SingleProc: A station in our simulation model that holds a Moving Unit for the stated processing time, after which it passes it on.
- Buffer: A buffer stores moving units during a given time, when the next stations are unavailable.

A1.1 The root frame

In Figure A1.1, the so called root frame of the simulation model can be seen. This is the frame at which the movements of the several moving units are visualized. This is also the place where the simulation can be started by clicking on the method ‘StartSimulation’. All aspects of the model are explained in more detail in the next sections.

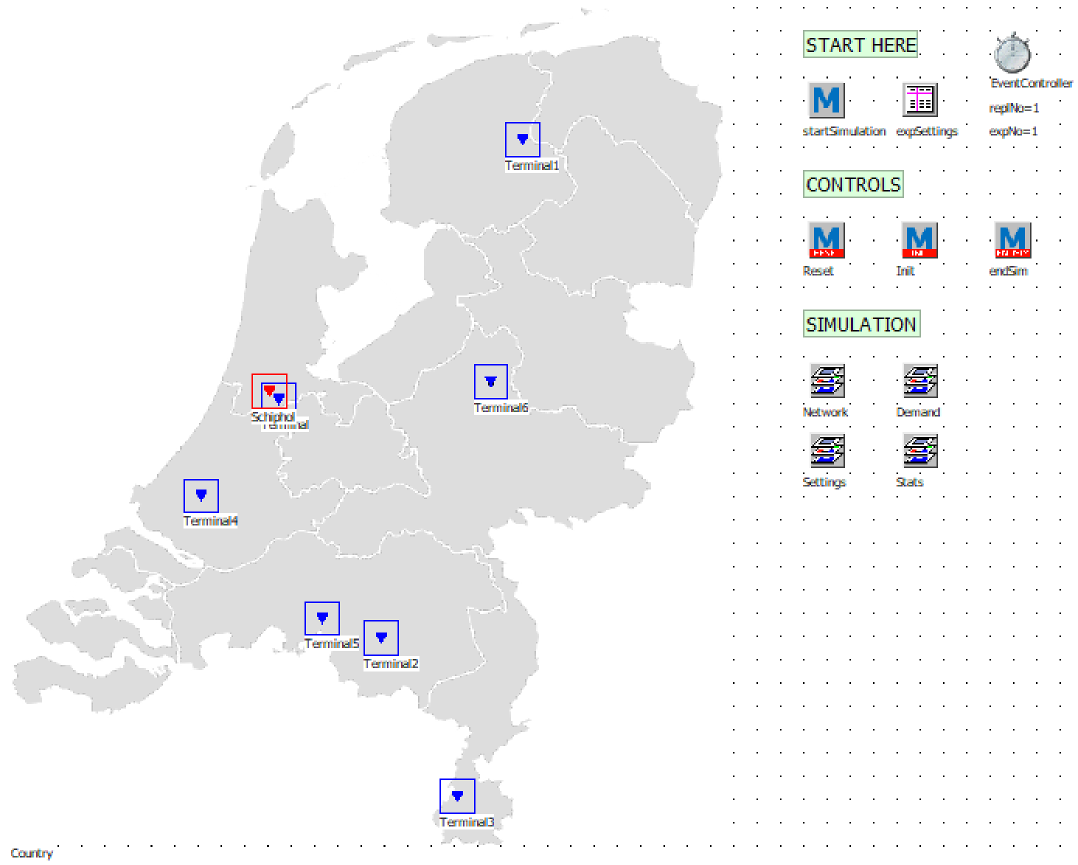

Figure A1.1.

A1.2 The country

The map of the Netherlands, is a frame as well. On this frame, 56 tracks are located. Each track can be seen as a unique road between two locations. When the simulation is running, the moving units will be moved along these tracks. Also, a method called ‘Arrival’ is located at this frame, which states what to do when a vehicle arrives at a certain location. This frame can be seen in Figure A1.2.

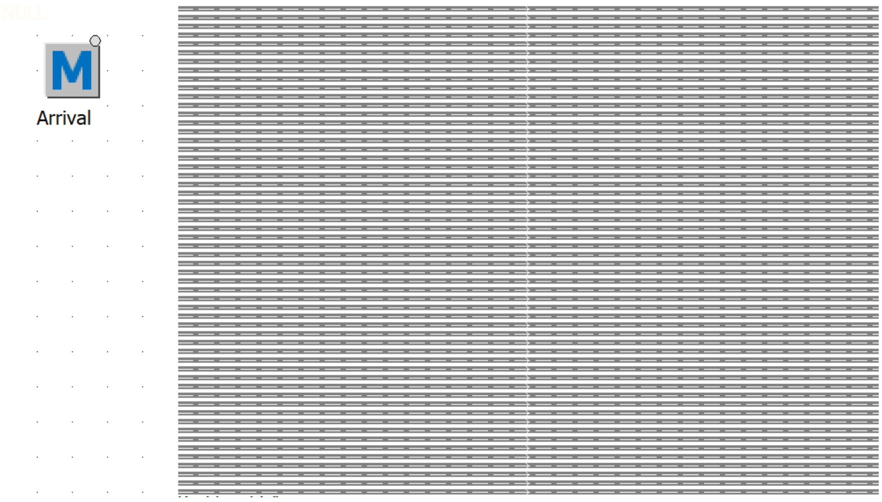

Figure A1.2.

A1.3 The terminals

As can be seen in Figure A1.3, seven terminals can be distinguished. These terminals are all frames. They are depicted on a map of the Netherlands on the places, where the company has their distribution centres. All terminals are made blue. The location of the company at Schiphol Airport is made red, since this location can be seen as the main hub where all freight gets transported to.

Each terminal consists of the same basic components, which can be seen below in Figure A1.3.

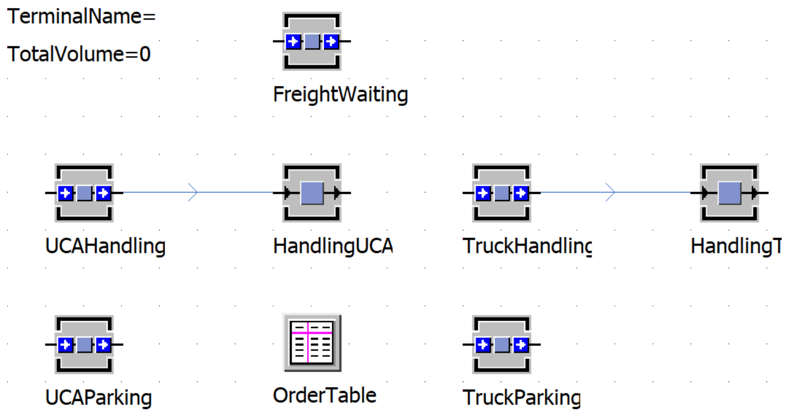

Figure A1.3.

Each terminal has its own unique name, which is the place where the terminal is located, which is for example Maastricht. The variable called ‘TotalVolume’ depicts the total volume of freight that is generated at a certain terminal. Each terminal consists of the same components for both UCA and trucks. When a vehicle arrives at a terminal, it always gets placed into the buffer called either ‘UCAParking’ or ‘TruckParking’. From there, it gets placed in the queue called either ‘UCAHandling’ or ‘TruckHandling’. The singleprocs called HandlingUCA or HandlingT make sure that the UCA gets handled in the terminal, before it is available for transport towards its destination.

The buffer called ‘FreightWaiting’ is a queue, where the freight is waiting that is not yet shipped towards its destination. In the tablefile called ‘OrderTable’, the statistics of the freight are written down. These include the volume of the freight and the time that a piece of freight is waiting at the terminal, before it gets loaded into a vehicle.

A1.4 Schiphol

At the main hub, Schiphol, the components of the frame are almost the same as on the frames of the terminals. It has its own name and just like at the other terminals, it consists of an UCA parking and an UCA handling as well as a singleproc to actually execute the handling. When a vehicle arrives at Schiphol, it can be either moved to the parking or to handling, depending on whether it is empty or not.

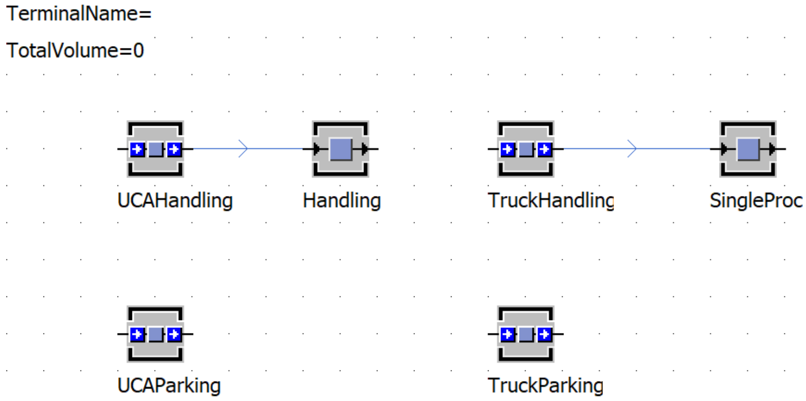

Figure A1.4.

A1.5 The Start

As can be seen in Figure A1.5 below, the start of the simulation model consists of two components.

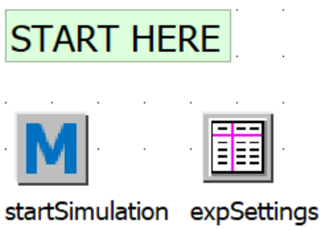

Figure A1.5.

The method called ‘StartSimulation’ works as a button, which can be clicked to let the simulation run. The tablefile called ‘expSettings’ contains all the settings that are used during the simulation. The name of these settings and their explanation are described below.

- KGCO2/250kmUCA: The number of kilograms of CO_2 an UCA emits when flying 250 kilometres
- OperatingCostsUCA: The operating costs of an UCA in dollars per hour
- GCO2/kmTruck: The number of grams of CO_2 a truck emits when driving 1 kilometre.
- OperatingCostsTruck: The operating costs of a truck in dollars per hour
- UCASpeed: The speed of an UCA in meters per second
- UCACapacity: The capacity of an UCA in tonnes
- Truckspeed: The speed of a truck in meters per second
- TruckCapacity: The capacity of a truck in tonnes
- NrTrucks: The total number of trucks
- NrUCA: The total number of UCA
- AvgTimeBetweenOrders: The average time between the generation of orders

- HomeBase: The distinction between a home base scenario and a scenario without home bases
- MinUtil: The minimum utilization of a vehicle before sending it towards its destination
- MaxTime: The maximum permissible waiting time of freight at a terminal
- UCAOnly: The distinction between a scenario with either UCA, or trucks only

A1.6 Initialization

As can be seen below in figure A1.6, the controls of the model consist of three methods. In Plant Simulation, the method 'Init' is the first method that will be executed when starting the simulation.

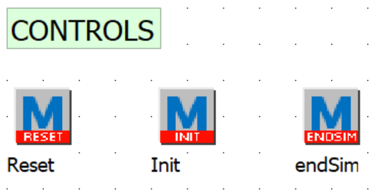

Figure A1.6.

In this method, the UCA or trucks get generated, depending on which scenario is chosen. When a home base scenario is chosen, seven UCA or trucks will be generated. This means each terminal is assigned one vehicle. In this case, the vehicles will be generated in the parking zone at the terminal that is their home base. In case of a scenario without home bases, the defined number of vehicles will all be generated at Schiphol. In the initialization phase, various so called user-defined attributes of the vehicles are given a value. In this phase, it means that for both UCA and trucks, their speed, capacity, operating costs and emission factors are defined. The total list of user-defined attributes for UCA are the following.

- KGCO_2_250km: The emission factor of the UCA in kilograms CO_2 emitted per 250 kilometres
- LastUpdate: The last moment in which an UCA is assigned a time in the simulation model
- OperatingCosts: The operating costs of flying an UCA in dollars per hour
- TheDest: The destination of the UCA
- TheOri: The origin of the UCA
- HomeBase: The terminal that is the home base of an UCA
- VolumeCapacity: The maximum capacity of an UCA in tonnes
- VolumeLoaded: The volume that is loaded in the UCA at a certain moment during the simulation.

The user-defined attributes for trucks are almost the same, despite the fact that 'KGCO2_250km' is called 'GCO2_km', since the emission factor of trucks is measured in grams CO_2 per kilometre.

Also in this phase, the generated vehicles are placed in a table, which is either called 'UCA' or 'Trucks', depending on the chosen scenario. At the end of this method, the method NewOrder gets called, about which more will be explained in section x.

A1.7 The simulation

As can be seen in Figure A1.7, the part of the root frame concerning the simulation, consists of four frames. Each frame and all of its components will be explained in the next sections.

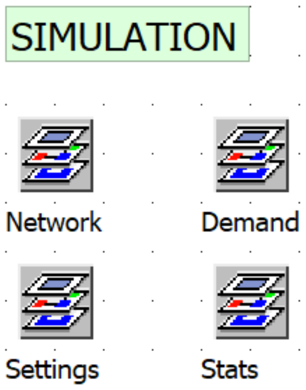

Figure A1.7.

A1.7.1 Network

The frame called 'Network', merely consists of tablefiles.

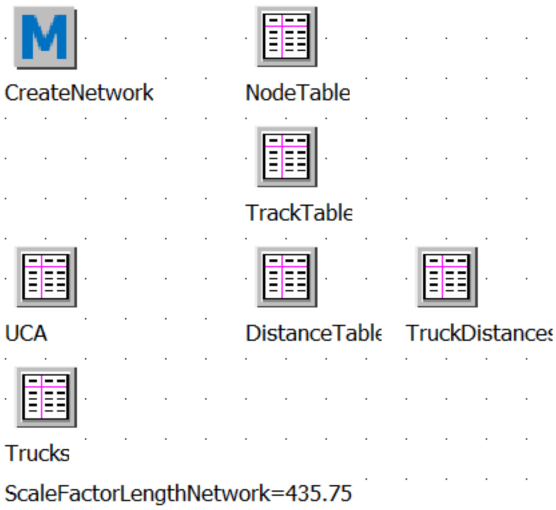

Figure A1.8.

The 'NodeTable' contains all the different locations. It also contains the amount of volume that is currently available at a location for getting shipped to its destination. Also it contains a column called 'WaitingForResource 'which states whether a certain terminal is still waiting for a vehicle or whether a vehicle is already on its way to this terminal. The last column denotes the maximum waiting time of the freight that is waiting at a terminal and is called 'MaxWaiting'.

The tablefile called 'TrackTable' is a matrix. All locations are the indexes of the rows and columns. The matrix is filled with all the different tracks, stating which track lays between which two locations. The tablefile called 'DistanceTable' is a matrix which contains the distances in meters between all locations. These are the distances, an UCA would fly, when flying straightforward all the time between two locations. In 'TruckDistances', the distances between two locations are denoted as well, but these are the distances, a truck need to travel between two locations, since a truck needs to follow roads and therefore travels longer distances.

In the tablefiles called 'UCA and 'Trucks', the vehicles are denoted, as well as their current location, destination and their availability.

A1.7.2 Settings

The frame called 'Settings' also merely consists of tablefiles as can be seen in Figure A1.9.

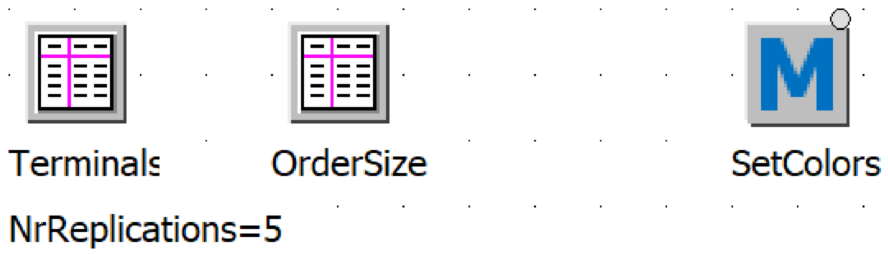

Figure A1.9.

In ‘Terminals’, the probabilities per terminal are denoted. These are the probabilities that freight will be generated at these terminals. The probabilities are equal for each terminal. Also the coordinates of these terminals on the map of the Netherlands are written down in this tablefile. Also, every location gets assigned its own colour. These colours are generated in the method ‘SetColors’ and are written down in ‘Terminals’. During the simulation, the freight gets the colour that belongs to the terminal where the freight was generated. In ‘OrderSize’, the probabilities that freight will have a certain volume are denoted. These volumes are between 1 and 5, all with equal probability.
The variable ‘NrReplications’ defines how many replications will be executed during each simulation experiment.

A1.7.3 Stats

The frame called ‘Stats’, consist of 12 tablefiles, as can be seen in Figure A1.10 below. All of them store the statistics of the simulation.

Figure A1.10.

Every row of three tablefiles stores a table of statistics with the same column names. However, every column stores the statistics for different moments during the simulation. During the simulation, the first column shows the statistics during the currently running replication. The second column, which contains the prefix ‘Repl’, stores the statistics for every replication during the currently running experiment. The third column, which contains the prefix ‘Exp’, stores the statistics for every experiment that was run.

The row that contains statistics about the UCA, stores the following statistics per UCA.

- TotalFlying: the total time an UCA has spent travelling between locations
- TotalWaiting: the total time an UCA has spent waiting in the UCA parkings
- TotalHandling: the total time an UCA has spent in the handling phase

- FlyingFull: The total time an UCA has travelled while carrying freight
- FlyingEmpty: The total time an UCA has travelled while carrying no freight
- TotalTrips: The total number of trips an UCA has travelled between all locations
- TotalShipments: The total amount of times an UCA has travelled while carrying freight
- TotalVolume: The total volume of freight an UCA has carried
- TotalOperatingCosts: The total operating costs of flying with the UCA
- TotalDistance: The total distance an UCA has travelled
- CO2Emission: The total amount of CO_2 an UCA has emitted while travelling
- Extratime: The time between the end of the simulation and the last updated time of the UCA

The row that contains the statistics about the trucks, contains the same statistics as the UCA. However, the only slight difference is that ‘Flying’ is changed into ‘Driving’ for trucks, since trucks obviously cannot fly.

The row that contains the statistics about the terminals, stores the following statistics per terminal.

- TotalLoads: The total number of loads that have been generated a terminal
- TotalVolume: The total volume of all loads that have been generated at a terminal
- TotalUCAParking: The total time an UCA has spent in the UCA parking at a terminal
- TotalHandling: The total time a vehicle has spent in the handling phase
- NrShipments: The total number of time a vehicle has carried freight from a terminal
- VolumeShipments: The total volume of the above mentioned shipments
- TotalTruckParking: The total time a truck has spent in the truck parking at a terminal
- TotalWaitFreight: The total time that all freight has spent waiting at terminal
- AvgWaitFreight: The average time a single piece of freight has spent waiting at a terminal

The row that contains the statistics about Schiphol, contains the same statistics as the terminals. However, the only difference is that the statistics about Schiphol do not contain ‘TotalWaitFreight’ and ‘AvgWaitFreight’, since freight only gets stored at terminals and not at Schiphol.

A1.7.4 Demand

As can be seen in Figure 13, the frame called ‘Demand’ consist of 8 methods, 1 generator and two variables. The function of each of these components will be explained in the following sections.

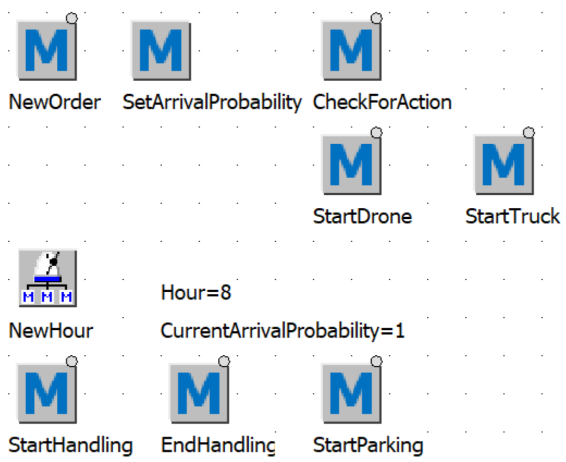

Figure A1.11.

A1.7.4.1 New order

After the initialization phase, new freight will be generated at the terminals. This happens in the method called ‘NewOrder’.

By means of a probability distribution, the freight gets generated at a certain terminal. The probability that freight is generated at a certain terminal, is equal for all terminals, except for Schiphol. No freight gets generated at Schiphol. When freight is generated in the waiting zone of a certain terminal, three kinds of attributes are given to the freight. These are the colour and the volume of the freight, as well as the time at which the freight is generated. The colour of the freight is chosen via the same probability distribution as with which freight was generated at a certain terminal. The volume of the freight gets determined via another probability distribution, in which the probability of all volumes between 1 and 5 is equal and equals 0.2. When the volume of the freight is determined, the total volume at a certain terminal is increased with this number as well.

The freight and it’s volume get written down in the order table of the corresponding terminal at which the freight is generated. In this table, the orders can be found that are not yet shipped to their destination. This list of orders is useful in determining whether freight will fit in the type of vehicle that is used or when determining how long freight is already waiting at a certain location. After generating the freight, it needs to get moved from the terminal, to its final destination. This happens in the following phases.

A1.7.4.2 Check for action

The first method that will be executed after the method ‘NewOrder’ is the method called ‘CheckForAction’. This method is the most complex method in the simulation model. There are two methods that could trigger this method: ‘NewOrder’ or ‘StartParking’. When freight is generated at a terminal in the method ‘NewOrder’, this terminal becomes the parameter in the method ‘CheckForAction’. When a vehicle has entered the parking zone of a terminal, the method ‘StartParking’ will execute the method ‘CheckForAction’ as well.

In this method, two scenarios can be distinguished: The terminal from which the method gets triggered is Schiphol, or it is not. In both these scenarios, another two scenarios can be distinguished: The type of vehicle is an UCA, or it is a truck. In the first scenario, where the terminal is Schiphol and the type of vehicle is an UCA, another two scenarios can be distinguished: A scenario in which a home base is used, or not. This also holds for the scenario in which the type of vehicle is a truck. In the scenario where the terminal that triggers the method is not Schiphol, there are three possible scenarios for both UCA and trucks: The UCA handling of the terminal is not empty, the UCA parking of the terminal is not empty, or none of these. All of this scenarios are numbered and can be seen in the conceptual model in Figure A1.12.

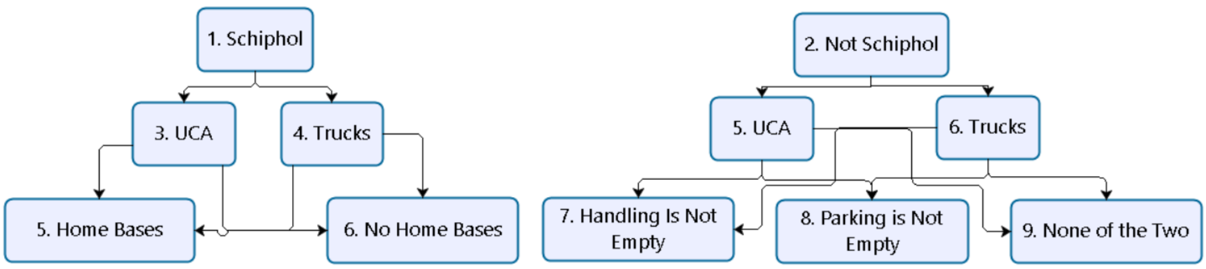

Figure A1.12.

Scenario 5 and 6 are the same for both UCA and trucks. This also holds for scenario 7, 8 and 9, so therefore, only these five scenarios will be explained into more detail in the next sections.

Scenario 5

In scenario 5, the method gets triggered from Schiphol and home bases are used. The vehicle that will be used is the first vehicle in line in the parking of Schiphol. The destination of this vehicle will be its home base, and the origin will be determined as its current location, which is Schiphol. Since freight cannot be generated at Schiphol, the volume that is loaded into the vehicle is set at zero. After all of this is determined, either the method ‘StartUCA’ or ‘StartTruck’ will be executed to make sure the vehicle starts moving.

Scenario 6

In scenario 6, the method gets triggered from Schiphol and no home bases are used. The vehicle that will be used is again the first vehicle in line in the parking of Schiphol. A table called ‘CandidateTerminals’ gets created from which the destination of a vehicle will be determined. In a for-loop, all terminals are passed. When the variable called ‘WaitingForResource’ is false, it means that no vehicle is already moving towards the corresponding terminal. When this is the case, a check is performed to see whether the terminal is a candidate terminal or not and could be added to the table called ‘CandidateTerminals’. The check checks whether the current available volume at a terminal is bigger than the minimum utilisation times the capacity of the vehicle or whether the maximum waiting time of the freight is bigger than the maximum permissible waiting time of the freight. Both the minimum utilisation and the maximum permissible waiting time can be found in the tablefile ‘ExpSettings’. When one of these is the case, the terminal gets added to ‘CandidateTerminals’. From all terminals that are in this list, one will be chosen randomly as the destination of the vehicle. Thereafter the availability of the vehicle will bet set as false and the vehicle is summoned to move.

Scenario 7

In scenario 7, the method gets triggered from another location than Schiphol and either UCA or trucks are used. In this scenario, there is a vehicle busy with handling, so the method does nothing and simply waits for a vehicle to become available.

Scenario 8

In scenario 8, the parking is not empty. This means that there is a vehicle available at the terminal. The vehicle that will be used, is the first vehicle in line in the parking. Before anything will be done at the terminal, the first check that is performed, concerns the variables ‘MinUtil’ and ‘MaxTime’ which can be found in the tablefile ‘ExpSettings’. When the available volume of freight at the terminal, is not bigger than the variable ‘MinUtil’ times the volumecapacity of the vehicle or the maximum waiting time of the freight is not bigger than the maximum permissible waiting time, the rest of the method will not be executed. When it is, the variable ‘remainingcapacity’ is determined as the capacity of the vehicle. The first order in the order table of the terminal gets checked. When this order has a lower volume than the capacity of the vehicle, it gets moved into the vehicle and the total volume that is loaded into the vehicle gets updated with the volume of the order. The volume of the order gets subtracted from the variable ‘remainingcapacity’ and after that, the next orders will be checked, until no order fits in the vehicle anymore. All orders that are moved into the vehicle, will be deleted from the order table of the terminal. After this, the destination of the vehicle gets determined as Schiphol and the Truck will be set as unavailable. In the NodeTable it will be set that the terminal is not waiting for a vehicle and the volume that is available at the terminal will be subtracted with the volume that is loaded into the vehicle. After all of this, either the method ‘StartUCA’ or ‘StartTruck’ will be executed.

Scenario 9

Scenario 9 is the scenario in which no vehicle is present at a terminal. When no vehicle is already going to this terminal, and there is no home base scenario, all vehicles are scanned and if one of them is still available, it will be used. When the volume at the terminal is bigger than the volume capacity of the available vehicle times the value of the variable 'MinUtil' or when the maximum waiting time of the freight is bigger than the maximum permissible waiting time, then the destination of this vehicle is set as the terminal and the origin is the current location of the vehicle. This origin can be any terminal, since there is no home base scenario. The vehicle is set as unavailable and the volume that is loaded in the vehicle is set as zero. After this either the method 'StartUCA' or 'StartTruck' is called.

A1.7.4.3 Start UCA and Start Truck

These are the methods that are called when a vehicle needs to start moving from a certain location to another. This method states that a vehicle can only be moved when the variable 'WaitingForResource' is set as true. This is done to prevent a vehicle from going towards a location where another vehicle is going to already. The track that will be used for moving the vehicle, will be the track that corresponds with the determined origin and destination from the method 'CheckForAction'. This track will be taken from the earlier mentioned tablefile called 'TrackTable'. When this track is determined, the vehicle gets a command to start moving over it.

A1.7.4.4 Arrival

When a vehicle is send over the track, it arrives at its destination. A separate method called 'Arrival', takes care of the arrival process. When a vehicle arrives at a terminal, which is its destination, this destination becomes his current location in the tablefile called either 'UCA' or 'Trucks'. When a vehicle is loaded with freight and arrives at Schiphol, it is directly send to handling. In any other situation, the vehicle is moved to the parking.

A1.7.4.5 Start Handling

The method 'StartHandling' only stores statistics. It gets triggered when a vehicle enters the handling phase of either a terminal or Schiphol. In this method, a difference is made between UCA and trucks. For both of them, the same statistics are denoted. First of all, the parking time is calculated as the current simulation time when the method gets executed, minus the last updated time of the moving unit that triggers the method. Thereafter, the total waiting time of the corresponding moving unit is increased with the just calculated parking time. Subsequently, a difference is made between Schiphol and the other terminals. When the origin of the triggering moving unit is Schiphol, then either 'TotalUCAParking' or 'TotalTruckParking' in the tablefile SchipholStats gets increased with the just calculated parking time. When the origin of the triggering moving unit is not Schiphol, either 'TotalUCAParking' or 'TotalTruckParking' in the tablefile TerminalStats gets increased with the just calculated parking time. At the end of the method, the user-defined attribute 'lastupdate' of the triggering moving unit gets updated again with the current simulation time at which the method is executed.

A1.7.4.6 End Handling

In this method, statistics get stored, but moving units get moved as well. For either UCA or trucks, the handling time of the triggering moving unit gets calculated the same way. This method gets executed when the handling time of a moving unit in the handling phase is over. The variable 'HandlingTime', can be calculated as the current simulation time of executing the method, minus the last update of the triggering moving unit. In either the tablefile 'UCAStats' or 'TruckStats' , the total handling time gets increased with the just calculated handling time. Thereafter, a difference is made between Schiphol and the other terminals. When the location of the moving unit that triggers the method is Schiphol, then the column called 'TotalHandling' in the tablefile called 'SchipholStats' gets increased with the just calculated handling time. When the location of the moving unit that triggers the method is not Schiphol, then the column called ‘TotalHandling’ in the tablefile called ‘TerminalStats’ gets updated with the just calculated handling time. After adding these statistics, the user-defined attribute ‘lastupdate’ of the triggering moving unit gets updated again with the current simulation time at which the method is executed.

In the rest of this method, moving units get moved. For both trucks and UCA, this process is the same. For the moving unit that triggers the method, a difference is made between Schiphol and the other terminals. When the location of this moving unit is not Schiphol, but another terminal, either the method ‘StartUCA’ or ‘StartTruck’ gets executed directly, to start moving the vehicle from its origin to its destination. When the location of the moving unit is Schiphol, the freight that is in in the vehicle, gets deleted. The user-defined attributes ‘theDest’ and ‘theOri’ are made empty and the user-defined attribute ‘VolumeLoaded’ is set to zero. In either the tablefile ‘UCA or ‘Trucks’, the destination of the vehicle is made empty and the availability of the vehicle is set as true. After this, the vehicle gets moved to the UCAparking of Schiphol.

A1.8 EndSim

As could be seen in Figure A1.6, the controls of the simulation model consist of 3 methods. In Plant Simulation, the method called ‘EndSim’ is always the last method that gets executed at the end of a simulation run. In this method, the statistics per replication and per experiment are collected. This method checks whether the current replication number is smaller than the number of replications set in the settings. When this is the case, a new replications gets started. This also holds for the experiments.

A1.9 Reset

The method called reset is also part of the 3 control methods of the model. It gets triggered before the start of every new simulation run. It deletes all movables and it deletes all the statistics in the tablefiles ‘UCAStats’, ‘TruckStats’, ‘TerminalStats’ and ‘SchipholStats’. When a new experiment gets started, it means that the replication number is 1. When that is the case, the tablefiles ‘UCA’ and ‘Trucks’ get emptied, which means that no UCA has still assigned a current location, destination or availability. When the replication number is not 1, the column ‘WaitingForResource’ in the tablefile ‘NodeTable’ gets emptied. In this NodeTable, the column ‘VolumeAvailable’ is set to zero and ‘WaitingForResource’ is set to false, since at the start of every new experiment, no terminal is already waiting for a vehicle to come. Also, all order tables of all terminals get emptied, and the total volume per terminal is set to zero.

Appendix 2

In this appendix, the scenarios of the experiments can be seen.

Table A2. 1. All possible experiment scenarios

Scenario	UCACapacity	AverageTimeBetweenOrders	HomeBase	UCAOnly
1	7	4:17	FALSE	TRUE
2	7	8:34	FALSE	TRUE
3	7	12:51	FALSE	TRUE
4	14	4:17	FALSE	TRUE
5	14	8:34	FALSE	TRUE
6	14	12:51	FALSE	TRUE
7	20	4:17	FALSE	TRUE
8	20	8:34	FALSE	TRUE
9	20	12:51	FALSE	TRUE
10	7	4:17	TRUE	TRUE
11	7	8:34	TRUE	TRUE
12	7	12:51	TRUE	TRUE
13	14	4:17	TRUE	TRUE
14	14	8:34	TRUE	TRUE
15	14	12:51	TRUE	TRUE
16	20	4:17	TRUE	TRUE
17	20	8:34	TRUE	TRUE
18	20	12:51	TRUE	TRUE
19	25	4:17	FALSE	FALSE
20	25	8:34	FALSE	FALSE
21	25	12:51	FALSE	FALSE
22	25	4:17	TRUE	FALSE
23	25	8:34	TRUE	FALSE
24	25	12:51	TRUE	FALSE

Appendix 3

In this appendix, all possible configurations of the settings that are varied during the experiments can be seen.

Experiment	NrTrucks	NrUCA	AvgTimeBetweenOrders (minutes)	ThuisBasis	MinUtil	MaxTime (seconds)	UCACapacity (tonnes)	UCAOnly
exp0	0	7	4.29	TRUE	X	X	7	TRUE
exp1	0	7	8.57	TRUE	X	X	7	TRUE
exp2	0	7	12.86	TRUE	X	X	7	TRUE
exp3	0	7	4.29	TRUE	X	X	14	TRUE
exp4	0	7	8.57	TRUE	X	X	14	TRUE
exp5	0	7	12.86	TRUE	X	X	14	TRUE
exp6	0	7	4.29	TRUE	X	X	20	TRUE
exp7	0	7	8.57	TRUE	X	X	20	TRUE
exp8	0	7	12.86	TRUE	X	X	20	TRUE

Figure A3. 1. Experiment settings for a home base scenario with small UCA

Experiment	NrTrucks	NrUCA	AvgTimeBetweenOrders (minutes)	ThuisBasis	MinUtil	MaxTime (seconds)	UCACapacity (tonnes)	UCAOnly
exp9	7	0	4.29	TRUE	X	X	0	FALSE
exp10	7	0	8.57	TRUE	X	X	0	FALSE
exp11	7	0	12.86	TRUE	X	X	0	FALSE

Figure A3. 2. Experiment settings for a home base scenario with trucks

Experiment	NrTrucks	NrUCA	AvgTimeBetweenOrders (minutes)	ThuisBasis	MinUtil	MaxTime (seconds)	UCACapacity (tonnes)	UCAOnly
exp12	0	9	4.29	FALSE	0	0	7	TRUE
exp13	0	10	4.29	FALSE	0	0	7	TRUE
exp14	0	11	4.29	FALSE	0	0	7	TRUE
exp15	0	4	8.57	FALSE	0	0	7	TRUE
exp16	0	5	8.57	FALSE	0	0	7	TRUE
exp17	0	6	8.57	FALSE	0	0	7	TRUE
exp18	0	3	12.86	FALSE	0	0	7	TRUE
exp19	0	4	12.86	FALSE	0	0	7	TRUE
exp20	0	5	12.86	FALSE	0	0	7	TRUE

Figure A3. 3. Experiment settings for a non home base scenario with small UCA

Experiment	NrTrucks	NrUCA	AvgTimeBetweenOrders (minutes)	ThuisBasis	MinUtil	MaxTime (seconds)	UCACapacity (tonnes)	UCAOnly
exp21	0	13	4.29	FALSE	0.3	10800	14	TRUE
exp22	0	10	4.29	FALSE	0.5	10800	14	TRUE
exp23	0	14	4.29	FALSE	0.3	10800	14	TRUE
exp24	0	11	4.29	FALSE	0.5	10800	14	TRUE
exp25	0	15	4.29	FALSE	0.3	10800	14	TRUE
exp26	0	12	4.29	FALSE	0.5	10800	14	TRUE
exp27	0	10	8.57	FALSE	0.3	10800	14	TRUE
exp28	0	8	8.57	FALSE	0.5	10800	14	TRUE
exp29	0	11	8.57	FALSE	0.3	10800	14	TRUE
exp30	0	9	8.57	FALSE	0.5	10800	14	TRUE
exp31	0	12	8.57	FALSE	0.3	10800	14	TRUE
exp32	0	10	8.57	FALSE	0.5	10800	14	TRUE
exp33	0	9	12.86	FALSE	0.3	10800	14	TRUE
exp34	0	7	12.86	FALSE	0.5	10800	14	TRUE
exp35	0	10	12.86	FALSE	0.3	10800	14	TRUE
exp36	0	8	12.86	FALSE	0.5	10800	14	TRUE
exp37	0	11	12.86	FALSE	0.3	10800	14	TRUE
exp38	0	9	12.86	FALSE	0.5	10800	14	TRUE

Figure A3. 4. Experiment settings for a non home base scenario with medium UCA

Experiment	NrTrucks	NrUCA	AvgTimeBetweenOrders (minutes)	ThuisBasis	MinUtil	MaxTime (seconds)	UCACapacity (tonnes)	UCAOnly
exp39	0	11	4.29	FALSE	0.3	10800	20	TRUE
exp40	0	9	4.29	FALSE	0.5	10800	20	TRUE
exp41	0	12	4.29	FALSE	0.3	10800	20	TRUE
exp42	0	10	4.29	FALSE	0.5	10800	20	TRUE
exp43	0	13	4.29	FALSE	0.3	10800	20	TRUE
exp44	0	11	4.29	FALSE	0.5	10800	20	TRUE
exp45	0	9	8.57	FALSE	0.3	10800	20	TRUE
exp46	0	7	8.57	FALSE	0.5	10800	20	TRUE
exp47	0	10	8.57	FALSE	0.3	10800	20	TRUE
exp48	0	8	8.57	FALSE	0.5	10800	20	TRUE
exp49	0	11	8.57	FALSE	0.3	10800	20	TRUE
exp50	0	9	8.57	FALSE	0.5	10800	20	TRUE
exp51	0	8	12.86	FALSE	0.3	10800	20	TRUE
exp52	0	5	12.86	FALSE	0.5	10800	20	TRUE
exp53	0	9	12.86	FALSE	0.3	10800	20	TRUE
exp54	0	6	12.86	FALSE	0.5	10800	20	TRUE
exp55	0	10	12.86	FALSE	0.3	10800	20	TRUE
exp56	0	7	12.86	FALSE	0.5	10800	20	TRUE

Figure A3. 5. Experiment settings for a non home base scenario with large UCA

Experiment	NrTrucks	NrUCA	AvgTimeBetweenOrders (minutes)	ThuisBasis	MinUtil	MaxTime (seconds)	UCACapacity (tonnes)	UCAOnly
exp57	14	0	4.29	FALSE	0.3	10800	X	FALSE
exp58	11	0	4.29	FALSE	0.5	10800	X	FALSE
exp59	15	0	4.29	FALSE	0.3	10800	X	FALSE
exp60	12	0	4.29	FALSE	0.5	10800	X	FALSE
exp61	16	0	4.29	FALSE	0.3	10800	X	FALSE
exp62	13	0	4.29	FALSE	0.5	10800	X	FALSE
exp63	10	0	8.57	FALSE	0.3	10800	X	FALSE
exp64	9	0	8.57	FALSE	0.5	10800	X	FALSE
exp65	11	0	8.57	FALSE	0.3	10800	X	FALSE
exp66	10	0	8.57	FALSE	0.5	10800	X	FALSE
exp67	12	0	8.57	FALSE	0.3	10800	X	FALSE
exp68	11	0	8.57	FALSE	0.5	10800	X	FALSE
exp69	8	0	12.86	FALSE	0.3	10800	X	FALSE
exp70	4	0	12.86	FALSE	0.5	10800	X	FALSE
exp71	9	0	12.86	FALSE	0.3	10800	X	FALSE
exp72	5	0	12.86	FALSE	0.5	10800	X	FALSE
exp73	10	0	12.86	FALSE	0.3	10800	X	FALSE
exp74	6	0	12.86	FALSE	0.5	10800	X	FALSE

Figure A3. 6. Experiment settings for a non home base scenario with trucks

Appendix 4

UCA capacity	7	14	20	
MinUtil	Average load size	Average load size	Average load size	
0.5	3.5	7	10	
0.3	2.1	4.2	6	
0	0	0	0	
MinUtil	# loads needed	# loads needed	# loads needed	
0.5	1.166666667	2.333333333	3.333333333	
0.3	0.7	1.4	2	
0	0	0	0	
So how long before flying?				
With 30 minutes per terminal and MinUtil 0.5	35	70	100	minutes
With 60 minutes per terminal and MinUtil 0.5	70	140	200	minutes
With 90 minutes per terminal and MinUtil 0.5	105	210	300	minutes
With 30 minutes per terminal and MinUtil 0.3	21	42	60	minutes
With 60 minutes per terminal and MinUtil 0.3	42	84	120	minutes
With 90 minutes per terminal and MinUtil 0.3	63	126	180	minutes
With 30 minutes per terminal and MinUtil 0	0	0	0	minutes
With 60 minutes per terminal and MinUtil 0	0	0	0	minutes
With 90 minutes per terminal and MinUtil 0	0	0	0	minutes

Figure A4.1 Calculation of the average load sizes, number of loads needed and average time before fyling of UCA

Correction for maximal permissible waiting time				
With 30 minutes per terminal and MinUtil 0.5	35	70	100	minutes
With 60 minutes per terminal and MinUtil 0.5	70	140	180	minutes
With 90 minutes per terminal and MinUtil 0.5	105	180	180	minutes
With 30 minutes per terminal and MinUtil 0.3	21	42	60	minutes
With 60 minutes per terminal and MinUtil 0.3	42	84	120	minutes
With 90 minutes per terminal and MinUtil 0.3	63	126	180	minutes
With 30 minutes per terminal and MinUtil 0	0	0	0	minutes
With 60 minutes per terminal and MinUtil 0	0	0	0	minutes
With 90 minutes per terminal and MinUtil 0	0	0	0	minutes

Figure A4.2. Average time before an UCA starts flying, corrected fort he maximal permissible waiting time

	Distance table UCA	
	4632.086038	
	133417.0865	
	101409.0522	
	167083.2791	
	46893.26009	
	87204.45174	
	82865.85698	
	Average is	
	89072.15323	metres
UCA Speed	125	m/s
which is	712.5772258	seconds on average
which is	11.8762871	minutes on average
Handling time is	15	minutes
So back and forth is	38.75257419	minutes on average

Figure A4.3. Calculation of the average travelling time of an UCA

UCA capacity	**7**	**14**	**20**	
Average time from UCA take-off until freight arrival				
With 30 minutes per terminal and MinUtil 0.5	73.75257419	108.7525742	138.7525742	minutes
With 60 minutes per terminal and MinUtil 0.5	108.7525742	178.7525742	238.7525742	minutes
With 90 minutes per terminal and MinUtil 0.5	143.7525742	248.7525742	338.7525742	minutes
With 30 minutes per terminal and MinUtil 0.3	59.75257419	80.75257419	98.75257419	minutes
With 60 minutes per terminal and MinUtil 0.3	80.75257419	122.7525742	158.7525742	minutes
With 90 minutes per terminal and MinUtil 0.3	101.7525742	164.7525742	218.7525742	minutes
With 30 minutes per terminal and MinUtil 0	38.75257419	38.75257419	38.75257419	minutes
With 60 minutes per terminal and MinUtil 0	38.75257419	38.75257419	38.75257419	minutes
With 90 minutes per terminal and MinUtil 0	38.75257419	38.75257419	38.75257419	minutes

Figure A4.4. The average travel time from UCA take-off until freight arrival

UCA capacity	**7**	**14**	**20**	
Average load in UCA with a minimal utilisation of	Average load			
0.5	3.5	7	10	tonnes
0.3	2.1	4.2	6	tonnes
0	3			tonnes
So number of loads needed with an utilisation of	Total loads needed	Total loads needed	Total loads needed	
0.5	28800	14400	10080	with 30 minutes
0.5	14400	7200	5040	with 60 minutes
0.5	9600	4800	3360	with 90 minutes
0.3	48000	24000	16800	with 30 minutes
0.3	24000	12000	8400	with 60 minutes
0.3	16000	8000	5600	with 90 minutes
0	33600			
0	16800			
0	11200			

Figure A4.5. Calculation of the average load in an UCA per UCA type and value for MinUtil as well as a calculation fort he number of loads needed per UCA type, value for MinUtil and interarrival time of the freight

Nr. UCA with cap 14 and MinUtil 0.5	With 30 minutes	With 60 minutes	With 90 minutes	Nr. UCA with cap 20 and MinUtil 0.5	With 30 minutes	With 60 minutes	With 90 minutes
1	14400	7200	4800	1	10080	5040	3360
2	7200	3600	2400	2	5040	2520	1680
3	4800	2400	1600	3	3360	1680	1120
4	3600	1800	1200	4	2520	1260	840
5	2880	1440	960	5	2016	1008	672
6	2400	1200	800	6	1680	840	560
7	2057.142857	1028.571429	685.7142857	7	1440	720	480
8	1800	900	600	8	1260	630	420
9	1600	800	533.3333333	9	1120	560	373.3333333
10	1440	720	480	10	1008	504	
11	1309.090909			11	916.3636364		
12	1200						

Figure A4.6. The total loads that can be transported by a medium and large type of UCA with a value for MinUtil of 0.5

Nr. UCA with cap 14 and MinUtil 0.3	With 30 minutes	With 60 minutes	With 90 minutes	Nr. UCA with cap 20 and MinUtil 0.3	With 30 minutes	With 60 minutes	With 90 minutes
1	24000	12000	8000	1	16800	8400	5600
2	12000	6000	4000	2	8400	4200	2800
3	8000	4000	2666.666667	3	5600	2800	1866.666667
4	6000	3000	2000	4	4200	2100	1400
5	4800	2400	1600	5	3360	1680	1120
6	4000	2000	1333.333333	6	2800	1400	933.3333333
7	3428.571429	1714.285714	1142.857143	7	2400	1200	800
8	3000	1500	1000	8	2100	1050	700
9	2666.666667	1333.333333	888.8888889	9	1866.666667	933.3333333	622.2222222
10	2400	1200	800	10	1680	840	560
11	2181.818182	1090.909091	727.2727273	11	1527.272727	763.6363636	509.0909091
12	2000	1000	666.6666667	12	1400	700	466.6666667
13	1846.153846	923.0769231	615.3846154	13	1292.307692	646.1538462	430.7692308
14	1714.285714	857.1428571	571.4285714	14	1200	600	400
15	1600	800	533.3333333	15	1120	560	
16	1500	750		16	1050		
17	1411.764706						

Figure A4.7. The total loads that can be transported by a medium and large type of UCA with a value for MinUtil of 0.3

Nr. UCA with cap 7 and MinUtil 0.0	With 30 minutes	With 60 minutes	With 90 minutes
1	33600	16800	11200
2	16800	8400	5600
3	11200	5600	3733.333333
4	8400	4200	2800
5	6720	3360	2240
6	5600	2800	1866.666667
7	4800	2400	1600
8	4200	2100	1400
9	3733.333333	1866.666667	1244.444444
10	3360	1680	1120
11	3054.545455	1527.272727	1018.181818
12	2800	1400	933.3333333
13	2584.615385	1292.307692	861.5384615
14	2400	1200	
15	2240		
16	2100		

Figure A4.8. The total loads that can be transported by a small type of UCA

Average number of minutes needed	With 30 minutes	With 60 minutes	With 90 minutes	Average number of minutes needed	With 30 minutes	With 60 minutes	With 90 minutes
Number of UCA				Number of UCA			
1	1566037.068	1287018.534	1194012.356	1	1398625.948	1203312.974	1138208.649
2	783018.5342	643509.2671	597006.1781	2	699312.9739	601656.487	569104.3246
3	522012.3561	429006.1781	398004.1187	3	466208.6493	401104.3246	379402.8831
4	391509.2671	321754.6335	298503.089	4	349656.487	300828.2435	284552.1623
5	313207.4137	257403.7068	238802.4712	5	279725.1896	240662.5948	227641.7299
6	261006.1781	214503.089	199002.0594	6	233104.3246	200552.1623	189701.4415
7	223719.5812	183859.7906	170573.1937	7	199803.7068	171901.8534	162601.2356
8	195754.6335	160877.3168	149251.5445	8	174828.2435	150414.1217	142276.0812
9	174004.1187	143002.0594	132668.0396	9	155402.8831	133701.4415	126467.6277
10	156603.7068	128701.8534	119401.2356	10	139862.5948	120331.2974	
11	142367.0062			11	127147.8134		
12	130503.089						

Figure A4.9. The calculation of the minimal number of UCA needed

Average number of minutes needed	With 30 minutes	With 60 minutes	With 90 minutes	Average number of minutes needed	With 30 minutes	With 60 minutes	With 90 minutes
Number of UCA				Number of UCA			
1	1938061.781	1473030.89	1318020.594	1	1659043.246	1333521.623	1225014.415
2	969030.8903	736515.4452	659010.2968	2	829521.6232	666760.8116	612507.2077
3	646020.5935	491010.2968	439340.1978	3	553014.4155	444507.2077	408338.1385
4	484515.4452	368257.7226	329505.1484	4	414760.8116	333380.4058	306253.6039
5	387612.3561	294606.1781	263604.1187	5	331808.6493	266704.3246	245002.8831
6	323010.2968	245505.1484	219670.0989	6	276507.2077	222253.6039	204169.0692
7	276865.9687	210432.9843	188288.6562	7	237006.1781	190503.089	175002.0594
8	242257.7226	184128.8613	164752.5742	8	207380.4058	166690.2029	153126.8019
9	215340.1978	163670.0989	146446.7326	9	184338.1385	148169.0692	136112.7128
10	193806.1781	147303.089	131802.0594	10	165904.3246	133352.1623	122501.4415
11	176187.4346	133911.8991	119820.054	11	150822.1133	121229.2385	
12	161505.1484	122752.5742		12	138253.6039		
13	149081.6754			13	127618.7113		
14	138432.9843						
15	129204.1187						

Figure A4.10. The calculation of the minimal number of UCA needed

Average number of minutes needed	With 30 minutes	With 60 minutes	With 90 minutes
Number of UCA			
1	1302086.493	651043.2464	434028.831
2	651043.2464	325521.6232	217014.4155
3	434028.831	217014.4155	144676.277
4	325521.6232	162760.8116	108507.2077
5	260417.2986	130208.6493	86805.76619
6	217014.4155	108507.2077	
7	186012.3561		
8	162760.8116		
9	144676.277		
10	130208.6493		
11	118371.4994		

Figure A4.11. The calculation of the minimal number of UCA needed