Aerial Transport System Design

Design of an Aerial Transport System for last mile parcel distribution with Unmanned Aerial Vehicles

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EXECUTIVE SUMMARY

Unmanned Aerial Vehicles (UAVs), also known as drones are aircraft with no human pilot on-board to perform controlling actions to the aircraft. In the past decades the military has been the driving force behind the development of UAV technology, but with the UAV technology becoming more accessible in the past years, the interest of companies for commercial applications of UAVs has been steadily increasing.

PostNL, a Dutch postal and parcel carrier active in the logistics industry, is also interested in the future application of UAV technology in their last mile parcel distribution logistics operations. Despite the recent developments and efforts of several companies, such as Amazon, Google and DHL in researching the application of UAVs for last mile distribution of goods, there remains a lack the knowledge and understanding on integrating UAVs in last mile parcel distribution.

The goal of this research was therefore to design a system, further referred to as the Aerial Transport System (ATS) for last mile parcel distribution. Where engineering Design literature has been used as a reference framework during the design process.

First the current state on last mile parcel distribution was analysed. Existing parcel services are characterised by the offered transit time and limitations in size and weight of parcels. While same-day courier services offer point-to-point transportation , express and regular parcel services use hub and spoke distribution networks to make time and day (un)certain deliveries. In the Netherlands, PostNL also uses a hub & spoke distribution network. In the distribution process, parcels are collected in the afternoon, sorted, transported and cross-docked overnight, sorted for a second time and finally delivered to the final destination in the morning. To measure the performance of the distribution process PostNL uses three KPI's which include customer satisfaction, delivery costs and environmental impact. All sub processes in the distribution process are scheduled in advance and have fixed cut-off times. As a result all these processes lie in the critical path of the distribution process and when a parcel does not reach the cut-off time of the process, it will have to wait until the next day to be distributed. In addition, parcels are pushed towards consumers who have almost no control over, when where or how they receive their parcels and the network is only capable of next-day delivery.

According to future state strategy of PostNL for 2020 , the trends influencing the future environment of last mile parcel distribution are urbanization, sustainability and demand for faster and more customer oriented parcel services. Based on these trends it is expected that the main opportunities for UAVs in the future last mile parcel distribution process lie in same-day and on-demand collection and delivery of parcels in densely populated areas.

The conceptual design of the ATS consists of a functional design for the equipment that includes payload containers, UAVs, docking platforms and (micro-)depots. Payload containers are consid-

ered to be parcels with size and weight limitations (as already used today) based on the payload capacity limitations of the UAVs used for transportation. Docking platforms perform loading and unloading of parcels or exchange batteries and (micro-)depots located at collection and delivery points, that have one or more docking platforms and store parcels before being transferred and transported. In this manner a large and dense network of (micro-)depots can be deployed in an urban environment and fixed routes between the (micro-)depots can be used to obtain a closed system. Further, due to the uncertainties in parcel demand, the system is controlled by a centralized dispatching control system, that can use various dispatching policies to make decisions on which parcels are transported by what UAVs.

In the detailed design of the system has been tested in two cases, namely for The Hague and Goes accordingly the most densely populated area and least densely populated areas in the Netherlands. The experiments in the detailed design included alternative dispatching policies for the control system and various values of the speed and endurance, and multi-payload carrying capacity operational characteristics of the UAVs.

Based on the research results the most important design criteria are the speed and endurance of the selected UAV. As these these have the largest impact on customer satisfaction and delivery costs. Furthermore, it can be concluded that from the perspective of the control system, that distance-based control policies are preferred over time-based policies in both operating environments, as they result in a slightly better performance.

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INTRODUCTION

In 2013 Amazon publicly announced to be developing a future transportation system to deliver goods to customers within 30 minutes using Unmanned Aerial Vehicles (UAVs), also known as drones. Many dismissed the announcement as a mere marketing stunt, but how realistic is this future actually? Will this emerging technology be the next paradigm shift in the logistics industry?

PostNL, a Dutch postal and parcel carrier active in the logistics industry, is also interested in this future. At present they have no specific knowledge about the technology, but would like to gain insight into the opportunities that could be gained from the technology in the near future. Therefore this research will examine how the emergence of UAVs as a new technology could have an important application in the logistics industry and more specifically how the technology could be integrated into future logistics operations of PostNL.

This chapter is used to familiarise the reader with the research context. It gives a brief introduction on the case company PostNL and provides an overview on the current state of UAV technology and its existing applications. Finally it specifically discusses the potential future application of UAVs in the logistics industry.

1.1 RESEARCH CONTEXT: POSTNL

PostNL is a Dutch postal and parcel carrier with more than 49.000 employees and over 3.4 billion euros revenue in 2015 (PostNL, 2015a). The company consists of three business segments: Mail in the Netherlands, Parcels and International.

PostNL Mail in the Netherlands is responsible for all postal activities and services in the Netherlands. The international business segment is active in the postal markets of the United Kingdom, Germany and Italy. Besides the mail activities, the business segment PostNL Parcels provides parcel services in both the Netherlands and Belgium, where a parcel is considered as mail that does not fit through the letterbox, but is small and light enough to be handled by a single person.

PostNL has commissioned this research for their business segment PostNL Parcels in the Netherlands and therefore this research will further focus on the parcel distribution activities of the busi-

ness segment in the Netherlands.
While the postal market has been declining, the parcel market has shown tremendous growth in recent years. In 2015 PostNL Parcels transported around 156 million parcels, resulting in a growth of 9.6% compared to 2014 and it is expected that the market will continue to grow at this rate in the coming years with the further rise of online sales (PostNL, 2015a).

The parcel market can be roughly divided into four categories based on the parcels sender and recipient, which can either be a business or consumer. In the Netherlands the company is mostly active in the segments where either a consumers home address or postal box are the final destination, with a market share of receptively 70% in the business-to-consumer (B2C) and 87% in the consumer-to-consumer (C2C) segments. In the declining business-to-business (B2B) the company has around 40% of the market. The research will focus on the B2C and C2C market as PostNL has the relative largest market share in these segments.

1.2 RESEARCH CONTEXT: UNMANNED AERIAL VEHICLES

An unmanned aerial vehicle (UAV) also referred to as, drone or remotely piloted vehicle (RPV), is an aircraft without a human pilot on-board to perform controlling actions to the aircraft during operation (Eisenbeiss, 2004). Its flight is either controlled remotely by a human operator from a ground control station, semi-autonomous, autonomous or a combination of the previous.

In the past decades the military has been the driving force behind the development of UAV technology, due to the distinct advantages that UAVs offer in missions that are considered either too dull, dirty or dangerous for manned aircraft (Bedford, 2013). Many military missions, involve operating above enemy territory and are considered dangerous for humans. Performing these missions with UAVs eliminates the risk of human operators being killed or captured. On the other hand some missions such as surveillance and reconnaissance can be dull and monotonous, which can lead to situations in which operators lose concentration, directly influencing mission effectiveness.

With the UAV technology becoming more accessible in the past years, the interest of companies for commercial applications of UAVs has been steadily increasing. And it is, therefore expected that the market for commercial applications of UAVs will grow faster than the military market within the next 5 years (Balleve, 2015).

However there are still several technological and regulatory issues that have to be resolved before widespread adoption of UAVs for commercial applications becomes possible. Up to now, very few regulations have been assigned for civil or commercial operation in unsegregated airspace. In addition, large differences exists between countries in terms of regulations, where civil or commercial UAV applications are often prohibited or require one-by-one review to receive limited authorization (Blyenburgh, 2006). From a technical perspective, several issues remain to be solved which include increasing the accuracy of navigation and localization technology, developing reliable sense-and-avoid algorithms and increasing battery capacity (Murray, Chu, 2015).

Despite these issues, in many different industries commercial applications for UAVs can already be found. In the agriculture industry, UAVs are being used to perform spraying and monitoring of crops (Pudelko et al., 2012). In the film making and photography industry, UAVs allow for unprecedented video recordings and provide a solution to build more accurate terrain maps against lower costs compared to conventional manned aircraft (Eisenbeiss, 2004). For security and monitoring, UAVs are being used to monitor sensitive areas for fires, illegal logging, poaching and environmental threats such as invasive species (Casbeer et al., 2005), but also to monitor traffic or inspect of infrastructure (Heintz et al., 2007).

After taking a broad look at use cases from a range of different industries, the next section will consider a more in depth view on the commercial application of UAV technology in the logistics industry.

1.2.1 FUTURE COMMERCIAL APPLICATION OF UAVS IN THE LOGISTICS INDUSTRY

At present, commercial use of UAVs in the logistics industry is limited, mainly due to regulatory issues that often prohibit operation beyond line of sight complicating deployment of the technology. To obtain insight into the adoption of UAV technology in the logistics industry, the potential use cases are set against the background of global trends affecting the logistics industry and their role within the logistics chain, including air cargo transportation between airports, the last mile distribution between retailers and consumers and intra-logistics applications.

The International Air Transport Association (IATA) Airline Industry forecast 2014-2018 shows that the international air cargo demand is expected to increase with an annual 4.1% over the next five years (IATA, 2014). From this perspective it is a logical prediction that UAVs will be commercially used for long distance air cargo transportation to further reduce costs and stimulate further growth. Where small cargo UAVs can make point-to-point cargo transportation economically feasible, by moving cargo volumes that are not big enough for existing forms of transportation or by transporting high value and time-critical goods (Hoeben, 2014).

In intra-logistics UAVs could play a vital role in the automotive industry with its massive production sites, just-in-time processes, and high costs of idle production lines. UAVs could support intra-plant transportation as well as the supplier-to-plant emergency deliveries which are typically performed by helicopter today. Another intra-logistics application lies in the use of UAVs inside the warehouses for inventory management.

Another development affecting the logistic industry is the fast growth of online sales. Worldwide online sales have grown with annual rate of more than 20% in the past 5 years and estimations are that this growth will continue in the coming decade (Ecommerce Foundation, 2015). The growth is accompanied by a change in behaviour of online retailers moving towards affordable same-day delivery to compete with existing 'brick and mortar' retailers and customers demanding more control over when, where and how goods are delivered (Hausmann et al., 2014). As a result some retailers are already re-thinking their fulfilment strategies by moving towards omni-channel retailing, local warehousing or anticipatory shipping to reduce cut-off times (Lowe, Khan, 2014). It is expected that retailers with few large distribution centres will combine them with smaller local warehouses located near densely populated urban areas. In the United Kingdom, Amazon is already adding regional distribution centres to its network, enabling them to introduce 1 hour delivery to consumers in London (Harrington, 2015). Another strategy used by Amazon to reduce delivery times is anticipatory shipping. The method represents an anticipatory supply chain mechanism in which goods are shipped towards consumers before they have been ordered (Bensinger, 2014).

Meanwhile the growing world population and rapid concentration of people in urban areas in the developed and developing world will lead to congested roads, pollution and also increased transportation times, caused by the delay in the transportation of goods. Local governments will therefore have to keep pace with urbanization and population growth and may need to introduce stricter vehicle emission regulations and look for alternative modes of transportation to meet the growing demand.

In this perspective, another likely application for UAVs is the distribution of parcels from retailers to consumers in the so-called last mile. DHL predicts that it could be in this market where UAVs could provide major relief for inner cities, taking traffic of the roads and reducing congestion, with delivery times maintained or even reduced (Heutger, Kuckelhaus, 2014). In rural environments with poor infrastructure or challenging geographic conditions, the potential of UAV technology is also evident, because low-volume remote locations represent a costly part of transportation. Furthermore, they typically require a non-standard infrastructure tailored to regional specifics. For remote island locations, a conceivable application is the delivery of parcels to near-shore islands, either replacing an existing (and complex) process often involving cars, boats, and postal workers, or providing new, additional services.

1.3 PROBLEM STATEMENT

Before the aforementioned commercial applications of UAVs in the logistics industry will become reality, it is clear that substantial hurdles must be overcome, particularly considering the current regulatory environment, privacy concerns, technical limitations and the requirements concerning integrating the technology into future logistics operations.

Seen the recent developments and efforts of several companies, such as Amazon, Google and DHL in researching the application of UAVs for last mile distribution of goods to consumers, initial short-term opportunities for commercial use of UAVs in the logistics industry are believed to lie in last mile distribution (Appendix B). With PostNL being the largest B2C parcel carrier in the Netherlands the application of UAVs in last mile parcel distribution would presently be most relevant for the company. However the question is where and how UAV technology can be used in the future last mile parcel distribution operations of the company. In this research this issue should be further assessed.

2

RESEARCH APPROACH

Chapter Abstract: *The objective of this research is to design an Aerial Transport System for last mile parcel distribution with Unmanned Aerial Vehicles. To reach the objective, Engineering Design theory will serve as a reference framework throughout the research. First, design requirements have to be formulated by analysing and describing the characteristics of the current parcel distribution process. These design requirements serve as input for the conceptualization phase, where the PROPER-model and steady-state model are used to describe the static function structure of the system and the equipment processes. Further, based on the requirements the type of control system needs to determined from literature. For the detailed design, a discrete-event simulation model is used in two test cases to study the time-dependent behaviour of alternative system configurations.*

This chapter contains a comprehensive explanation on the research approach. Section 2.1 discusses the problem that was stated in the previous chapter and formulates the research objective. Section 2.2 then transforms the research objective into a main research question and a number of supporting research questions to serve as a research framework. The research methodology and various methods used to analyse, design and test the alternatives are explained in section 2.3. Finally, section 2.4 covers the boundaries that are set to limit the scope of the research and a further outline of the report is given in section 2.5.

2.1 RESEARCH OBJECTIVE

According to Verschuren, Doorewaard (2000) the research objective should be clearly formulated in stating what should be solved and already contain a rough outline on what aspects of the system should be considered. By setting the outline early in the research, it can limit the solution space and offer a comprehensive result within the time frame set for the research.

From the introduction, it has become clear that the knowledge and understanding on integrating UAVs in last mile parcel distribution at PostNL is still lacking. In literature this knowledge gap is also present, as most previous research on last mile parcel distribution with UAVs concerns only a single aspect of these systems, such as vehicle design, vehicle navigation and localization and vehicle coordination.

For instance, Hochstenbach, Notteboom (2015) have designed a UAV for parcel distribution in their paper, but the design requirements for payload capacity have been chosen arbitrarily. Ali et al. (2015) has presented a cost driven decision support tool to select and configure commercially available UAVs for parcel distribution, even though existing UAVs are not specifically designed for this application. Furthermore, most vehicle coordination studies focus on the specific case of optimizing the delivery coordination between a delivery truck and UAV for simultaneous parcel distribution, but do not consider the implications of combining these to resources (Agatz, 2015) (Murray, Chu, 2015). No previous research was found that attends to the design of a system with UAVs for last mile parcel distribution that combines all these implementation aspects.

The goal of this research is to analyse the current state on last mile parcel distribution including the characteristics of existing parcel distribution process of PostNL and design a system, further referred to as the Aerial Transport System (ATS), which uses UAVs and possibly other equipment. The objective of this research has therefore been formulated as followed:

Design an Aerial Transport System for last mile parcel distribution with Unmanned Aerial Vehicles, while taking feasibility and implementation aspects into consideration.

The research serves two purposes. First, it must provide a better insight into the operation and requirements behind the integration and implementation of UAVs into the last mile parcel distribution. And second to quantify the behaviour and performance of these systems.

2.2 RESEARCH QUESTIONS

To achieve the stated research objective, a main research question is formulated:

What are the key design parameters behind the development and integration of an Aerial Transport System for last mile parcel distribution with Unmanned Aerial Vehicles?

In order to answer the main research question, the content is broken down into several supportive research questions that can act as a framework for the remainder of this research. Question 1 and 2 are needed to gain knowledge on the current state of last mile parcel distribution and determine the requirements based on the potential customer needs to integrate UAVs into the future distribution process. Question 3 is needed to determine the (key) performance indicators that are presently used to measure the performance of distribution process. Question 4 and 5 are specifically focussed on the conceptual design of a system that meets the requirements and is used to determine the processes of the different types of equipment together with the required control strategies that can be used.

1. What are parcel services?
2. What are the characteristics of current last mile parcel distribution process of PostNL?
3. What (key) performance indicators are used by PostNL to quantify the performance of last mile parcel distribution?
4. Which types of equipment need to be modelled for the ATS to function and what are their characteristics?

5. What kind of control system and control strategies are required to control the ATS?

2.3 RESEARCH METHODOLOGY: ENGINEERING DESIGN

A research methodology serves as a framework to systematically come from an initial problem statement to a comprehensive conclusion. As already indicated in the objective, this research is design oriented and therefore Engineering Design theory is chosen to serve as a reference framework. Engineering Design can be considered as a decisions making process to devise a system, component or process to meet desired needs (Ertas, Jones, 1993) (Pahl et al., 2007).

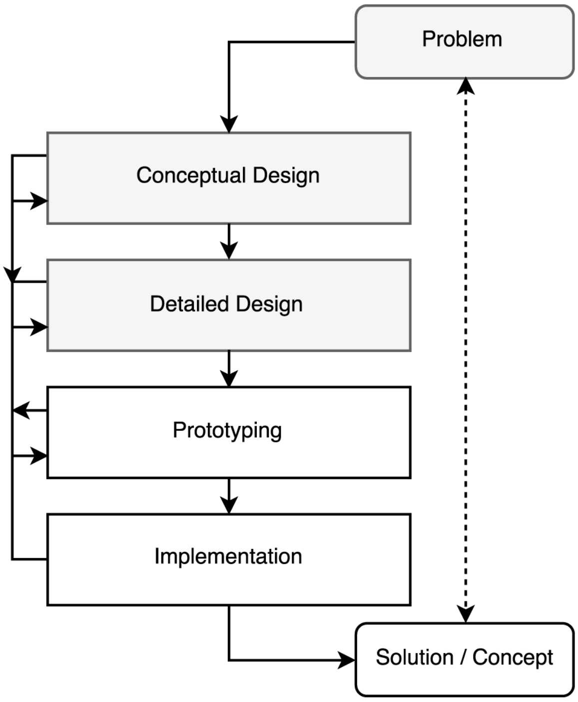


Figure 2.1: Engineering Design methodology

In the first phase of the Engineering Design process the available literature on and actual use of the system, component or process under design is analysed. Needs are identified and translated into requirements that will serve as input for the subsequent phases of the design process.

Conceptualization of the design takes place on a high level and is needed to defined feasible and implementable concepts that satisfy the earlier set minimum requirements. This is achieved by establishing function structures, searching for suitable working principles and then combining those principles into a design that is evaluated and tested in the following detailed design phase. Because the system should operate without intervention of a human operator, the conceptual design of the system will be supported with literature on the design of automated transport systems.

The final phases of the Engineering Design process include the prototyping and actual implementation of the design. These phases however are outside the scope of this research, due to the limited amount of time and available resources for this research.

Although a clear distinction has been made between the different design phases, in practice it is not always possible to draw such a clear border between these phases. Moreover the design process is highly iterative and as a result iteration loops almost always occur between the mentioned phases.

The remainder of this section contains a comprehensive explanation about the methods used during the conceptual and detailed design phases.

2.3.1 CONCEPTUAL DESIGN OF AN AERIAL TRANSPORT SYSTEM

Because the ATS must be capable of operating without human intervention it can be considered as an automated transport system, which is defined by Pielage (2005) as; a set of interacting elements, working together to take goods from one place to another with little or no direct human control.

Designing automated transport systems, is often difficult, due to the high level of interaction and system dynamics, but also because the design involves at least three different aspects; the infrastructure of the operational system, the equipment used within the operational system and the control system that is responsible for the logistic decisions(Versteegt, Verbraeck, 2006). The relations between these aspects can be presented in a layer structured model, combined with the operational organization (PostNL) and transport market (B2C parcel market segment) as two additional aspects of automated transport systems. (Fig. 2.2)

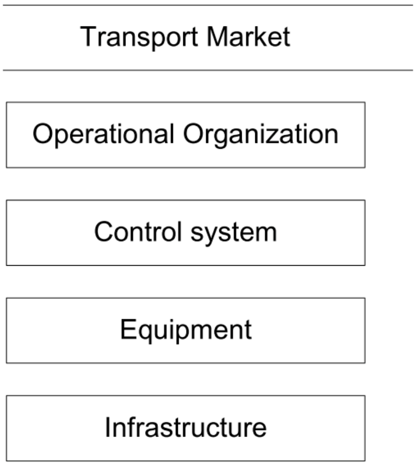


Figure 2.2: Automated Transport Systems layer model from (Pielage, 2005)

Each layer in figure. 2.2 supports or needs the layers below and/or above. Starting from the top, the operational organization fulfills the service demand in the transport market and needs the control system to control the equipment, which in turn requires the underlying infrastructure to operate. These interrelations are also reflected at the different levels of the decision-making process during the design. According to Le-Anh, De Koster (2006) the infrastructure design can be seen as a problem at strategic level and is directly related to decisions at tactical and operational levels, such as how many equipment is required and the complexity of the control system.

To support an integrated design approach this research will focus on both equipment of the operational system and the control system, as these aspects usually have the largest influence on the systems performance, but also because the design of infrastructure is a decision made at strategic level based on the chosen operating environment (Le-Anh, De Koster, 2006).

Besides these aspects the involvement of different parties with different interests, the fact that the system will need to operate in the future and uncertainty around new technologies further complicate the design process.

SYSTEMS APPROACH

The systems approach is a technique that is widely used to investigate organizational and logistic processes and supports both the improvement and/or design of logistic systems (Veeke, Ottjes, 1999). In this research, two models developed within the Delft Systems Approach will be used for the analysis and design of the system; the steady-state model and the PROcess-PERformance (PROPER) model.

The steady-state model can be used for function modelling of repetitive processes (ie. systems) and is used during the conceptualization phase to create a function model of the parcel distribution process using the various types of equipment that are available. The design process should consider multiple aspects, namely the product flow, order flow and resource flow combined with their interrelations. Because the steady-state model can only model one of these aspects at the time, the PROPER model is used in combination with the steady-state model. Where the PROPER model consists of three steady-state models for the processes of the material, order and resource flows (Veeke et al., 2008). The systems approach will be used both to analyse the current last mile parcel distribution process, but also support the conceptual design of the functional design for the future system.

2.3.2 DETAILED DESIGN TEST CASES

During the detailed design the layout and form of the designed system are quantified and more insight is gained into the behaviour and performance. The goal is to conceptualize an ATS and thereafter build a detailed design used in two test cases. As time in this project is limited only two cases are chosen that are representative of a possible operating environment for the system.

MODELLING & SIMULATION: DISCRETE EVENT SIMULATION

Modelling and simulation both play an important role in the design process of automated transport systems, because they can offer a common frame of reference for designers involved and provide both quantitative and qualitative insights into many aspects of the system. (Versteegt, Verbraeck, 2005) Modelling is used to define the system in terms of process descriptions and procedures, after which simulation can be used to give quantitative or qualitative support to modelling by showing the consequences of alternative system models or reveal unexpected problems.(Veeke, Ottjes, 1999)

Most logistic and transport systems are often modelled using a discrete worldview, where discrete objects in the system are the focus of attention. These discrete objects represent the infrastructure and equipment, such as vehicles moving on the infrastructure through the system, which enables the use of discrete event simulation.

Within (discrete event) simulation two different approaches can be distinguished; the flow-oriented and the object-oriented approach. (Law, 2007) The flow-oriented approach focuses on entities flowing through the system and using resources in the process, while the object-oriented approach focuses on the different entities in the system and describes the sequence of events and activities that these entities execute or undergo during their stay in the system. Although both approaches are suited for logistics of transport system analysis, the object-oriented approach allows modeling of complex control structures. According to Veeke, Ottjes (1999) the object-oriented approach also plays a central role during the modelling phase using the systems approach.

2.4 RESEARCH SCOPE

To make the research concise, boundaries need to be set to limit the scope of the research. With an abundance of UAVs available on the market today, with different characteristics, an existing UAV has been selected to serve as reference case for the ATS and contains the characteristics which are considered to be important for transportation applications. It is assumed that these UAVs require no human guidance or intervention and are capable of fully autonomous operation. System capacity will need to be determined based on demand of a peak day within an average week, within an average month and is based on the size and customer density within the operating environment. To determine the behaviour of the system in different operating environments the depots in Goes and The Hague have been selected as test cases based on their opposite distribution region characteristics. Further, existing regulations and privacy concerns around integrating UAVs in the last mile parcel distribution are left out of the scope of this research as they currently prohibit commercial use of UAVs in the Netherlands.

2.4.1 LAST MILE PARCEL DISTRIBUTION

According to Gevaers et al. (2009) last mile parcel distribution is considered as the final leg in a logistics chain running from a business to the end consumer, where parcels are collected at a depot and delivered to either the end consumers home or a collection and delivery point (Fig. 2.3).

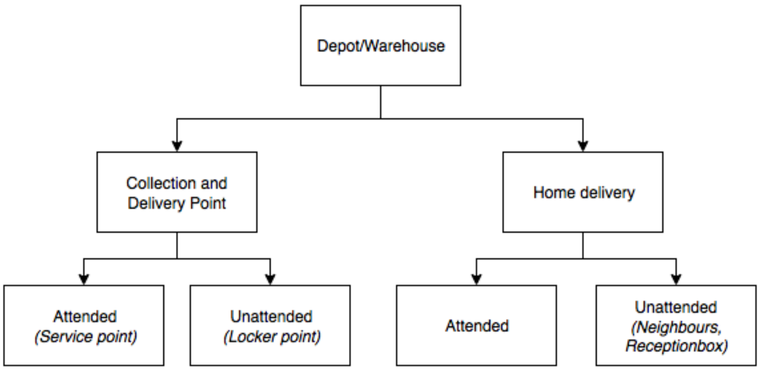


Figure 2.3: Last mile distribution topology adapted from Gevaers et al. (2009)

HOME DELIVERY

In home delivery parcels are directly delivered to the consumers front-door. In case a consumers is not at home during delivery, the parcel can sometimes be delivered to the neighbours or an available reception box. Otherwise the parcel is often returned to the depot by the delivery driver for a second delivery attempt the following day. However, the selected method depends on the delivery policy of the parcel carrier and the availability of the first two options.

COLLECTION AND DELIVERY POINT

Weltevreden (2008) divides these collection and delivery points (CDPs) into two types; *attended service points* and *unattended locker points*. A locker point can be considered as a micro-depot consisting of a collection of lockers, where customers can collect, pay and if necessary return their parcels

7 days per week and 24 hours per day. Whereas a service point is a shop-in-shop concept, where parcels are delivered and returned to a supermarket, petrol station or post office during opening hours.

2.4.2 UNMANNED AERIAL VEHICLES

At present, there is no commercially available UAV that has been specifically designed for last mile parcel distribution. While it is not the goal of this research to design a UAV for this application, it should gain insight in the decisions behind what type of UAV should be favoured for the application and which UAV characteristics play an important role in the application.

While most design considerations for UAVs have emerged from the existing knowledge of modern aviation, the absence of a human operator on board of the aircraft has provided designers with more freedom in terms of fuselage design (Sarris, 2001). As a result there are many types of UAVs available on the market with different sizes, build types and capabilities, depending on the type of payload, users needs and their application.

In part because of the large differences between existing UAVs there is no universally accepted standard to distinguish among them. Regularly, the UAVs operational characteristics, type of airframe design and level of autonomy are used to compare them against each other (Dalamagkidis, 2015).

OPERATIONAL CHARACTERISTICS

Most often UAVs are distinguished based on their operational characteristics, which generally include maximum or average speed, average endurance, maximum payload weight capacity, maximum take-off weight and/or maximum flight altitude(Blyenburgh, 2006). UVS-international has developed a classification scheme to differentiate among existing UAVs based on these operational characteristics and divide them into several categories. These categories range from Micro UAVs which are extremely small, have a limited endurance and can carry only small payloads up to HALE UAVs capable of carrying heavy payloads during an extended period of time.

Accoring to Austin (2010), the most important UAV operational characteristics for transportation applications are the maximum or average speed, endurance, range and the maximum payload weight capacity. Hochstenbach, Notteboom (2015) states that these characteristics are not independent, as increasing speed of the UAV would reduce the endurance or flight time.

Besides these operational characteristics, the method for launching and recovery of the UAV is driven by the requirements from the operating environment, which is important in determining the required type of airframe and the potential need for supporting equipment.

AIRFRAME TYPES

Another method to distinguish between UAVs is based on their type of airframe, also considered as the structural design (Fig. **??**). Manned aircraft are often classified in a simi A manner of classifiction that is also regularly used for the classification of manned aircraft for regulatory purposes and is also deeded suited for UAV classifiction (Maddalon et al., 2013). Characteristics of propulsion are often divided into motorized and non-motorized, where motorized UAVs often use fossil fuels, such as jet fuel and diesel or electric propulsion.

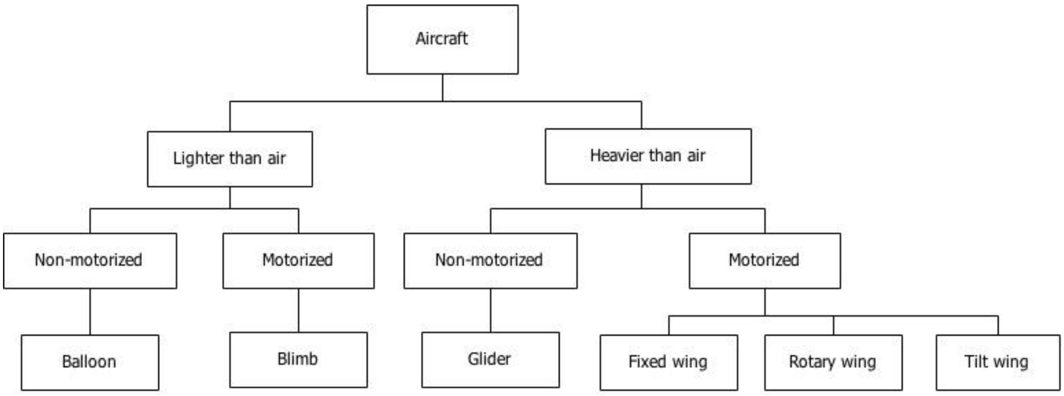


Figure 2.4: Unmanned Aerial Vehicles classifiction scheme adopted from Maddalon et al. (2013)

Most existing UAV designs are conventional fixed wing and rotary wing build types, each with their advantages and disadvantages. For example, fixed wing aircraft (Fig. 3.12a) are capable of fast and efficient flight, but cannot hover and required runway infrastructure for take-off and landing. Rotary wing aircraft (Fig. 3.12b) on the other hand, have the capability of vertical take-off and landing (VTOL), can hover and are highly maneuverable, but are generally less efficient in forward flight than fixed-wing aircraft.(Floreano, Wood, 2015) However because of their VTOL capability and maneuverability they are more often used for civil and commercial applications in urban areas. Bento (2008)

(a) Fixed wing UAV (b) Rotary wing UAV (c) Tilt wing UAV

Figure 2.5: Different types of UAS

Tilt wing or combined aircraft attempt to achieve a compromise between the VTOL capabilities of rotary wing aircraft and the long endurance of fixed-wing aircraft. A downside to this build type is that these configurations generally suffer a payload weight penalty compared to either a rotary- or fixed-wing aircraft.(Austin, 2010)

AUTONOMY

Autonomous systems are capable of handling uncertainties in their environment without pre-programmed control rules that are used in automated systems (Dalamagkidis, 2015). Implementing autonomy in UAVs is an essential step for the integration of UAVs in parcel distribution, as this capability would allow performing some of functionalities without the need for a human guidance or interfere.

Many different levels of autonomy can be distinguished. Ranging from remotely piloted operation, where a human pilot has full responsibility over the flight or the UAV, semi-autonomous where the human pilot must still interact with the UAV during specific parts of the mission and fully autonomous operation, where the UAV performs all tasks without the need for any human intervention.

Although the technology to support fully autonomous operation of UAVs is still under development, it is assumed that in the near future UAVs will be capable of performing fully autonomous missions and do not require human guidance.

UAV REFERENCE CASE

As mentioned it is not the goal of this research to design a UAV for parcel distribution, but rather to determine the design decisions from a high level perspective. The design framework should therefore accommodate the various types of UAVs based on the earlier mentioned airframe types and operational characteristics.

In terms of airframe type, an airframe should be selected based on the characteristics of the environment and the availability of infrastructure to support take off and landing. As last mile distribution takes place in in both rural and densely populated areas, it can occur that there is limited space to operate in. According to Google the average available space for take-off and landing in urban areas lies around the 4 square meters and therefore either only rotary wing or tilt wing UAVs with VTOL capabilities should be considered for last mile parcel distribution (Warwick, 2014).

Further, the most important operational characteristics of the UAV in relation to transportation applications are speed, endurance and payload capacity (Austin, 2010). Hochstenbach, Notteboom (2015) states that these characteristics can be taken generic, albeit they are not all independent as for example a higher speed, reduces endurance. The relation between these two characteristics can be simplified based on the following relation of conservation of energy. The energy required for flying a battery powered aircraft can be approximated by:

$$E_{req} = \frac{1}{2}mgh + \frac{1}{2}mv^2 + \frac{1}{2}\rho v^2 C_D A_{ref} R \tag{2.1}$$

Where m is the total mass of the UAV including the payload, g is the gravitation acceleration, h the flight altitude, v the cruise speed, ρ the air density, C_D the drag coefficient, A_{ref} the frontal area service and R the flight distance. The total available energy is calculated based on the maximum flight distance, that consists of the cruise speed and average endurance.

$$R = vt \tag{2.2}$$

For simplicity it is assumed that all values in the equation are linear assuming constant speed. With aerodynamic efficiency being highly dependent on the design of the aircraft (Floreano, Wood, 2015), appropriate values for these characteristics serving as input for the simulation model should be selected from an existing UAV, deemed capable of being used for last mile parcel distribution .
According to Sunil et al. (2015) an existing UAV that would be capable for the last mile parcel distribution application is the MD4-3000. The MD4-3000 can carry a payload of up to 3 kilograms, has an average speed of 16 meters per second (57,4 km/h) and an endurance of 45 minutes.
The operational characteristics of the MD4-3000 will serve as input for the simulation experiments, as they represent the capabilities of an existing UAV. Because in the future, the endurance of UAVs might further improve as a result of battery technology advances, or the cruise speed of UAVs may be increased at the expense of endurance as the result of alternative UAV designs, the influence of

Figure 2.6: Case Reference UAV: MD4-3000

these varying operational characteristics should be taken into consideration during the simulation experiments.

2.4.3 SYSTEM CAPACITY

System capacity depends on the size and customer density of the operating region (Murray, Chu, 2015). The size of the operating region is determined by the endurance of the UAV and the possibility to extend it by means of refuelling or charging stations placed within the operating region (Ghahari, 2015). On the other hand the consumer density within the operating region depends on the type of operating region, such as rural areas where consumer density is generally much lower compared to densely populated urban areas.

Furthermore, system capacity also depend on the parcel demand of customers that fluctuates on a daily basis and is subject to seasonal influences. It is therefore not advisable to design and dimension the system on the absolute peak demand, as this would result in an expensive system with overcapacity during normal operating conditions. Instead, demand on a peak day within an average week in an average month will be used as input to dimension the system (Pielage, 2005).

HOURLY DEMAND

Besides fluctuations in daily demand, customer demand is also not equally spread across the time of day. Therefore it is interesting to determine the influence of these peaks on the performance of the system. At present, home delivery and collection and delivery points are already dealing with peak demand occurring throughout the time of day (Fig 2.7).

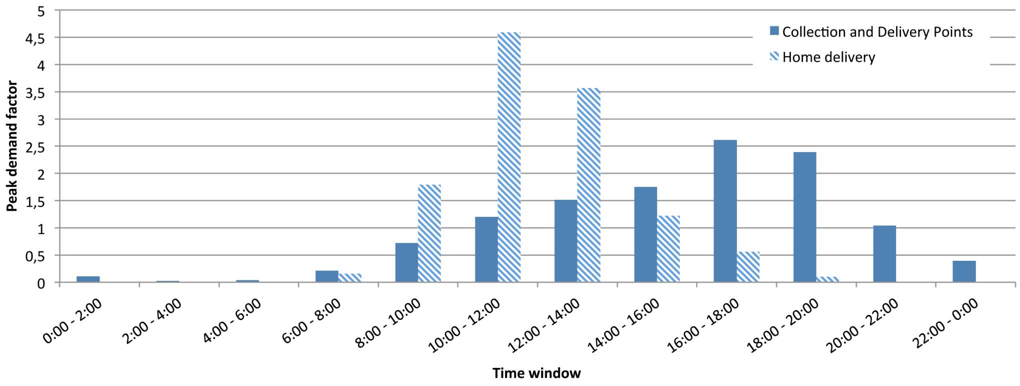


Figure 2.7: Daily demand distribution

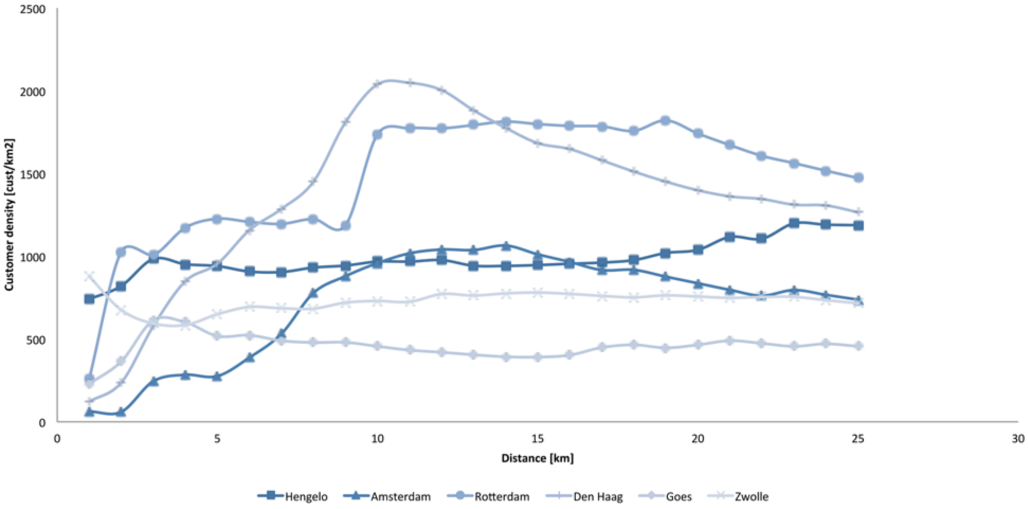


Figure 2.8: Customer Density in Operating Regions

Because home delivery is scheduled, the demand during daytime is distributed differently compared to demand at collection and delivery points. Because the distribution of demand peak factors from figure 2.7 for collection and delivery points gives a more accurate representation of the consumers preferences this distribution is used during the simulation to represent these fluctuations during daytime.

2.4.4 SELECTED TEST CASES: GOES AND THE HAGUE

Both The Hague and Goes have been chosen to serve as test case operating regions for the system during the detailed design phase. Due to time restrictions for this research, only two operating regions have been selected, taking into account that they should represent two distinctly different operating regions.

The differences between the operating regions has been based on the earlier mentioned demand characteristics, including customer density combined with increasing size of the operating region. In figure 2.8 the customer density in operating regions of PostNL near the three largest cities in the Netherlands are compared to three operating regions in the Hinterland. While Goes has the lowest customer density in its operating region, The Hague has one of the highest customer densities of the three largest cities. Therefore these two operating regions are selected as test cases for the system.

For all operating regions, the customer density slowly declines after 15 kilometres. Thus the operating regions are chosen to have an operating region with a 15 kilometre radius around a central location.

2.4.5 REGULATIONS AND SAFETY CONCERNS

At present aviation regulations throughout Europe prohibit the widespread use of UAVs for commercial applications. European aviation regulations are complicated, due to the fact that the individual member states are responsible for their own airspace. While aircraft that weigh more than 150 kg fall under the general regulations of the European Aviation Safety Agency (EASA), aircraft below this weight fall within aviation legislation of the according member state (Blyenburgh, 2006).

In the Netherlands commercial operation of UAVs is currently only allowed under strict regulations and requires a permit or exemption from the Inspectie Leefomgeving en Transport (ILT). Flight restrictions include operating in the daytime, within line of sight of the operator (eg. within a range of 500 meters) and below an altitude of 120 meters. Besides this, flight is not permitted near crowds, roads, buildings or industrial sites(Ministerie van Infrastructuur & Milieu, 2015).

From these restrictions it can be concluded that commercial parcel distribution with UAVs could not be effectively deployed in the Netherlands at the moment. However the numerous research efforts to enable autonomous beyond line of sight flight and the fact that laws are continuously subject to change allows for the assumption that these limitations could be cleared in the near future

Public opinion surrounding parcel distribution with UAVs varies from person to person, mostly caused by a lack of information and the fact that the subject is relatively new to the public(Macsween-George, 2003).

Especially safety and security issues surrounding the commercial use of UAVs for parcel distribution is a frequently mentioned topic in literature. Some of these issues include the risk of people getting injured by crashing UAVs or coming into contact with rotor blades, but also the risk that parcels get stolen during transport or delivery.

Although intercepting parcels could become a low risk-high gain crime, especially with the fact that the vehicle is unmanned, shooting down a UAV could be prevented by flying at high speeds and high altitude. Also on-board cameras, which transmit the video images to a ground station, could be a way to mitigate these risks, but could inflict with privacy concerns.
In terms of safety, the operation of UAVs should as reliable as manned aircraft and the contact between humans, animals and the UAVs should be reduced to a minimum.

2.5 REPORT OUTLINE

The following chapters are used to answer the supporting research questions. In chapter 3 the current state of last mile parcel distribution is considered. Available literature on last mile parcel distribution services and distribution networks is considered, followed by a description of the existing parcel distribution process of PostNL in the Netherlands. Chapter 4 continues with the conceptual design phase, where first the role of the UAVs is discussed within the future state of parcel distribution and system boundaries and requirements are formulated. Next the types of system equipment are described and the function structure is designed together with the assignment of equipment to the various functions. Finally, the type of control system that would be needed based on the design requirements is selected. Chapter 5 then covers the translation of the conceptual design into a simulation model and the simulation experiments that are performed for the two test case operating environments, The Hague and Goes. Thereafter chapter 6 discusses the research results and reflects on the decisions that have been made during the design process. Finally, in chapter 7 conclusions are drawn from the research, answering the main research question and gives recommendations for future research.

3

CURRENT STATE ANALYSIS LAST MILE PARCEL DISTRIBUTION

Chapter Abstract: *Parcel services are characterized by the high volume of small and low weight parcel shipments. Depending on the offered transit time (e.g. the time between pick-up and delivery) these services can be categorised into same-day courier services, time- and day definite express services or time- and day undefined regular parcel services. Many of these services use hub & spoke distribution networks to cost efficiently move parcels with many origins and many destinations. PostNL also operates a hub & spoke network, called the New Logistics Infrastructure (NLI), where parcels are collected at a depot, sorted, line haul transported overnight between the depots and finally delivered to the consumer. In the NLI all these processes are scheduled in advance with fixed cut-off times and as a result parcels are pushed into the network towards customers, who have limited control over when, where and how they receive their parcels. Due to pushing of these parcels the number of failed first-time deliveries is relatively high.*

Developing a future state where UAVs could play a role in last mile parcel distribution begins with an analysis of the current parcel distribution situation. This chapter will therefore give a comprehensive explanation on the current state of last mile parcel distribution with a specific focus on the present distribution operations of PostNL in the Netherlands. In section 3.1 the differences between the existing types of parcel services currently found in the market is explained, where after section 3.1.1 covers the differences in distribution networks that are used by these services. Section 3.2 then gives a comprehensive description of the current last mile parcel distribution landscape in which PostNL operates together with the current distribution process. The description is followed by an analysis of the characteristics of parcels flowing through the distribution network and the (key) performance indicators that are used by PostNL to measure the performance of the parcel service.

3.1 PARCEL SERVICES

Existing parcel services have only emerged in the past 20 years. Where previously distribution involved the movement of bulk shipments from warehouses to retail stores, the fast growth of online sales has resulted in an increased volume of smaller direct shipments between businesses and consumers. As this large share of smaller shipments was easy to standardize a new segment for parcel services was established in the logistics industry.

Because of these developments parcel services are characterised by their limitations in size and weight of parcels, where parcel weight often limited to approximately 31,5 kilograms or less to ensure that a single person is able to handle the parcel. Meanwhile parcel size is often limited to standardize the material handling equipment such as sorting machines.

Although there is no single definition for existing parcel services, these services are often divided into three categories based on the transit time (e.g. time between pick-up and delivery) that is offered by the service and include courier, express and regular parcel services (Bakker, 2005).

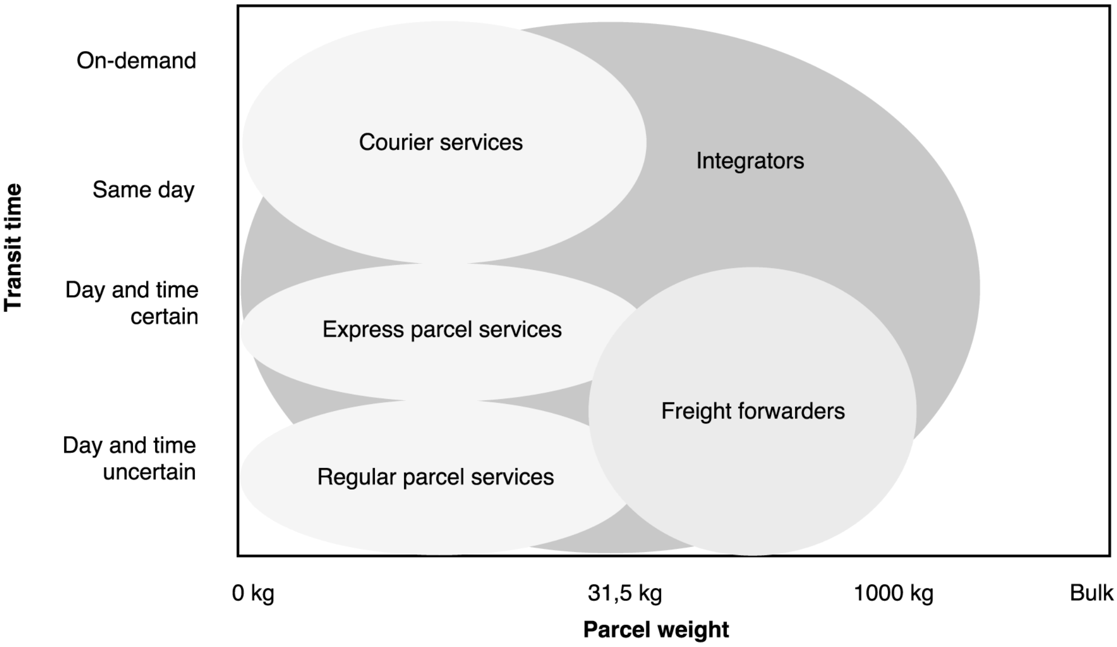


Figure 3.1: Courier, Express and Parcel services

COURIER SERVICES

Courier services are considered as the fastest and most exclusive shipping service offing same-day and on-demand/instant transit times. They are frequently used for high value or time-critical goods that require fast and secure transportation. Parcel shipments are transported directly from their origin to their destination and usually handled by a single person. Depending on the distance and the availability of the courier either on-demand/instant pick-up and delivery is performed or scheduled on the same-day.

EXPRESS SERVICES

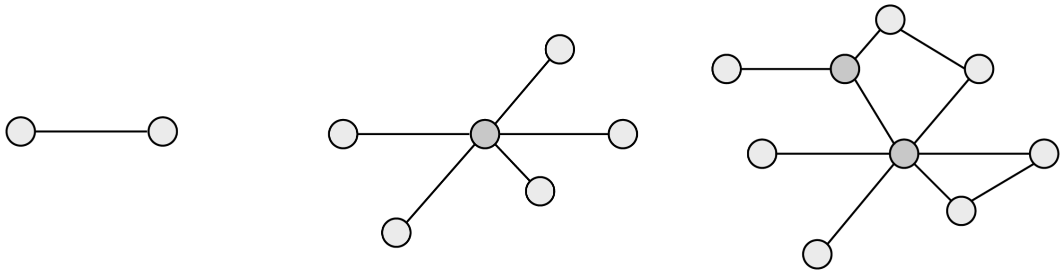
Express services offer day and time definite transit times, where pick-up and delivery takes place on a pre-defined day and within a guaranteed time window. Therefore most express shipments are business-to-business shipments that require shipments to arrive on a guaranteed day or time. Express services use large structured networks instead of direct delivery from the origin to the destination.

REGULAR PARCEL SERVICES

Regular parcel services are often time and day indefinite services that also use large structured networks instead of direct delivery. Regular parcel services are specialized in standardized shipments with predefined weight and size limits and are therefore less flexible compared to express and courier services.

3.1.1 DISTRIBUTION NETWORKS

Most parcel services use distribution networks with a particular network structure that has specific characteristics to move parcels between their origin and destination. Below these network structures and the parcel services that regularly used these types of networks are briefly discussed.



(a) Point-to-Point network (b) Pure Hub & Spoke network (c) Hybrid Hub & Spoke network

Figure 3.2: Parcel Distribution Network Structures

POINT-TO-POINT

Direct distribution networks with a point-to-point network structure are the simplest type of network structure (Fig. 3.2a). In practice point-to-point networks are mostly used by national and international courier services, particularly for shipments of time-critical or valuable goods.

One of the drawbacks of point-to-point distribution networks is that when the number of origins and destination in the network increases the number of connections increases with the square number of origins and destinations (Rodrigue et al., 2013). As for each connection a vehicle is needed to connect these locations to each other, the transportation costs to operate these networks are often high for larger parcel volumes with many origins and destinations. Therefore most parcel carriers use distribution networks with so-called hub & spoke network structure instead when facing large parcel volumes with many origins and many destinations.

PURE HUB & SPOKE

Distribution networks with a pure hub & spoke network structure consist of a central hub and distant spokes (Fig. 3.2b). A single connection exists between all the individual spokes and the central hub, which minimizes the necessary number of connections in the network and thus reduces overall transport costs.

Parcel distribution networks with a hub & spoke network structure, collect parcels in the operating region of the spoke with (small) delivery trucks, which are then consolidated at a spoke. Next, all parcels are transported over long distance to the central hub, where the goods are sorted and cross-docked either with or without intermediate storage. Finally, parcels are sorted for a second time before being delivered to the final destination by small delivery trucks (Zäpfel, Wasner, 2002).

One of the drawbacks of pure hub & spoke networks is that they are vulnerable to disruptions at the hub and that the total capacity of the hub determines the maximum capacity of the entire network. To reduce these drawbacks some parcel carriers are using using hybrid hub & spoke networks.

HYBRID HUB & SPOKE

The hybrid hub & spoke network structure is almost similar to pure hub & spoke networks, but has additional point-to-point connections between several spokes in the network 3.2c). These additional connection allow for redirection of the goods when there are capacity or sorting issues at the central hub due to disturbances at the hubs.

Although PostNL at present offers all types of parcel services in the Netherlands, the remainder of this chapter will further focus on the current state on the regular parcel service offered by the company as this parcel service is most frequently used for distribution of parcels between businesses and consumers which falls within the scope of the last mile parcel distribution of this research. In the next section a closer look is taken at the parcel distribution network used by PostNL and the characteristics of the distribution process for regular parcels.

3.2 CHARACTERISTICS OF LAST MILE PARCEL DISTRIBUTION BY POSTNL

In this section the characteristics of the current last mile parcel distribution process of PostNL is considered. First the relevant system is identified and a description is given of the last mile parcel distribution process. This is followed by an analysis on the size and weight characteristics of parcels flowing through the network and the . Finally, the key performance indicators used by PostNL to measure the performance of the distribution process are described.

3.2.1 PARCEL DISTRIBUTION PROCESS DESCRIPTION

In 2008, PostNL decided to build a new parcel distribution network called the New Logistics Infrastructure (NLI) to cope with the increasing parcel volumes in the Netherlands (Fig. 3.3). Where previously the parcel distribution network of PostNL consisted of 3 sorting hubs and 37 distribution spokes placed in a pure hub & spoke network structure, the NLI consists of 18 identical depots with integrated sorting and distribution functions that are placed in a hybrid hub & spoke network structure. All depots in the network are interconnected by three centrally located depots (hubs) also referred to as depot+, which have an additional cross-dock function and are each connected to five regular depots without cross-dock function.

Figure 3.3: New Logistics Infrastructure

To identify the relevant system from the environment a root definition can be formulated that gives a clear statement of the activities which take place in the relevant system that is analysed. For the NLI, the following root definition has been formulated according to the Soft Systems Methodology(Checkland, 1989).

The New Logistics Infrastructure is a system used by PostNL to deliver parcels for customers from origin to destination in a cost effective manner and within 24 hours or less by truck drivers that provide transportation to, from and between depots and employees that handle the parcel at the depots.

With the relevant system being identified, the different functions within the system can now be further analysed using the conceptual modelling methods from the Delft Systems Approach. In a top-down approach the various functions within the system are distinguished starting from a blackbox perspective that relates to the primary function of the system.

In the NLI different processes can be distinguished based on the type of parcel that must be distributed. These parcels may include for example, cross-border parcels or parcels that must be delivered to a post box, but also parcels that require special handling, such as breakable goods or parcels that require a signature. Within the scope of this research only the distribution process for regular parcels is further considered, as this process covers the majority of the business-to-consumer parcel volume and such parcels do not require any special treatment. Where regular parcels are considered as parcels that do not require special handling, a signature, are not destined for abroad or a postal box and parcels that are within the weight and size limitations set by PostNL.

The primary function of the NLI is to facilitate the distribution of parcels from origin to destination and is represented in figure **??**. The input and output of the system is known and consisted of 140 million parcels in 2015.

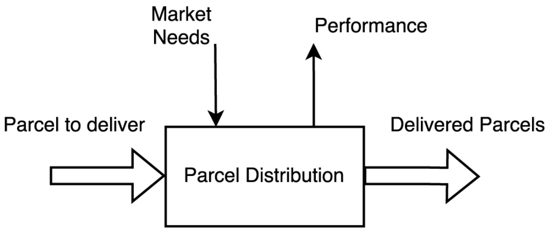


Figure 3.4: Blackbox PostNL

When approaching a logistics system from the viewpoint of its primary function, three aspect flows and their interrelations have to be included in the model: the order flow, the product flow and the resource flow (Fig. 4.5) (Veeke et al., 2008). The order flow represents the transport requests for parcels that are made by customers, the product flow consists of the parcels that are moved from their origin to their destination and the resources flow represents the use of equipment to facilitate the movement.

Orders from customers for transportation of their parcels must be handled by the system. The order flow consists of (electronic) information that is used in the transportation process and contains among other information on the sender, the final destination and the size and weight of the parcel. Further, each parcel has a unique bar-code that is related to the order information and is used during the transportation process to measure the results. For the transportation process regular parcels flow trough the system and are transformed from parcel to deliver to delivered parcels when leaving the system. For transportation of parcels and to handle the orders, different resources are required. These resources include employees, such as truck drivers, sales persons, depot managers that handle parcels, but also different types of equipment used by these employees such as depots, roll containers and (small) trucks.

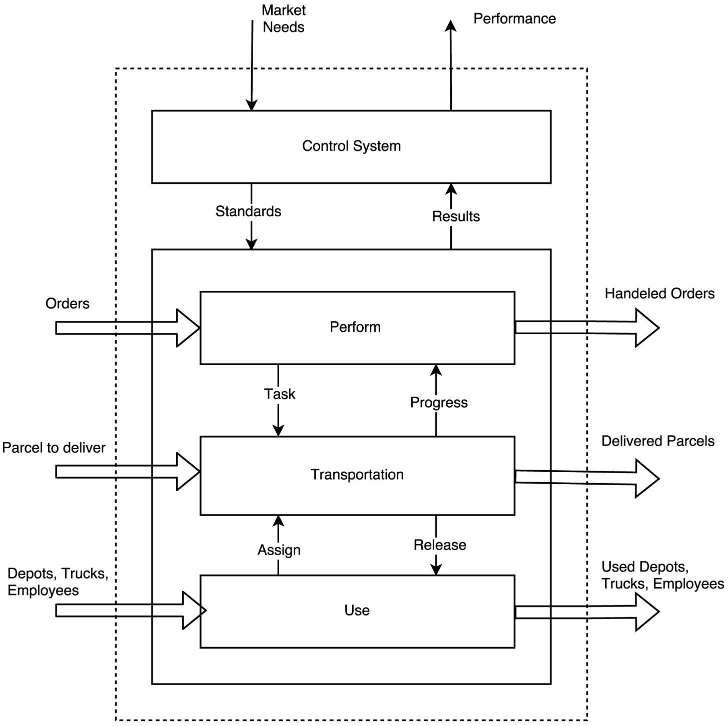


Figure 3.5: PROPER-model PostNL

For customers of PostNL the transportation function is the most important, as this function adds value to the product. Because the function concerns a single aspect the flow can be modelled with a steady-state model. The transportation function can be further divided into three separate sub functions, namely collection, line haul transportation and delivery (Fig. 3.6).

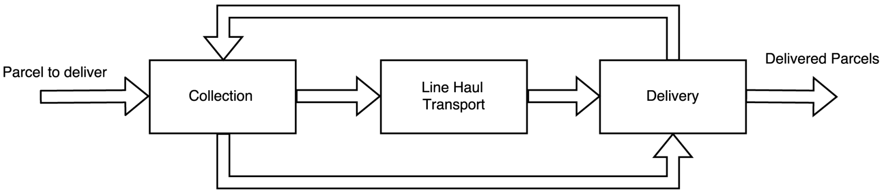


Figure 3.6: Transportation function

COLLECTION

The transportation function always starts with the collection of parcels. (Fig. 3.7) Throughout the day customers of PostNL deliver parcels at almost 2800 postal offices and business points. At these locations orders are generated and parcels are stored in roll containers before being picked up in the afternoon. Customers that offer larger quantities of parcels such as Bol.com, Wehkamp and Zalando also buffer parcels in roll containers, but are directly pick-up at the customers location.

In the pick-up process, the truck drivers drives a scheduled route based on the expected number of parcels to pick up and visits one or multiple locations within fixed time windows to spread the pressure of incoming parcel volumes at the depots.

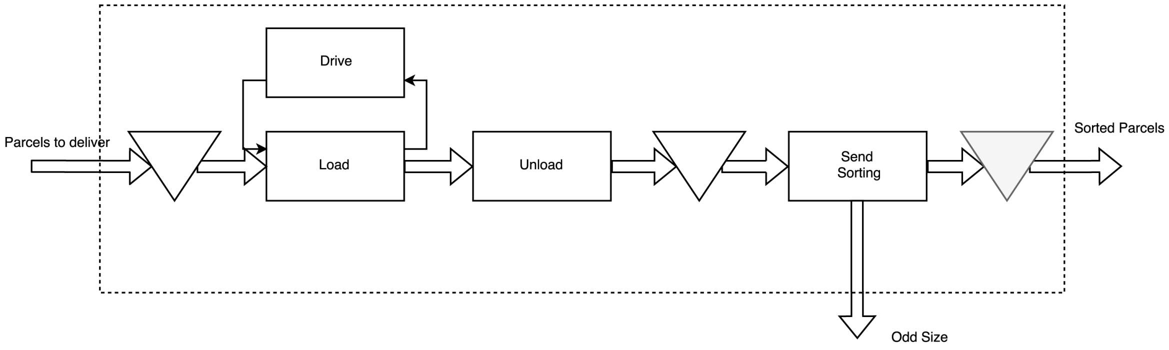
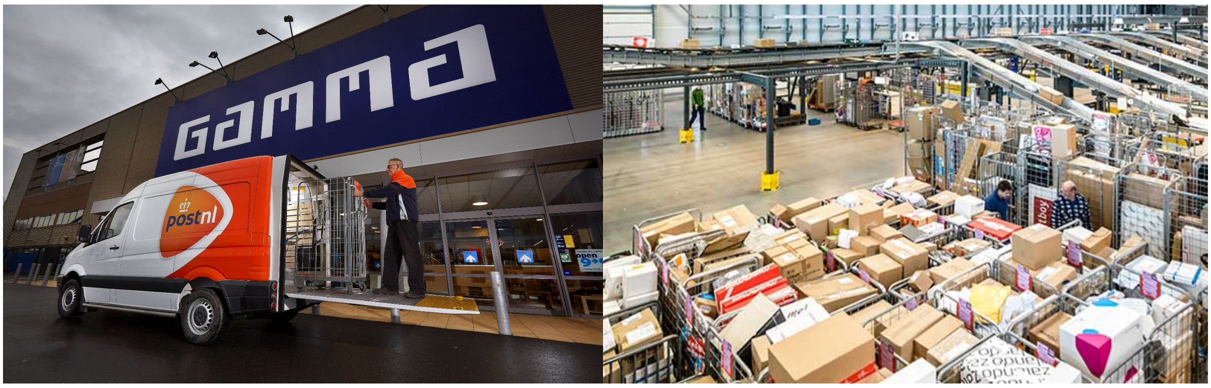


Figure 3.7: Collection Function

After the driver has finished its collection route, the parcels are brought to the (nearest) depot. At the depot the roll containers are unloaded and stored until the send sorting process is started in the evening. At around 19:00 the send sorting process is started and parcels are feeded into the sorter, where for each parcel the bar-code is read to determine the final destination based on the destination postal code and the according depot to which the postal code belongs. After being sorted parcel are put into roll containers based on their final delivery routes and destination depot. For example, when a parcel is sorted in Sassenheim and has the destination Den Hoorn and is assigned to the route belongs to the first delivery shift, it is put in a roll container with destination Den Hoorn with parcels for the first delivery shift.



(a) Collection at Business Points (b) Send Sorting Process

LINE HAUL TRANSPORTATION

Around 94% of all collected parcels have a postal code that does not fall within the service region of the collecting depot and must therefore be transported to another depot with long distance or so-called line haul transportation.

In line haul transportation, parcels with a similar destination depot are placed in roll containers and put into trucks for long haul transportation (Fig. 3.9) In case there are enough parcels to fill an entire truck for a single destination all parcels are directly transported to the destination depot using a so-called inter 3 line haul transportation trip. Otherwise parcels are loaded into a truck and transported to a depot+ that is connected to the destination depots using an inter 1 line haul transportation trip. At the depot+ the roll containers are unloaded at a cross-docking platform. At the cross docking

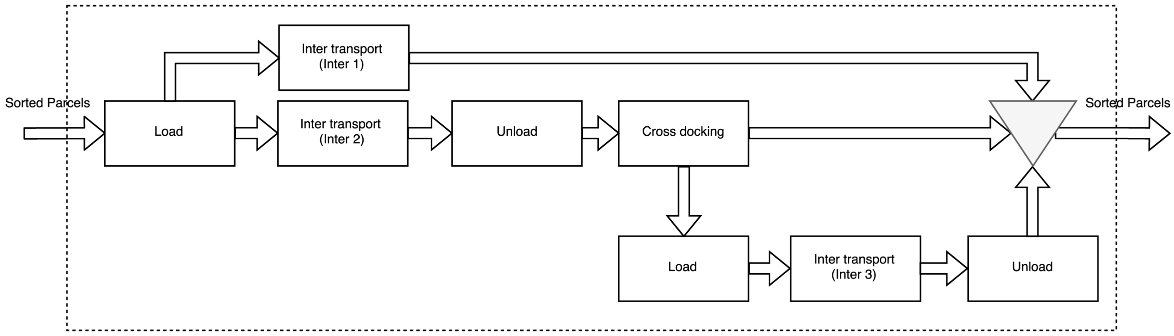


Figure 3.9: Line Haul Transport Function

platform the destination of each roll container is checked. When the depot+ is not the final destination, the parcels are loaded into another truck waiting at the cross-dock platform with the depots destination. There after the parcels are transported with an inter 2 line haul transportation trip to the final destination depot. By consolidating many parcels with similar approximate origins and designations, the needed number of connections in the network are reduced. As mentioned this principle is considered as the economies of scale and reduces the overall transportation costs per parcel as utilization of vehicles is increased (Rodrigue et al., 2013).

Figure 3.10: Cross Dock

DELIVERY

In the morning parcels start arriving at the depots for delivery to their final destination. (Fig. 3.11) When parcels arrive at the depot they are temporarily buffered in the trucks or in special storage areas within the depots. At around 7:00, preparation starts for the final delivery.

Parcels are feeded manually into the sorter and are sorted according to their final delivery route. During the sorting process, parcels end up at the loading dock where the delivery truck driver of that route is waiting to load the parcels into the delivery truck. In around 7 shifts of 45 minutes an average of 350 delivery trucks is loaded, where parcels with a destination farthest away from the depot are loaded first. The number of parcels to be delivered per delivery truck depend on the drop density (eg. number of parcels per delivery route) of the delivery route but lies on average around 180 parcels per route. In densely populated areas, delivery trucks tend to have a higher drop density as driving distances between customers are shorter compared to rural areas. This so-called drop

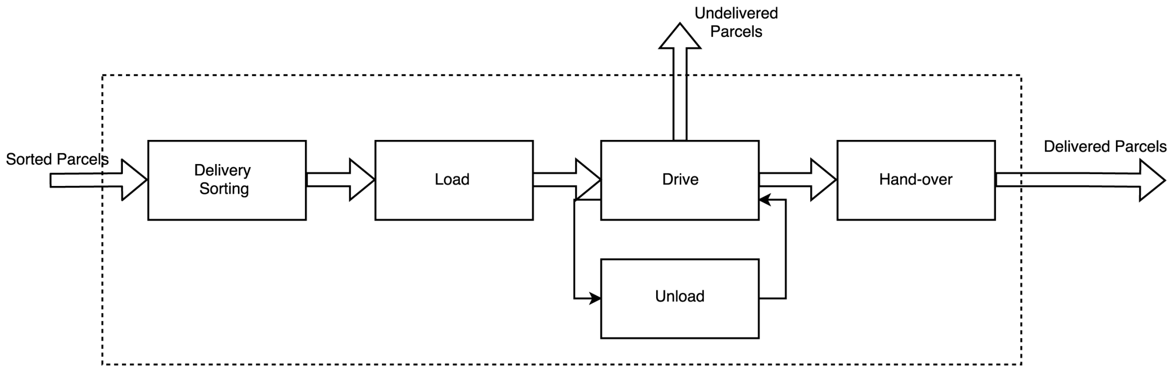


Figure 3.11: Delivery Function

density often determines the final delivery costs per parcel.

(a) Delivery Sorting

(b) Loading Delivery Truck

After loading the delivery truck, the driver performs a delivery route, visiting all customers on the route and handing over parcels to the final consumers. When a consumer is not at home, it is either delivered to the neighbours or returned to the depot after which a second delivery attempt is performed the following day. Because PostNL has the policy that regular parcels can be delivered at neighbours, the first time delivery failure rate lies around 10%.
The final delivery of the parcel to the customers door is logistically challenging and often the most expensive process in distribution networks, due to a number of factors. Delivery efficiency mostly depends on the transit time and the customer density in the delivery region. In general, a higher customer density in a given region facilitate greater efficiency, which is also referred to as economies of density (Boyer et al., 2009).

3.2.2 PARCEL WEIGHT AND SIZE CHARACTERISTICS

As described in section 3.1 parcel services are generally characterized by the limitations in terms of maximum parcel size, parcel weight and the offered transit time. It is expected that not all parcels currently distributed by parcel carries such as PostNL will be eligible for transpiration by UAV, as the size of the UAV puts an upper limit on the size and weight of the goods it can carry (Agatz, 2015). In order to determine the importance of these characteristics in relation to the possible design decision on the operational characteristics of the UAV, a closer look is taken at these characteristics from regular parcels that have been distributed by PostNL in the Netherlands. Therefore data on the

Fitz-Gibbon (1990) defines a (key) performance indicator (KPI) as a type of performance measurement, which can be used to evaluate success (or failure) on what the performance indicator evaluates. A KPI must be quantifiable and should preferably reflect the organizational goals. PostNL employs different KPI's, that give a representation of the overall system aspects. The following three KPI's will be considered:

- Customer Satisfaction
- Delivery Costs
- Environmental Impact

These KPI give an overall indication of the respective system aspects and are a combination of several supporting Performance Indicators (PIs)

CUSTOMER SATISFACTION

Customer Satisfaction (CS) is often expressed in terms of how a product or service performs in perspective to the expectations of customers for the product or service (Esper, T. L., Jensen, T. D., Turnipseed, F. L., & Burton, 2003).

Customer Satisfaction is one of the most important KPI's for PostNL as it reflects how customers value the service of the company. At present PostNL measures Customer Satisfaction through an online survey, which includes questions on how the company resolves complaints, the delivery of parcels (e.g. transit time and time window reliability), and the quality of delivery (e.g. damaging or loss of parcels).

Although Customer Satisfaction can be considered as a qualitative KPI, it can be expressed as a quantitative KPI when only using the number of deliveries performed within the expected time frame as the main PI. In this manner the measured Customer Satisfaction is still expressed according to the definition, namely the actual results versus the expected results in a quantifiable manner.

$$CS = \frac{N_{delivered-on-time}}{N_{delivered}} \tag{3.1}$$

According to Amazon an automated transport system using UAVs should be capable of delivering goods within 30 minutes after ordering (CBS, 2013). Although Amazon also assumes this time to include the order picking time, in this research the 30 minutes time window is assumed to be the maximum transport time within a range of 15 kilometres between the moment a parcel becomes available for pick-up until it has been delivered at its destination.

DELIVERY COSTS

Besides Customer Satisfaction, another KPI used by PostNL is the costs of delivery. Setting up large distribution networks, such as the NLI have a significant impact on the financial position of the company. The investments required to set up these distribution networks are composed of both capital costs and operational costs, which ultimately results in the overall costs per delivery.

Captial Costs

The capital costs factors that are applicable to an distribution network are:

- Vehicles (Trucks, delivery vans)
- Depots
- Sorting machines
- Locker points
- Postal offices
- Roll Containers

Not all capital costs factors should be considered in this research, as most of the underlying infrastructure is already present today and will be used in the test cases. Instead only the required additional vehicles and any other equipment required in the design should be considered part of capital investments for an ATS. The delivery costs are calculated from the capital costs by dividing the daily debit costs based on the expected lifetime of the equipment by the total daily parcel volume.

Operational Costs

Operational costs for a distribution network include:

- Maintenance costs
- Fuel costs
- Labour costs

Human labour cost will not be considered as PI in this research, because the ATS is an automated system and only a handful of employees are needed in the control room to monitor the system.

Further, operational costs are dictated by the usage of the system, which is expressed in vehicle fuel cost and vehicle maintenance cost. Both factors are PIs for this research and can be measured with the covered distance of the UAVs.

ENVIRONMENTAL IMPACT

The last aspect that is measured is the environmental impact of the parcel distribution operations on the external environment. PostNL is increasingly focussing on more sustainable operations, striving to reduce their environmental impact by lowering the energy consumption of their buildings, small trucks, vans and large trucks.

Although PostNL expresses their environmental impact in multiple emission types, such as NO2, and PM(x), these emissions are just as CO2 directly proportional to the covered distance. It is therefore chosen to only monitor the effects in terms of CO2 emissions. For these calculations PostNL uses energy conversion factors taken from the 2015 UK DEFRA tables, which relate to internationally acknowledged organisations, such as the Intergovernmental Panel on Climate Change, the International Energy Agency and the Greenhouse Gas Protocol and is also used in the calculations of PostNL for the emissions.

3.3 CONCLUSION

Parcel services are characterised by the offered transit time and limitations in size and weight of parcels that are transported. While courier services offer point-to-point transportation of parcels within the same day, express and regular parcel services use hub and spoke distribution networks. These hub & poke distribution networks are used to distribute large volumes of parcels in a cost efficient manner by consolidating many parcels with different origins and different destinations into large shipments for long distance transport, a principle that is also referred to as economies of scale. In the Netherlands, PostNL also uses a hub & spoke distribution network. In the distribution process, parcels are collected in the afternoon, sorted, transported and cross-docked overnight, sorted for a second time and finally delivered to the final destination in the morning. All these processes are scheduled in advance and have fixed cut-off times to ensure that parcels can reach the subsequent processes on-time. As a result all these processes lie in the critical path of the distribution process and thus when a parcel does not reach the cut-off time of the process, it will have to wait until the next day to be distributed. In addition, due to the scheduled processes, there exists a minimum transit time for parcels which cannot be further reduced and therefore most of these networks are currently only capable of next day delivery.

Although PostNL has set the weight and size limitations for of regular parcel at 30 kilograms and 176 x 78 x 58 centimetres, most parcels are much smaller and lighter than these limitations. However, when considering the payload carrying capacity of the selected case UAV, approximately only 68% of all parcels can be transported by this UAV.

Finally, customer satisfaction, delivery costs and environmental impact serve as key performance indicators for PostNL to measure the performance of the distribution process. Although customer satisfaction is originally a qualitative performance indicator, it can be expressed as a reliability quantitative performance indicator by assuming a transit time delivery reliability to be measured.

4

CONCEPTUAL DESIGN OF AN AERIAL TRANSPORT SYSTEM FOR FUTURE LAST MILE PARCEL DISTRIBUTION WITH UNMANNED AERIAL VEHICLES

Chapter Abstract: *According to future state strategy of PostNL for 2020 , the trends influencing the future environment of last mile parcel distribution are urbanization, sustainability and demand for faster and more customer oriented parcel services. Based on these trends it is expected that the main opportunities for UAVs in the future last mile parcel distribution process lie in same-day and on-demand collection and delivery of parcels in densely populated areas. With consumers in these areas often living in high rise building, collection and delivery points will serve as locations where consumers can deliver or pick-up their parcels. At these points micro-depots are located where parcels can be stored before being pick-up by consumers or a UAV. Docking platforms on top of these micro-depots transfer the parcel to an available UAV assigned to transport the parcel to it final destination, which can either be a depot or another micro-depot. When the UAV cannot reach its destination with the remaining battery capacity, it visits one or more intermediate (micro-)depots to exchange its battery. Due to the uncertainties in parcel demand, the system is controlled by a centralized dispatching control system, that can use various dispatching policies to make decisions on which parcels are transported by what UAVs.*

In section 4.1 the system boundaries and requirements for an ATS are formulated based on the knowledge of the current state combined with trends influencing the future state of last mile parcel distribution. Section 4.2 then gives a description on the different types of equipment that have been found in literature on other ATS, followed by the design of the function structure and assignment of the equipment to the various system functions. In section section 4.3 literature on different types of control systems is considered, where after the conclusion considers the design decisions that have been made in this chapter related to the types of equipment and the selected control system and how these are interconnected (section 4.4).

4.1 SYSTEM BOUNDARIES AND REQUIREMENTS

The first step of the conceptual design involves setting the system boundaries and requirements to focus the further design activities and determine the means of input and output that are part of the interaction between the system and its environment (Veeke et al., 2008).

With the knowledge on current state of last mile parcel distribution, the question is now where UAVs could play a role within the future last mile parcel distribution process and what the requirement are to integrate them into the process. In order to answer this question both the knowledge on the current state and the trends influencing the future state are combined to come to a general understanding of the future state environment for the ATS and the role that it can play within this environment.

FROM CURRENT STATE TO FUTURE STATE

According to future state strategy of PostNL for 2020 (PostNL, 2015b), the trends influencing the future environment of last mile parcel distribution can be divided into three categories (PostNL, 2015a). First the technological developments, which includes UAVs. Second the acceleration of online sales including the change in retailer and consumers needs and third the sustainable society influenced by urbanization and sustainability trends.

When considering the sustainable society trends, it can be argued that future last mile parcel distribution in urban areas will play a more prominent role, as more consumers will live in (densely populated) urban areas due to ongoing urbanization (PostNL, 2015a). With the acceleration of online sales the parcel volumes collected and delivered within these urban areas can also be expected to increase. Hence sustainability of delivery services will become more important, as local governments will presumably take measures to reduce congestion and emissions caused by increasing transportation movements in urban areas. Meanwhile, with the shift of consumers to urban areas, the population in rural areas will further diminish, increasing the costs of delivery to these areas due to lower economy of density (Boyer et al., 2009).

Meanwhile the acceleration of online sales is driven by the changes in the needs and behaviour of both retailers and consumers. In most developed countries existing regular parcel services already offer standard next day delivery. A next logical evolution for many larger online retailers is the move towards same-day and on-demand delivery to compete with existing brick-and-mortar retailers. Some larger retailers are therefore already rethinking their fulfilment strategies, by moving towards omni-channel retailing, local urban warehousing or anticipatory shipping to reduce cut-off times (Harrington, 2015). However, these developments increase delivery costs and at present only 30% of the consumers is willing to pay higher delivery costs for same-day or on-demand parcel services, whereas around 70% of the consumers still prefers the parcel service with the lowest delivery costs (Joerss et al., 2016). This means that potential faster parcel services should be cost competitive with existing next-day delivery services. Furthermore, an increasing number of consumers is demanding more control over when, where and how delivery takes place, meaning a shift towards more consumer oriented delivery services.

Based on these developments the opportunities of UAVs in the distribution process will depend on both the type of environment in which the UAV has to operate and on the the transit time that is offered by the parcel services in the future. By combining these two aspects, the opportunities for UAVs in future last mile parcel distribution can be put into perspective (Fig. 4.1).

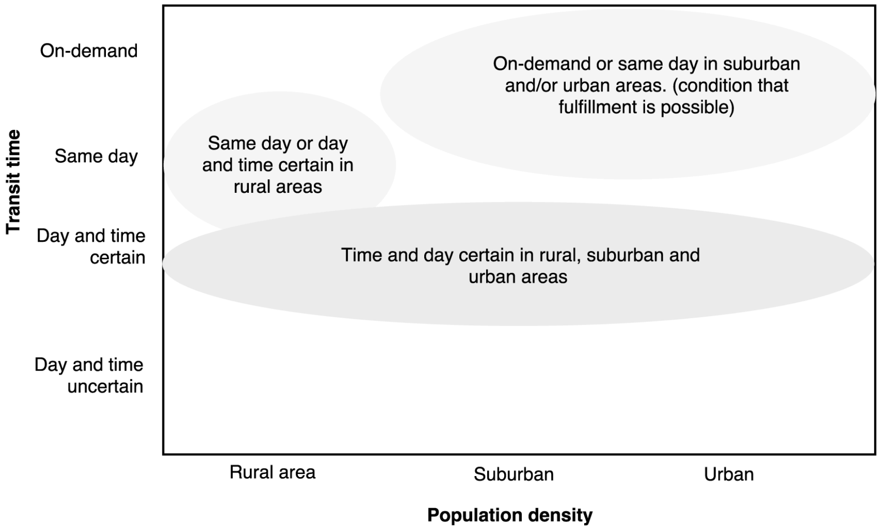


Figure 4.1: Opportunities Future State Last Mile Distribution with UAVs

The first opportunity for the UAVs is in day and time certain parcel services offered to rural, suburban and urban areas. With the development of large online retailers demanding later cut-off times of the processes, UAVs could be used to transport parcels outside the cut-off times of regular scheduled processes. However, this would only be a solution for

In rural areas, UAVs could be used to delivery parcels the same-day in a cost effective manner combined with a delivery truck. On-demand delivery with UAVs in rural areas will presumable not become available, as the distance between retailers and consumers in rural areas will remain too large.

The last and most promising opportunity is expected to lie in same-day or on-demand parcel distribution in (sub)urban areas. For regular parcel distribution networks to accommodate same-day or on-demand collection and delivery similar to courier parcel services, UAVs could play a role in lowering on-demand delivery costs, increase sustainability and reduce traffic in these areas. However, this is only possible, under the assumption that some of the largest online retailers will move their inventory closer towards the edges of (densely populated) urban areas.

SYSTEM BOUNDARIES FOR FUTURE STATE

Because large online retailers are the main customers of PostNL for the regular parcel service, it is expected that the largest benefits to be gained lie in on-demand collection and delivery of parcels in (densley) populated areas. Therefore the system boundaries will concentrate on the potential future application of UAVs for on-demand last mile parcel distribution in (densely populated) urban areas. The ATS will provide distribution of goods between the depots of online retailers to consumers in urban areas. Because consumers in urban areas tend to live in high-rise buildings with no directly accessible front door, home delivery with UAVs is complicated, as UAVs do not have the capability to enter these buildings. In addition, home delivery requires additional on-board systems to identify the consumer and the UAV might have to wait until the parcels can be handed over to the consumer.

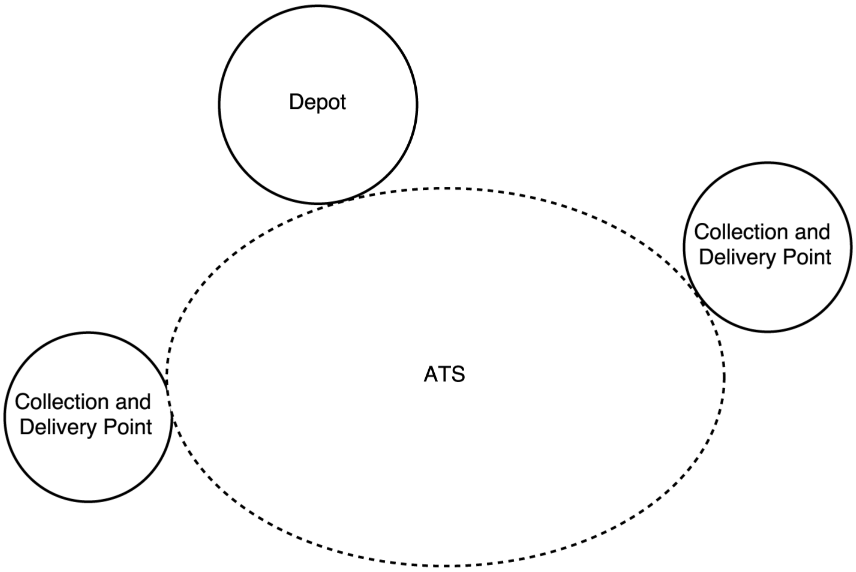


Figure 4.2: ATS system boundaries

Therefore CDP's will serve as the final delivery location for parcels. With customers demanding more control over when and where they receive their parcels, these CDP's should be accessible 24 hours per day and 7 days per week and preferably should be located within a short distances of customers, giving a dense network of CDP's in these urban areas (Fig 4.2).

SYSTEM REQUIREMENTS FOR FUTURE STATE

Based on the system boundaries and its operating environment a number of requirements have been for the system which are summarized below:

- Operate in (densely populated) urban environment.
- No human intervention or guidance should required during operation.
- Operational 24 hours per day, 7 days per week.
- Capable of handing regular weather conditions.
- Capable of handing large volumes
- Covering a service region of at least 15 kilometres around a depot.
- Sustainable operation by use of battery powered UAVs
- Scalable to handle increasing or fluctuating parcel demand and coverage of the operating area.
- Support on-demand collection and delivery within 30 minutes.
- Safe interaction with humans and animals.

4.2 SYSTEM EQUIPMENT

This section gives a description on the different types of equipment and their general characteristics based on ATS found in literature. Further, the function structure of the system is described using a top-down approach and the types of equipment are assigned to the various functions to come to a functioning concept. As mentioned in the research methodology, designing a system is an iterative process and while some of the equipment and its characteristics are described before the function structure has been defined, the design decisions are somewhat interrelated.

Most literature on ATS is limited to newspaper articles and patent applications. From these sources a number of commonly used types of equipment with certain characteristics can be distinguished. These types of equipment include:

- Payload containers
- Unmanned Aerial Vehicle
- Docking platform
- (Micro-)depot

The general characteristics, the functions and consideration behind the use of these types of equipment will now be motivated within the system boundaries and requirements that have been set in the previous section.

PAYLOAD CONTAINER

In the existing parcel distribution process, goods are often restrained in parcels that fall within the size and weight restrictions set by the parcel carrier such as PostNL. These parcels can be considered as a type of unit load, which is defined as an item or a number of items arranged and restrained in such a way that they can be pickup and transported between two points as a single object(Vis, 2006). Examples of other well known unit loads are containers and pallets. Unit loads are a fundamental part of automated transport systems, as they offer the possibility to standardize the material handling equipment.

Many of the early presented ATS for last mile parcel distribution, including those of Amazon, Google and DHL use small containers as unit loads to contain the goods that are transported. (CBS, 2013) (DHL, 2014) Although containers offer the possibility to standardize material handling equipment Gee et al. (2015) indicates that a payload container reduces valuable payload carrying capacity of the UAV.

Instead a more preferred approach would be to implement parcel size and weight restrictions specifically for the ATS, similar to the restrictions of many parcel carriers for their services today. The most recent ATS concept unveiled by Amazon and DHL, have also shown that the small containers have been replaced with cardboard parcels of a fixed size, that are loaded into the body of the UAV (Moran, 2016).

UNMANNED AERIAL VEHICLE

In an ATS the main function of the UAV is transportation of goods. However the UAV can also be outfitted with an loading or unloading mechanism to transfer goods. In his patent, Graham et al. (2015) describes the use of a cable for lowering the payload container down from the UAV and using a safety release mechanism to detach it from the cable. Meanwhile Kimchi et al. (2014) uses gravity and a release mechanism to drop the payload container on the ground when the UAV has landed. No literature was found about on-board loading mechanisms for UAVs, potentially as this again would reduce valuable payload capacity. Instead many ATS concepts use an external (manual) loading mechanism.

One of the system requirements is that UAVs should be capable of operating in urban areas. This requires the UAVs to be small and manoeuvrable enough to maintain accessibile to urban areas that often have limited space. Research from Google has shown that UAVs with a maximum wingspan of 2 meters would be capable of servicing 90% of the customer within populated urban areas Warwick (2014). Because of these space limitations the UAVs should have Vertical Take-off and Landing (VTOL) capabilities to operate without the need for runway infrastructure.

Besides the requirements to operate in urban areas, the UAV should also be capable of coping with certain weather conditions, including wind and precipitation. In case of wind conditions, UAVs should be capable of handling wind speeds of up to 10 m/s, which wou 90% of all rurban areas.Warwick (2014).

A short market exploration of commercially available UAVs has been performed to gain insight into the capabilities of commercially available battery powered UAVs within the set requirements. For all UAVs the operational characteristics that have been identified in the research scope to be important for transportation applications have been collected and presented in table 4.1.

Table 4.1: Market Exploration Commercially Available UAVs

Unmanned Aerial Vehicle	**Manufacturer**	**Cruise speed [m/s]**	**Average endurance [min]**	**Max. Payload capacity [kg]**
MD4-3000	Microdrones	16	45	3
Draganflyer X6	Dragonfly Innovations Inc.	13,89	18	0,5
Draganflyer X4-P	Dragonfly Innovations Inc.	13,89	30	0,8
Multirotor G4 Surveillance	Service Drone	21	18	2,3
Multirotor G4 Skycrane	Service Drone	13,89	12	6,5
HL48 Pregasus	SABRE	16	45	4
Agras MG-1	DIJ	18,33	24	3,7
Parcelcopter 3	DHL	20	30	2
MD4-1000	Microdrones	11,94	45	1,2
AT-10	Advanced UAV Technology	13,89	30	1,5
AT-20	Advanced UAV Technology	22,22	55	4,5
VertiKUL	KU Leuven	16,94	33	1
Matrice 600	DIJ	18,06	30	2,5
Spreading Wings SJ1000+	DIJ	21,94	25	3
Speading Wings S900	DIJ	16	18	3,5

Most of the selected UAVs have a relatively low payload capacity (often 2 kilograms or less). This suggests that there are physical limitations to the payload size that UAVs within these requirement are capable of carrying. This also means that there is a high probability that current delivery with trucks is remain to exists. Furthermore, there are also large differences in endurance-payload combinations and cruise speeds between the UAVs. Many of the UAVs with higher payload and endurance characteristics are based on a single-rotor design, whereas the lower payload and endurance combinations are often multi-rotor designs which is a result of the difference in efficiency between these types of air frame designs (Fillipone, 2006).

The market exploration shows that within the requirements that have been set for UAVs to operate in urban areas, there are large differences between the operational characteristics. The influence of these characteristics will therefore need to be further explored during the detailed design.

DOCKING PLATFORM

Accoring to Warwick (2014) research has shown that when customers directly interact with a UAV during unloading, 60% of them where likely to grab their parcels before being unloaded, increasing the risk of injuries or damaging the UAV. Furthermore, transferring parcels directly between consumers and UAVs, would require additional on-board systems for the UAV to identify the person handing over the parcel and the UAV might have to wait until the customer is ready to hand over the parcel, reducing the utilization of the UAVs.

To reduce direct interaction between the consumers and the UAV, Hoekstra et al. (2015) proposes the use of an automated docking platform as an external automated transfer mechanism, to increase safety and ensure fast processing times. These docking platforms could be located on higher buildings, where parcels are automatically distributed to an automated storage facility within the building or located on separate stand alone storage facilities such as parcel lockers.

Because battery powered UAVs cannot operate continuously without charging or exchanging their batteries after a certain operating period, docking platforms are also mentioned by Swieringa et al. (2010) to serve as battery charging or exchanging function to extend the operating area and increase the mission duration of UAVs.

While there have been numerous efforts in developing docking platforms for battery charging or exchanging of ground based vehicles, only a few studies have focused on aerial vehicles. Godzdanker et al. (2011) designed and developed a mobile charging docking platform for UAVs and has proposed an algorithm to determine the optimal placement of these platforms in the operating area.

Although battery charging is a low costs solution, letting vehicles wait for a battery to properly recharge is very time-consuming, and can cause delays in the overall mission objective. A much faster approach is to exchange the drained battery for a fully charged battery. Swieringa et al. (2010), Kemper et al. (2010) and Suzuki et al. (2011) have designed various mechanisms for battery exchange docking platforms and suggest that in areas with a high target coverage, exchanging batteries is more economically viable compared to recharging. Therefore docking platforms will also be used to exchange depleted batteries.

MICRO-DEPOT

Micro depots can function as an interface between customers in the external environment and the internal elements of the system during delivery.
At present, several companies are developing micro-depots for their ATS concepts, including DPDGroup, DHL and Matternet. Most of these micro-depots function as a storage facility to handover parcels to customers similar to a parcel lockers. Some of these micro-depots are also outfitted with automated docking platforms to automate the transfer process between the UAV and the micro-depot, but also

(a) DHL Skyport (Varnholt, 2016)

(b) DPDGroup terminal (DPDgroup, 2015)

(c) Matternet terminal (Raptopoulos et al., 2013)

Figure 4.3: ATS micro-depots

to exchange and recharge depleted batteries. While all micro-depots are very different in terms of shape, size and working principles they have a few generic characteristics in common:

- Storage capacity
- Docking platform(s)

Most micro-depots under development have a certain storage capacity used for temporary storage of parcels before they are either transferred to another UAV or are picked up by a customer. For example, the modified Packstation of DHL has the capability to store five parcels at once.(Varnholt, 2016)

Besides micro-depots, most retailers and parcel carriers use larger depots. The general characteristics of these larger depots are similar to micro-depots However, it is expected that the required storage capacity and number of docking platforms are much higher compared to micro-depots, as more parcels would need to be stored and the loading and unloading frequency would be much higher.

These larger depots could also function as a central location to position idle UAVs, in order to prevent occupation of docking platforms at the micro-depots. One of the questions is how many idle UAVs on average would be positioned at the depots, when deciding to let the depot function as a central positioning location for idle UAVs.

4.2.1 SYSTEM EQUIPMENT FUNCTION DESCRIPTION

With the possible types of equipment that can be used in the ATS having been described, the function structure model for the ATS needs to be established in order to determine the different functions that need to be fulfilled by the system and the processes that are performed by the equipment.

To establish the function structure, a top down approach is used, starting from the highest level of abstraction using the black-box. The primary function of the ATS is similar to the primary function of PostNL as defined in section 3.2 (Fig. 4.4)

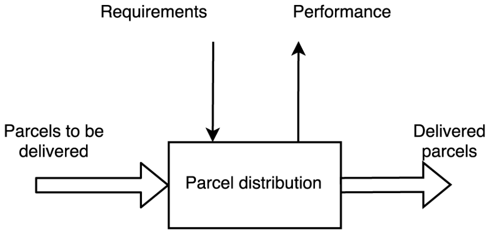


Figure 4.4: Black-box ATS

Similar to the analysis of the current state distribution process of PostNL, again a PROPER-model is used to model the relations between the different aspect flows. The used PROPER-model is again similar that of PostNL as the system is part of the organization.

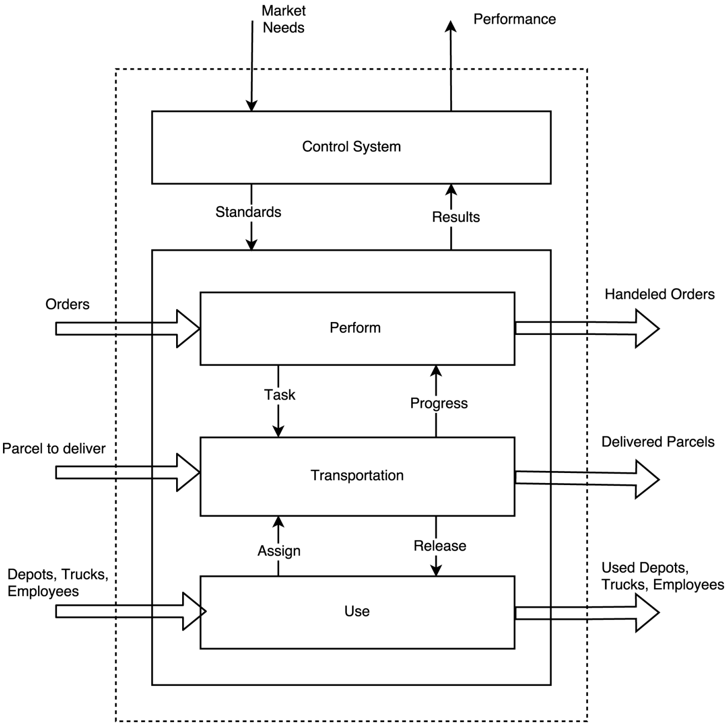


Figure 4.5: PROPER-model ATS

One level down zooming into the black-box of the transportation function, three different functions can be distinguished, again similar to the current function of the transportation process of PostNL, namely, collection, transport and delivery. (Fig. **??**)

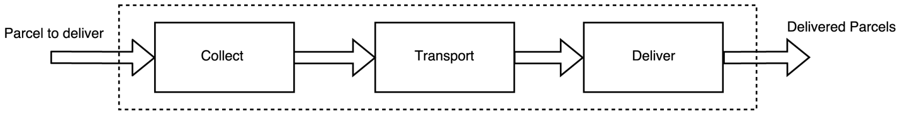
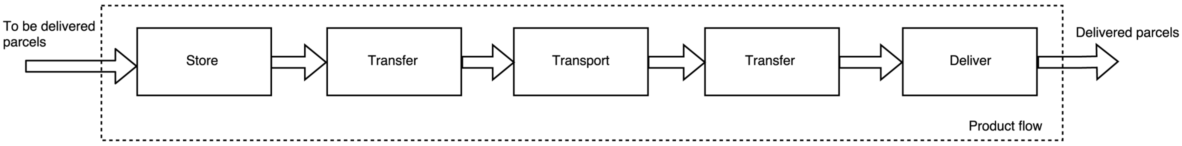


Figure 4.6: Sub-functions of the ATS transportation function

When a parcel enters the system, it is assumed that in many cases there are no immediate UAVs available at the origin to pick-up the parcel, which is similar to the current state distribution process in which parcels are stored in roll containers before being pick-up by a collection driver. Therefore when a parcel enters the system it must be stored. After the parcel has been stored it must be transported to its final destination where the parcel is delivered. In order to keep the function model as generic as possible, a transfer function is added between the other functions. (fig. **??**) The transfer function represents the possibility that the different functions could be fulfilled by different types of equipment.



Sub-functions of the ATS transportation function of the ATS

At this stage the function structure is rather abstract, which raises some important questions. For example, what type of equipment should be used for which functions? A single type of equipment, such as the UAV could be used to handle all functions, but another possibility is that specialized equipment would be used for each function separately. In case separate types of equipment are used they must interact in some manner. To make these decisions the resource flow is added to the function structure in order to further elaborate on the assignment of equipment as illustrated in figure 4.7.

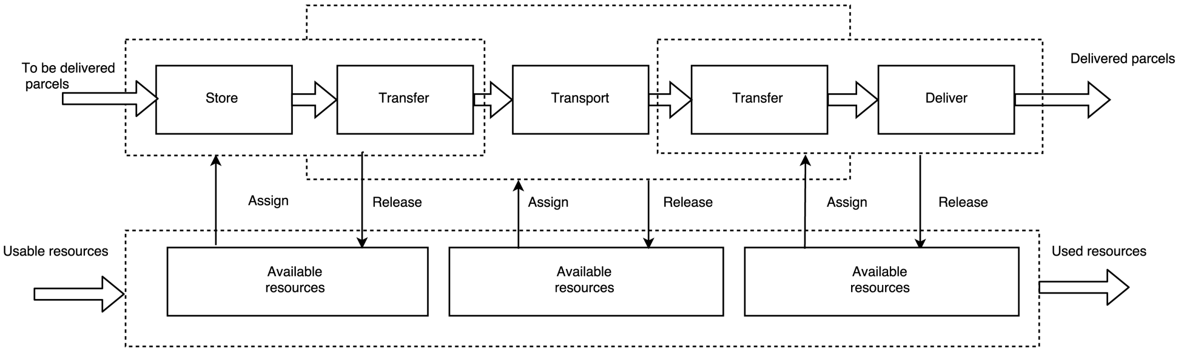


Figure 4.7: Combined product- and resource flow of the ATS

Based on the available types of equipment and the functions they can full fill, they are now assigned to the various functions. The storage function is performed by a micro-depot or depot depending on the origin of the parcel. The size of the storage buffer from the (micro-)depot will determine if a a parcel can enter the system. For example, when a parcel wants to enter the system and there is no storage capacity left at the (micro-)depot, it must either wait until capacity becomes available or entirely leave the system. The storage function should check whether there is still buffer capacity left and decides if the parcel can be stored or should be rejected. As stated earlier for the transfer function it is preferred to use a docking platform, as the docking platform ensures reliable loading and unloading times, but also reduces the need for additional loading or unloading mechanisms on-board the UAV which reduces potential payload capacity.

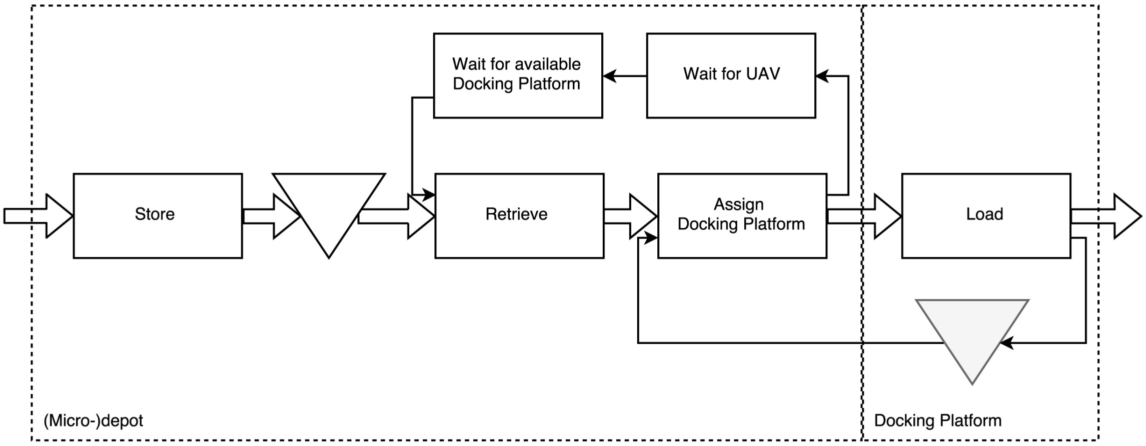


Figure 4.8: (Micro-)depot storage and loading process

When the UAV arrives for the pick-up, the (micro-)depot first assigns an available docking platform to the UAV. Meanwhile the parcel is retrieved from the storage. Next the docking platform is prepared for the UAV to land. This preparation could include opening a hatch that protects the inner mechanisms of the (micro-)depot or aligning the UAV with the docking platform before it can securely and safely land. After the UAV has landed on the docking platform the parcel is loaded into the UAV and the (micro-)depot waits for another UAV or parcel to be handled.

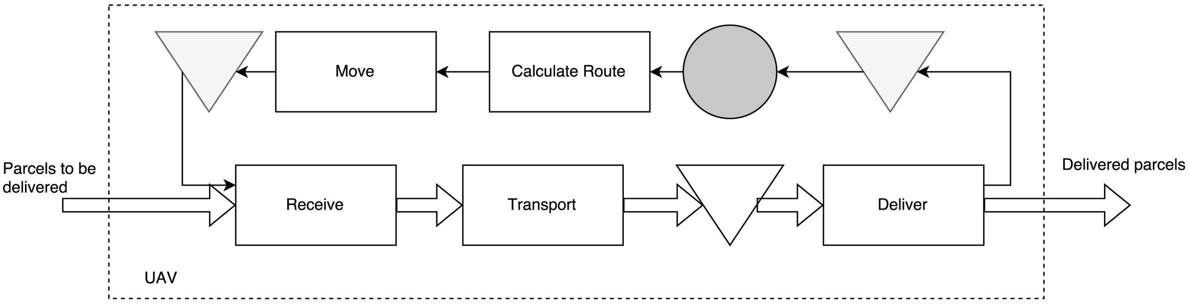


Figure 4.9: UAV transport process

When the UAV has received the parcel from the docking platform, it then transports the parcel to its destination (Fig 4.9). At the destination it must wait until a docking platform or for storage capacity to become available. After the UAV has landed it can be unloaded by the docking platform and the parcel is considered as delivered. Then the UAV waits for another assignment from the control system, which can either be a new parcel to be collected or move to an idling location when there are no assignments available.

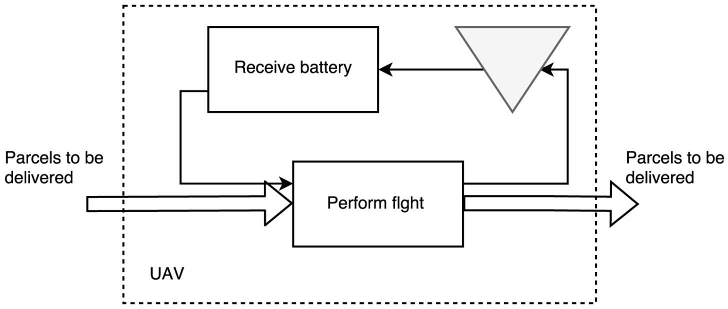


Figure 4.10: UAV transport function

Because the UAV has a limited flight range, it sometimes needs to make intermediate stops at (micro-)depots to receive a fully charged battery. Therefore the transport function includes the reception of a new battery. (Fig. 4.10) The contents of the move function, without a parcel on-board is similar to that of the transport function.

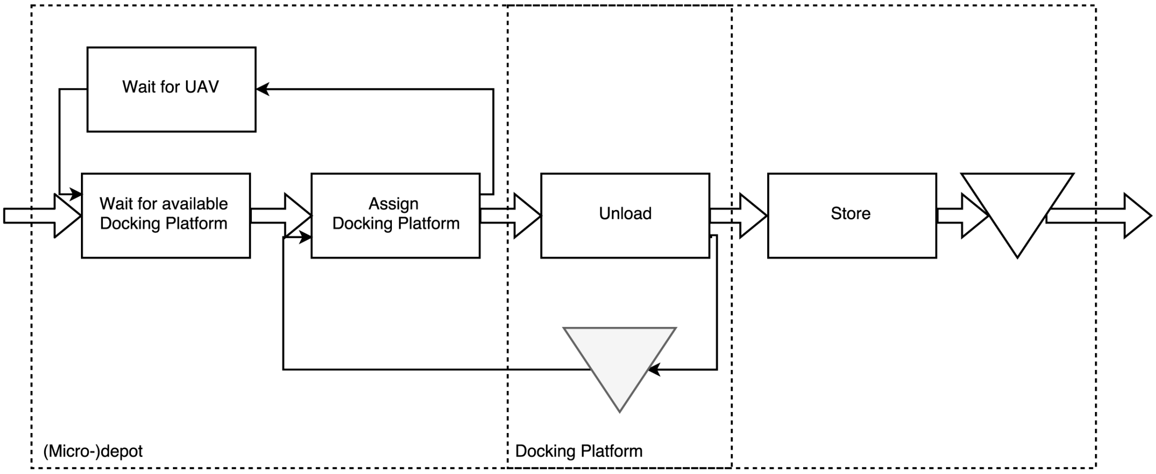


Figure 4.11: (Micro-)depot storage and unloading process

When the UAV has arrived at the destination, it must wait for the (micro-)depot to have a docking platform available. The transfer process after transport is considered to be the reverse of the first transfer process. Finally, the goods leave the system when retrieved by a customer. However, because of the uncertainty about the distribution what time it takes before consumers collect their parcels, it is assumed they would immediately leave the system without any waiting time.
When there are multiple UAVs queued at the (micro-)depot, a decision must be made on what process is performed by the first available docking platform. (Fig. 4.12 The selection decision on what UAV to serve can be done in several ways, such as a first come-first served basis, least remaining endurance or the type of process for which they are visiting. Because the goal is to increase customer satisfaction and thus reduce overall delivery time, it was chosen to serve UAVs that require charging first, then unloading and finally loading of UAVs.

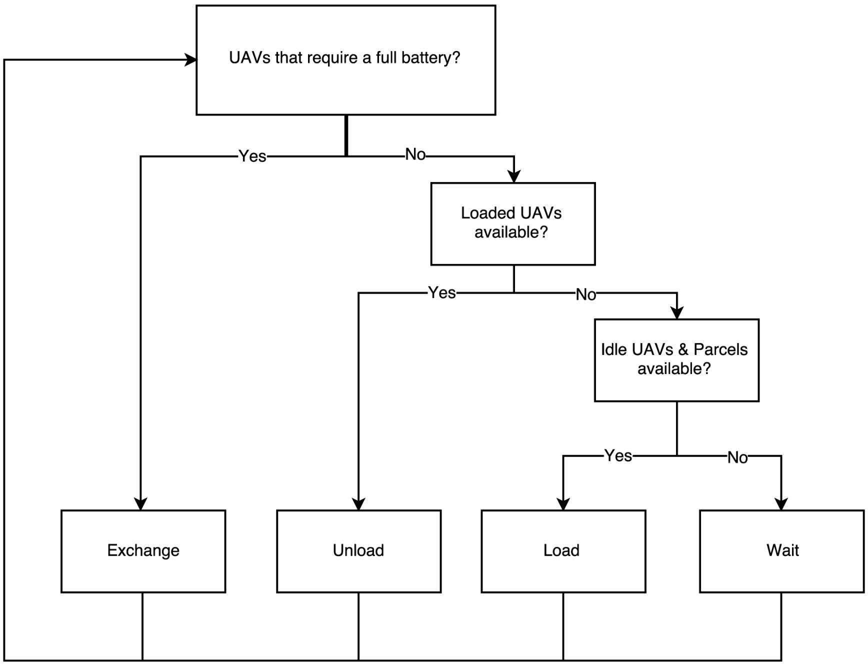


Figure 4.12: (Micro-)depot process decision scheme

4.3 CONTROL SYSTEM DESIGN

The control system focuses on the coordination among vehicles in terms of scheduling, dispatching and routing, ensuring fast and efficient operation of the system independently of the number of vehicles used (Vis, 2006). If these requirements are not guaranteed, the overall performance of the system will decline, become less efficient and generate less profit or operate at higher costs (Vivaldini, 2015).

Literature on scheduling, dispatching and routing methods have a long history in the domain of Automated Guided Vehicle (AGV) systems. According to Bednowitz (2010) these strategies would also be suited for systems with UAVs in certain settings. In order to determine what control strategies would be most appropriate for the ATS, existing literature on scheduling, dispatching and routing methods is reviewed.

4.3.1 SCHEDULING

A vehicle scheduling system decides when, where and how a vehicle should act to perform tasks, including the routes it should take. If all tasks are known prior to the planning period, the problem of assigning tasks to vehicles and determining the order of execution can be solved as an off-line scheduling problem (Le-Anh, De Koster, 2006). This allows the construction and optimization of complete vehicle routes before vehicles carry them out. These combined routing and scheduling problems are also known as Traveling Salesman Problems (TSP) or Vehicle Routing Problems (VRP) in case of multiple vehicles. In general these problems are either solved with exact or heuristic methods to find a (near) optimal solution.

In literature several papers have been found that specifically address the scheduling problem for systems with UAVs, focusing on either uncapacitated, capacitated or persistent missions. Shima et al. (2005) proposed a genetic algorithm to efficiently search for feasible solutions to a scheduling problem of assigning multiple UAVs to multiple moving ground targets in an uncapacitated mission (eg. maximum flight duration or distance are not taken into consideration). In many cases however, the mission duration is limited by the fuel or battery capacity of the UAV and thus concerns a capacitated mission. In these cases, the limited flight duration or distance must be taken into consideration in the scheduling problem. Weinstein, Schumacher (2007) formulated the assignment problem of multiple UAVs visiting targets from a single take-off and landing depot as a capacitated vehicle routing problem with time windows. Different mixed integer linear programming (MILP) model formulations were developed which included several real word scenario constraints and were solved with multiple objectives, such as minimization of makespan, costs and distance. When (automated) refueling stations are used to support persistent missions, the visits of UAVs to these stations during their mission must be incorporated into the scheduling problem. Kim et al. (2013) were the first to develop a MILP model for the problem of scheduling a fleet of UAVs in the presence of refueling stations.

While all scheduling problems above assume task information to be known prior to the mission, in practice environments are much more stochastic of nature and exact information about tasks is usually only known at a very late instant. When there are small changes in task arrival times, changes in travel times, failure of vehicles or any other disruptions, it can destroy the entire schedule, making off-line scheduling impractical. In these cases online control systems, such as dynamic scheduling or dispatching systems must be used. Dynamic scheduling systems, use a rolling planning horizon in which the schedule for vehicles is updated when new task assignments arrive and are often more efficient compared to dispatching systems (Le-Anh, De Koster, 2006).

4.3.2 DISPATCHING

A dispatching control system can be considered as a scheduling system with a zero planning horizon and uses dispatching rules to make decisions, when a vehicle finishes a task, when a vehicle has research its parking location or when a new transport task becomes available (Le-Anh, De Koster, 2006). According to literature, dispatching control systems can be divided into either decentralized and centralized systems.

DECENTRALIZED CONTROL SYSTEM

In decentralized control systems, dispatching decisions are performed by vehicles using only local information. An example of a decentralized control system was presented by Bartholdi, Platzman (1989), where a vehicle operating on a simple loop layout using a greedy *Fist-Encountered-First Served* (FEFS) policy. With the FEFS, the vehicle continuously circulates the loop and picks up the first load it encounters.

While the main advantage of decentralized control systems is their simplicity and they are often useful when there are communication limitations or robustness issues that prohibit communication between the vehicles and a central control system, the efficiency of these dispatching systems is often low compared to centralized control systems, which are more complicated as they need to keep track of all movements in the system.

CENTRALIZED CONTROL SYSTEM

In centralized control systems, dispatching decisions are based on global information about the position of loads and vehicles and the state of the collection and delivery locations. In general, dispatching policies for centralized dispatching control systems can be divided into two types of operation decisions: workstation-initiated when the system has queued transportation requests and vehicle-initiated when the system has idle vehicles (Egbelu, Tanchoco, 1984).

Workcentre initiated dispatching

In case of workcentre initiated dispatching, a vehicle is selected from a number of idle vehicles by the load to perform a task. The following rules are the most commonly used in workcentre initiated dispatching systems.

Table 4.2: Workcentre Initiated Dispatching Policies

Rule	Acronym	Description
First Available Vehicle	FAV	The vehicle that has the shortest distance to the load is assigned to the transportation task.
Longest Idle Vehicle	LIV	the vehicle that has remained idle the longest among all the idle vehicles is assigned to the task. Meaning the first available vehicle is selected for the task.
Least Utilized Vehicle	LUV	The vehicle with the lowest utilization rate is assigned to the transportation task.
Nearest Available Vehicle	NAV	The vehicle that has the shortest distance to the load is assigned to the transportation task.
Random Vehicle	RV	A load is randomly assigned to any available vehicle.

Vehicle initiated dispatching

Vehicle initiated dispatching, determines how a vehicle is routed when a vehicle has done its task and is ready for the next task. The following rules are the most commonly used in vehicle initiated dispatching systems.

Many papers concerning centralized dispatching control systems are related to automated guided vehicles systems. De Koster et al. (2004) has simulated three real-world operating conditions of automated guided vehicle systems with different combinations of both time-based and distance-based policies. Stating that in all operating conditions the distance-based policies outperformed the time-based policies.

In previous reseach only one paper adresses the performance of centralized dispathing control system for a system with UAVs. Bednowitz (2010) has simulated a system with three UAVs using different combinations of dispatching policies for a centralized dispatching control system. While his

Table 4.3: Vehicle Initiated Dispatching Policies

Rule	Acronym	Description
First-Come-First Serve	FCFS	Assigns the first available load in system to the available vehicle.
Modified First-Come-First Serve	MOD-FCFS	Assigns any available load at the available vehicles location and thereafter the first available loads in the system.
Longest Travel Time or Distance	LTTD	The vehicle that has the longest travel time or greatest distance to the load is assigned to the transportation task.
Shortest Travel Time or Distance	STTD	The vehicle that has the shortest travel time or distance to the load is assigned to the transportation task.
Maximum Outgoing Queue Size	MOQS	Assigns a vehicle to the workstation with the largest number of loads waiting in its outgoing queue.
Random Job	RJ	a load is randomly assigned to any idle vehicle, regardless of the vehicle location or type of task.

research concludes that distance-based policies (e.g. Shortest Travel Time Distnace) outperform time-based policies (e.g. First-Come-First Served), the research focusses on long duration uncapacitated target surveillance, which cannot be compared to the dynamic demand occuring in on-demand last mile parcel distribution.

Although most studies related to dispatching policies conclude that distance-based policies outperform time-based policies, these papers cannot directly be related to the parcel distribution application and its operational conditions. As a result further insight is needed into what policies in a centralized dispatching control systems would be recommended for parcel distribution with UAVs.

4.3.3 ROUTING

Routing of electric vehicles, such as battery powered UAVs is very different from regular fossil fuel vehicles, which can cover much larger distances without refuelling. To increase the range of electric vehicles, either battery charging or exchanging has to be taken into consideration during the routing process from their origin to their destination.

For routing of the UAVs in the network, a modified version of Dijkstra's shortest path algorithm proposed by Geertsen et al. (2015) is used to determine the fastest route between the origin and destination while taking recharging points into consideration.

The algorithm works in a similar way to the original Dijkstra algorithm, but differs on two aspects. On the one hand, the algorithm uses travel time instead of path weights, and on the other hand it does not visit all nodes in the network. When a node of a certain path becomes out of range, that node and the remaining nodes are skipped. This is possible because the nodes are sorted according to the shortest distance in ascending order.

4.3.4 IDLE VEHICLE POSITIONING

Vehicle idleness in automated transport systems is unavoidable. When a vehicle becomes idle and there is no immediate task to be assigned, a decision must be made on where the vehicle should be positioned. Rather than forcing a vehicle back to return to a single vehicle depot, it would be better to position vehicles near locations with a high probability of new load releases. (Le-Anh, 2005) Idle vehicle positioning methods can be divided into static and dynamic methods.

STATIC VEHICLE POSITIONING

Four of the major static idle vehicle positioning methods proposed in literature are (Egbelu, 1993);

Strategy	Description
Central-zone positioning	A single location has been designated for buffering of idle vehicles. This location can be located close to stations with a high probability of new task arrivals, or at charging capabilities.
Circulatory loop positioning	One or more circulatory loops are defined. When a vehicle becomes idle it travels to and on the loop until a new task arrives.
Point of release positioning	If a vehicle is released, it remains at the location where it became idle until it is reassigned.
Distributed positioning	In the distributed positioning strategy multiple locations are defined for idle vehicles instead of a single location. When a vehicle becomes idle, it is routed to one of these idling location.

DYNAMIC VEHICLE POSITIONING

When collection locations change over time, the positioning location for idle vehicles may also need to change. In order to adapt to this situation the optimal positioning location for idle vehilces can be dynamically calucalated by incorporating the demand changes into the static strategies as done by Kim (1995). Another approach has been proposed by Bednowitz (2010) who uses several p-median policies to dynamically recalculate idling locations for UAVs, a technique that is for example similarly used in determining the optimal locations for distribution centres in their service regions.

Bednowitz (2010) has studied the performance of both static and dynamic idle vehicle positioning strategies for a system with three UAVs. He concluded that the performance of the idle vehicle positioning strategies varies under different conditions. As a result it is not immediately apparent what idle vehicle positioning strategy would result in the best performance.

Because in the ATS most parcel collection demand will originate at a central depot, a static central location positioning strategy will be implemented in the control system.

4.4 CONCLUSION

Based on knowledge of the current last mile distribution process and the trends affecting the future state, the boundaries for the system have been set to include distribution of parcels between collection and delivery points in a (densely populated) urban environment, under the assumption that large retailers will relocate their inventory towards the edges of these urban areas in the near future. The system is required to operate safely, handle large volumes of small and light weight parcels, operate in (densely populated) urban areas and perform on-demand collection and delivery demand of parcels between businesses and consumers.

The systems equipment is composed of payload containers, UAVs, docking platforms and (micro-)depots. Payload containers are considered to be parcels with size and weight limitations (as already used today) based on the payload capacity limitations of the UAVs used for transportation. Docking platforms perform loading and unloading of parcels or exchange batteries and (micro-)depots located at collection and delivery points, that have one or more docking platforms and store parcels before being transfered and transported. In this manner a large and dense network of (micro-)depots can be deployed in an urban environment and fixed routes between the (micro-)depots can be used to obtain a closed system.

4.4.1 CENTRALIZED DISPATCHING CONTROL SYSTEM

From literature it has become clear that often for complex systems, off-line vehicle scheduling control systems are implemented to decide when, where and how a vehicle should act to perform given a certain demand. Most of these scheduling control systems however assume demand information to be known in advance, but in practice environments, demand is often much more stochastic of nature and exact information is often only known at a very late instant. With parcel demand strongly fluctuating on a daily basis, and the requiring on-demand allocation there is no planning horizon available for a scheduling approach, making an off-line scheduling control system impractical.

Instead on-line control systems, such as dynamic scheduling or dispatching systems can be used. Although a dynamic vehicle scheduling control system is more efficient compared to a dispatching control system, these scheduling algorithms would require too much processing time and too much time to develop. Therefore it is decided to implement a more simplistic dispatching control system.

Dispatching control systems can be divided into either decentralized and centralized control systems. While decentralized control systems are very simple and robust in areas with communication limitations as they only use local information to make decisions, centralized control systems are more efficient as all the available information is centralized. As it is expected that UAVs will not encounter any issues concerning the robustness of communication between a central controller and the UAV, it is chosen to use a centralized control system to increase the performance of the system.
In figure 4.13 the role of the selected centralized dispatching control system is displayed within the function structure. The centralized dispatching controller uses information on both the location and number of available UAVs and unassigned parcels in the system to make a decision on which UAV will transport what parcel. The available parcels and UAVs are compared, where after a decision is made based on the control policy standard that is assigned to the dispatching process controller. When a parcel is assigned the UAV calculates the route while taking battery energy restrictions into consideration.

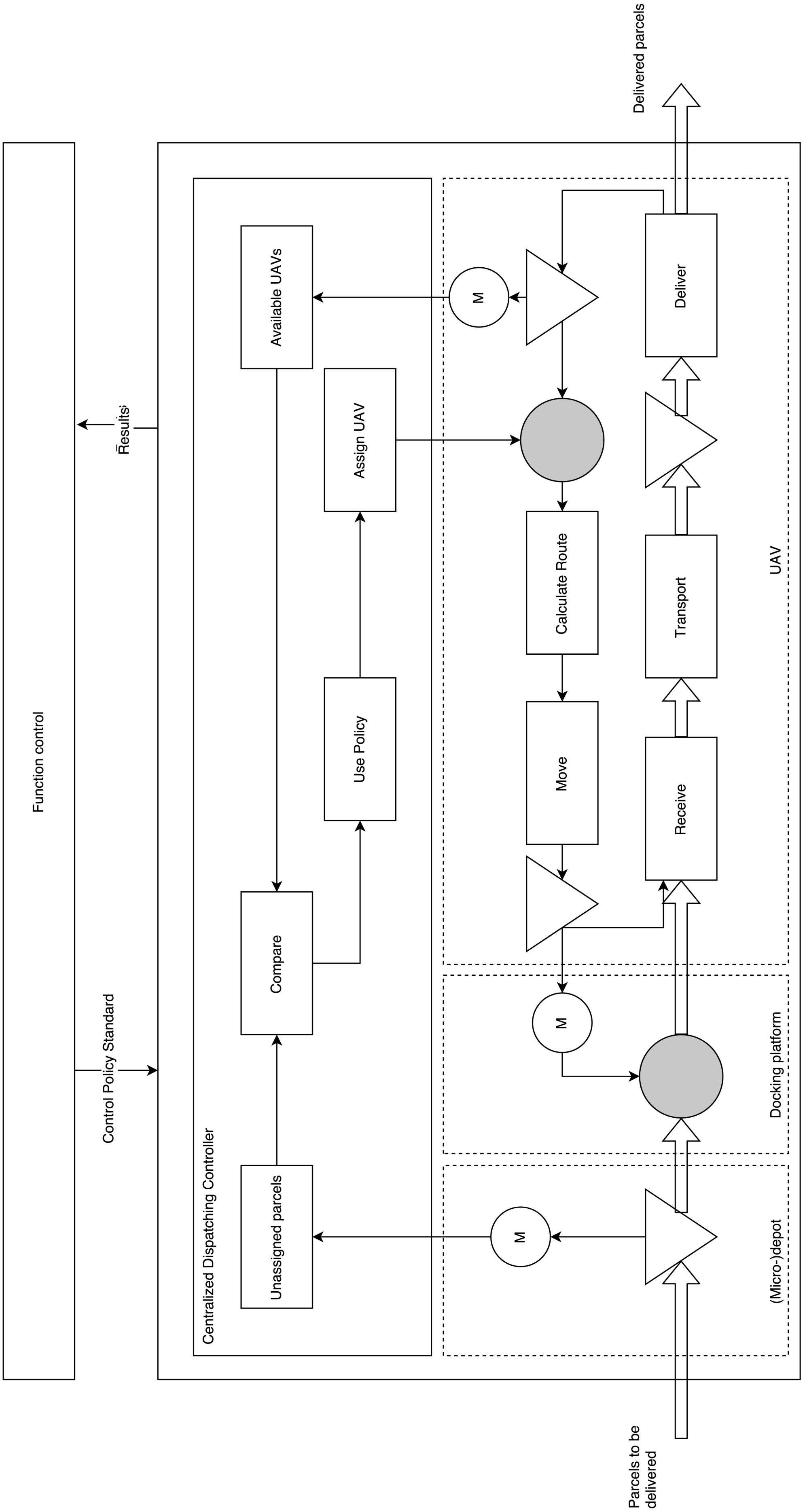


Figure 4.13: Centralized Dispatching Process Control Structure

In case there are no parcels in the system, a static idle vehicle positioning strategy used and assigned the UAV to a central location.

4.4.2 ALTERNATIVE CONTROL POLICIES

The centralized dispatching control system can use different combinations of dispatching policies to determine which UAV must be assigned to what parcel or vice versa. These dispatching policies are divided into workstation-initiated and vehicle-initiated policies. When the condition arises that unassigned parcels can immediately be assigned to available UAVs a workstation-initiated policy is used, otherwise when available parcels cannot be immediately assigned to an available UAV the vehicle-initiated dispatching policies are used.

For the centralized dispatching control system, the three ’First-Come-First Serve’, ’Modified-First-Come-First Serve’ and the ’Shortest-Travel-Time-Distance’ vehicle-initiated dispatching policies are combined with the two ’First Available Vehicle’ and "Nearest Available Vehicle’ workstation-initiated dispatching policies. These dispatching policies have been selected, as they are frequently used in literature and are focusses on reducing the waiting time of parcels as much as possible, which relates to the primary objective of the system.

Furthermore,the three workcentre-initiated dispatching policies ’Longest Idle Vehicle’, ’Least Utilized Vehicle’ and ’Random Vehcile’ policies are excluded as potential alternatives, since the ’Random Vehcile’ policy is considered to be inefficient compared to the other policies and the ’Longest Idle Vehicle’, ’Least Utilized Vehicle’ policies are used to balance workload within the system, which is not necessary considered as the primary goal of the system, considering customer satisfaction as the most important key performance indicator. Concerning vehicle-initiated dispatching policies, the ’Random Job’, ’Longest Travel Time Distance’ and ’ Maximum Outgoing Queue Size’ are not included, as they are also not relevant to the systems primary objective.

FIRST-AVAILABLE VEHCILE/FIRST-COME-FIRST SERVED

The FAV/FCFS dispatching policy, always selects the oldest parcel in system, which is then assigned to the first available UAV in the system. If a parcel enters the system it will always wait for service until all older parcels have been served.

FIRST-AVAILABLE VEHCILE/MODIFIED-FIRST-COME-FIRST SERVED

Opposed to the FAV/FCFS policy, under the FAV/MOD-FCFS dispatching policy, when the UAV has delivered a parcel it will first be determined if there are any parcels that need to be transported at the UAVs current location. In case there are multiple parcels, the oldest parcel at the location will be assigned first. However, when there are no parcels at the location, the oldest parcel in system is assigned to the available UAV.

FIRST-AVAILABLE VEHCILE/SHORTEST-TRAVEL-TIME-DISTANCE

Under the FAV/STTD policy combination, the closest parcel in distance is calculated for the first available UAV. Because the closeness is measured in distance, it can occur that some remote micro-depots are not near locations where UAVs are released and therefore not always qualify for dispatching of a UAV, which illustrates the drawback of the policy as some parcels may be queued for a longer period of time, reducing the overall customer satisfaction.

NEAREST-AVAILABEL-VEHICLE/SHORTEST-TRAVEL-TIME-DISTANCE

Under the NAV/STTD policy combination, the control system either selects the closest available UAV based on distance when only a single parcel is unassigned or the control system selects the closest available parcel in distance in case there is only a single available UAV in the system.

5

DETAILED DESIGN: TEST CASES GOES AND THE HAGUE

Chapter Abstract: *A simulation model is developed based on the conceptual design explained in the previous chapter. Simulation experiments with the model are performed for two test case operating environments: The Hague and Goes. The Hague, is one of the most congested and densely populated areas in the Netherlands, where demand is concentrated in a small part of the operating environment. Meanwhile Goes has a much lower population density and demand is more spread across the operating environment. Simulation results show that in both operating environments, UAVs with higher speeds are preferred compared to UAVs with longer endurance in terms of customer satisfaction. Furthermore, little difference exists in the performance between the dispatching policies , although distance-based policies slightly outperform time-based policies.*

This chapter contains an explanation on the detailed design phase, in which a simulation model has been developed based on conceptual design of the previous chapter. Section 5.1 briefly explains the development of the simulation model including the interactions between objects in the model, the input and output of the model and the assumption that have been made during the development. Section 5.2 gives a description of the characteristics of the two different operating environments that are used as test cases during the simulation experiments. Finally, section 5.4 discusses the simulation results of the experiments for both test cases based on the (key) performance indicators that have been described in section **??**.

5.1 SIMULATION MODEL

For the detailed design a simulation model of the system is developed based on the conceptual design described in the previous chapter. The simulation model allows to experiment with alternative system configurations within different operating environments to gain insight in the behaviour and performance of the system.

This section gives a brief description on how the simulation model operates and what assumption have been made during the development. A more detailed explanation on the development and model set up, including the validation and verification of the simulation model can be found in appendix C.

MODEL STRUCTURE

For the simulation model the types of equipment and the control system are modelled as objects with different attributes and processes based on the description from the conceptual design phase.

Figure **??** shows the objects that have been modelled and the relations between them within the model. Parcels are generated by the parcel generator, which assigns several attributes including a weight, an origin and a destination to the parcel. When there are multiple (micro-)depots in a postal code area, the (micro-)depot is uniformly selected form all available (micro-)depots in the postal code area. Finally, it is added to the (micro-)depot buffer. The control system then assigns an available UAV to the parcel to perform the transportation from the origin to the destination. The UAV then moves on flight paths between the postal code areas where the (micro-)depots are located. When arrived at a (micro-)depot, an available docking platform is assigned to waiting UAVs for loading and unloading of parcels or exchange a depleted battery.

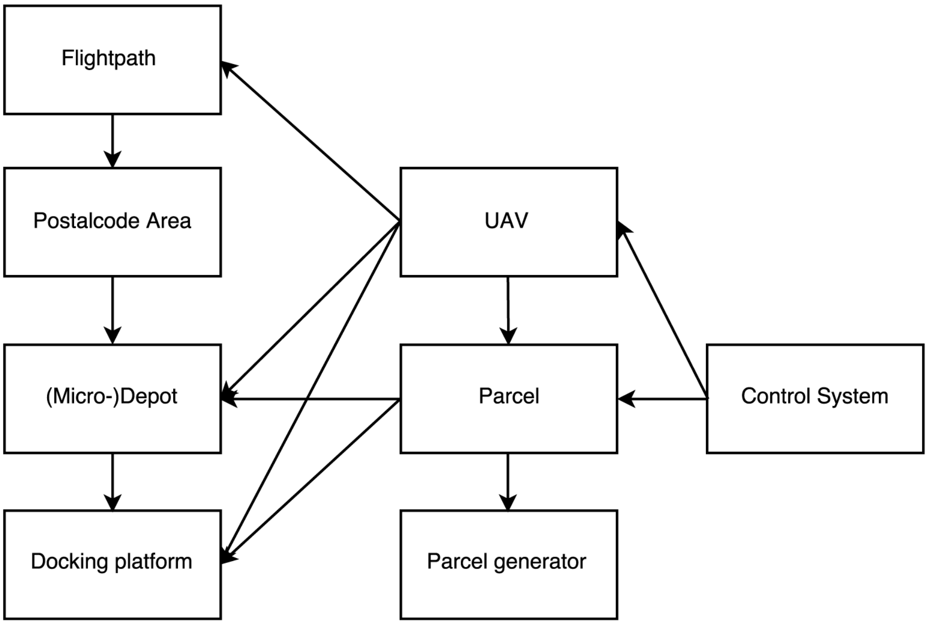


Figure 5.1: Overview simulation model objects

A more detailed description of the objects, their attributes, processes and relations can be found in the appendix C.

GENERAL ASSUMPTIONS

During the development of the simulation model, a number of assumptions must be made to simplify the model. The general assumptions that have been made are listed below:

- The fleet of UAVs is assumed to be homogeneous in cruise speed and average endurance.
- The UAVs cruise speed and average endurance are assumed to be constant.

- All equipment can operate 24 hours per day for 7 days per week without failure.
- Flightpath are unobstructed straight lines between two postal code areas.
- Collision due to coinciding UAVs on the same flightpath is neglected and assumed to be resolved by the UAVs.
- UAVs will never fly to the ground due to depleted batteries.
- Weather conditions are not considered to influence the system.
- Parcels size is neglected and parcel weight is restricted to the maximum payload capacity of the UAV.
- UAVs are assumed to be flying at an altitude of 100 meters.
- Buffer capacity of (micro-)depots is assumed to be infinite to prevent deadlocking.

MODEL INPUT AND OUTPUT

The input and output of the simulation model have been schematically depicted in figure **??**. Parcel demand distributions serve as input for the parcel generated in the simulation model and include the daily parcel demand distribution of the test case operating environment, parcel weight distribution and the hourly demand distribution to generate parcels. Further, the infrastructure, equipment characteristics and general model configuration settings (eg. runtime, warm-up time) serve as input for the model.

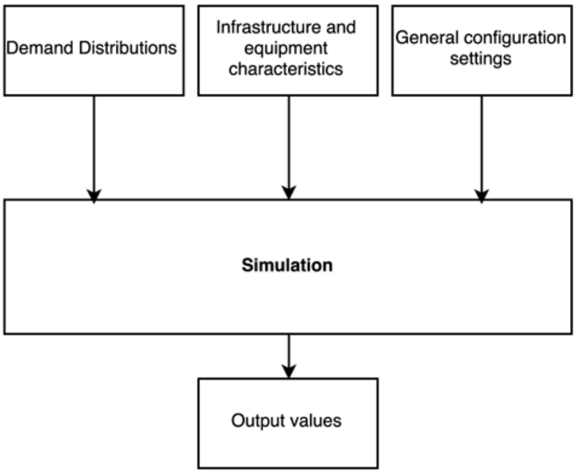


Figure 5.2: Overview simulation model input and output

The output generated by the model includes output values for the required PI's and KPI's that are used in the results analysis.

5.2 SIMULATION ENVIRONMENTS

The performance and behaviour of the system will be studied within two different operating environments. In the research scope the selection of these operating environments has already been motivated based on the differences in characteristics of these operating environments. In this section, the specific characteristics of these environments is further defined.

5.2.1 THE HAGUE

South-Holland is a province in the midwestern Netherlands and the most densely populated and congested urban areas in the Netherlands. Within this region lies The Hague, the third largest city of the Netherlands with a population density of 6.344 inhabitants per square kilometre. In the region parcels are collected and distributed by PostNL from a depot located in the town of Den Hoorn near the edge of The Hague. (Fig. 5.3)

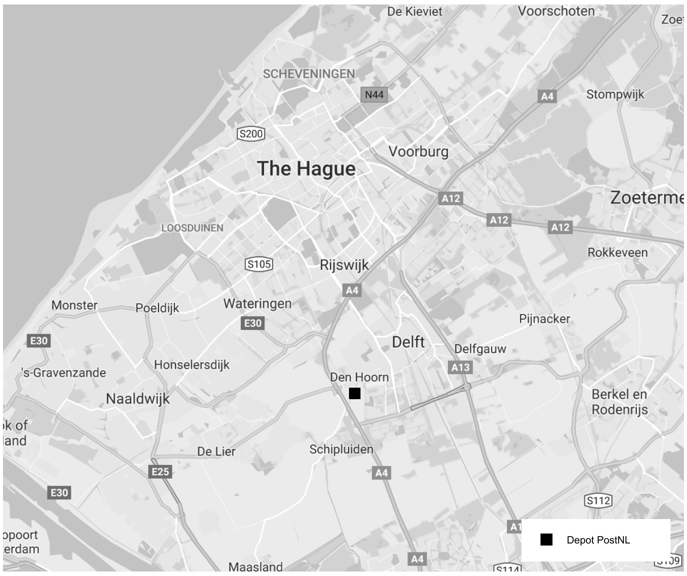


Figure 5.3: Service region The Hague

For the test case every postal code area within a 15 kilometer radius of the operating region surrounding the depot is modelled with a predetermined number of micro-depots, which are assumed to be uniformly spread across the postal code area. While the postal code of the depot is also modelled, it only contains the depot of PostNL and no additional micro-depots are located in this postal code area.

DEMAND

Daily demand for collection and delivery of parcels in the operating region of The Hague is strongly affected by seasonal influences as can be seen in figure 5.4. Especially, during the holidays in December, more parcel are collected and delivered. Furthermore, no collection and delivery takes place on Sunday. Resulting in a lower number of parcels distributed on Monday and a higher number of distributed parcels on Tuesday compared to the other days.

On average 20.188 parcels per day are distributed within a 15 kilometre radius of the PostNL depot in Den Hoorn, which accounts for almost 80% of the parcel volume distributed daily from the depot. When considering the collection and delivery flows between the postal code areas within a 15 kilometre radius, only 4% of all parcels has its origin and destination within postal codes in the similar radius, while 96% of all parcels is either collected from or delivered to the depot. Furthermore, around 75% of all parcels is collected from the depot. As a result most parcels have to be transported between the postal codes and the postal code where the PostNL depot is located. A situation that would be similar to a retailer delivering orders and collecting returns from its local distribution center at the edge of an urban area.

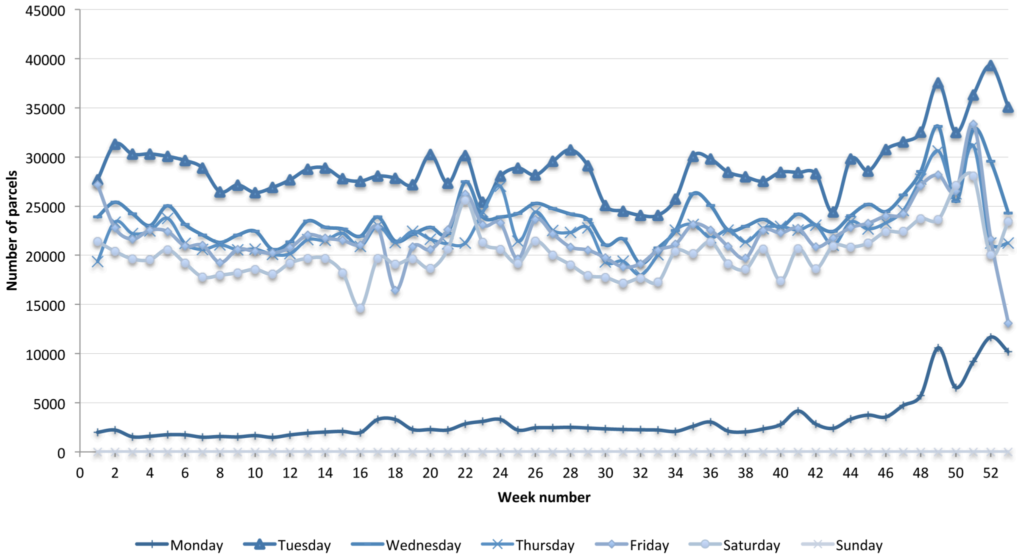


Figure 5.4: Daily parcel demand The Hague 2014

5.2.2 GOES

Zeeland is the westernmost province and one of the least densely populated areas in the Netherlands. Within the region lies the small city Goes with a population density of 400 inhabitants per square kilometre (Centraal Bureau voor de Statisiek, 2016). Parcels in the region are collected and distributed from the depot of PostNL located at the edge of Goes. (Fig. 5.5)

Figure 5.5: Service region Goes

Again all postal code areas within 15 kilometers of the service region depot are modeled as service areas each containing a predetermined number of micro-depots, which are assumed to be uniformly spread across every service area. Meanwhile the service area where the PostNL depot is located contains no additional micro-depots, but only the PostNL depot.

DEMAND

Daily parcel demand in the operating region of Goes shows a similar seasonal demand fluctuations to The Hague. However, because the population density of the service region is much lower, the overall daily demand is also lower with an average demand of 8.602 parcels per day in 2014.

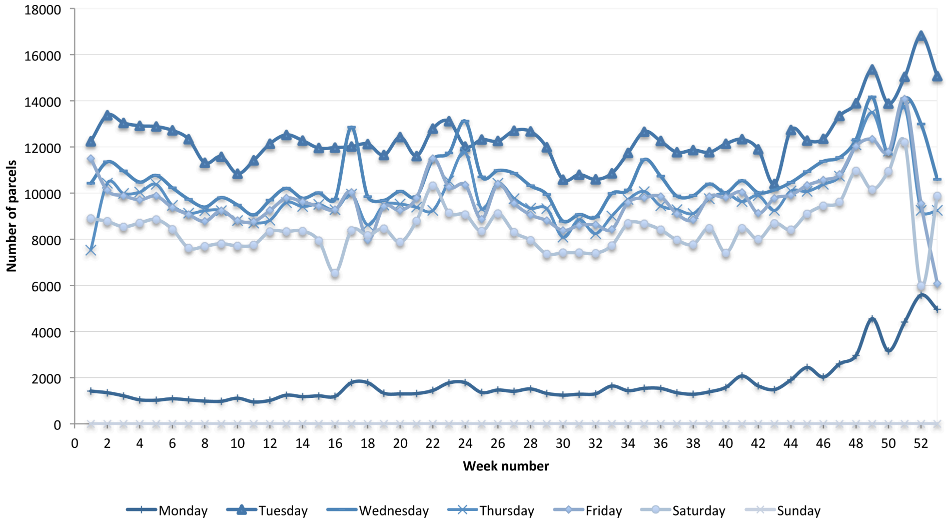


Figure 5.6: Daily parcel demand Goes

Another difference between the operation regions of Goes and The Hague is the spatial distribution of parcels that need to be collected and delivered across the service areas. While in The Hague around 75% of all collected parcels originate from the PostNL depot and are almost uniformly delivered to the postal code areas, in Goes this share is only 38% of all distributed parcels.

The main reason behind this difference in spatial distribution of parcels between the test cases, is the presence of a large distribution center from an online shoe retailer near Goes. Because the retailer uses the parcel service of PostNL to ship their products to customers, a large number of parcels needs to be collected at this retailers distribution center, which results in 48% of the parcels originating from this location of which almost all parcels need to be transported to the PostNL depot.

5.3 DESIGN OF EXPERIMENTS

With the simulation model several experiments will be performed. The 28 experiments stated in table 5.1 will be performed in both test cases. Each of these experiment is replicated a number of times for a certain run duration. Depending on the test case a different number of replications is performed.

Table 5.1: Simulation Experiments

Number	Control Policy	Remarks
1	FAV/FCFS	
2	FAV/MOD-FCFS	
3	FAV/STTD	
4	NAV/STTD	
5	FAV/FCFS	cruise speed 18 m/s
6	FAV/MOD-FCFS	cruise speed 18 m/s
7	FAV/STTD	cruise speed 18 m/s
8	NAV/STTD	cruise speed 18 m/s
9	FAV/FCFS	cruise speed 20 m/s
10	FAV/MOD-FCFS	cruise speed 20 m/s
11	FAV/STTD	cruise speed 20 m/s
12	NAV/STTD	cruise speed 20 m/s
13	FAV/FCFS	endurance = 15 min
14	FAV/MOD-FCFS	endurance = 15 min
15	FAV/STTD	endurance = 15 min
16	NAV/STTD	endurance = 15 min
17	FAV/FCFS	endurance = 30 min
18	FAV/MOD-FCFS	endurance = 30 min
19	FAV/STTD	endurance = 30 min
20	NAV/STTD	endurance = 30 min
21	FAV/FCFS	Multi-load capacity 2 parcels
22	FAV/MOD-FCFS	Multi-load capacity 2 parcels
23	FAV/STTD	Multi-load capacity 2 parcels
24	NAV/STTD	Multi-load capacity 2 parcels
25	FAV/FCFS	Multi-load capacity 4 parcels
26	FAV/MOD-FCFS	Multi-load capacity 4 parcels
27	FAV/STTD	Multi-load capacity 4 parcels
28	NAV/STTD	Multi-load capacity 4 parcels

Experiments 1 to 4 are used to determine the difference between the four control policies to be used by the centralized control system that have been selected in the previous chapter. The experiments are used to determine what type of control policy would be preferred for an ATS in on-demand last mile parcels distribution.

Due to large differences in operational characteristics between existing UAVs, a number of experiments is performed to determine the influence of these characteristics on the systems performance.

Both endurance and speed are varied based on speed and endurance capabilities of existing UAVs.

In experiments 5 to 12 the average cruise speed is increased to 18 m/s and 20 m/s, which is comparable to alternatives in speeds of existing UAVs. Again for each of these experiments all dispatching policies are used to determine if there are differences in performance when the speed is increased.

Experiments 13 to 20 are used to reduce the average endurance to 15 and 30 minutes, which are also similar to endurance of existing UAVs. Actually, the endurance of the reference UAV is rather high compared to other existing UAVs, thus it is interesting to determine what happens when the endurance decreases.

Finally, experiments 21 to 28 consider the capability of UAVs to carry multiple payloads at once. Although the UAV already has a limited payload capacity, it is interesting to consider what happens to the systems performance if UAV would be capable of transporting multiple parcels at once. In combination with the control policies, a multi-load UAV will pick-up as many parcels as it can carry from its origin before moving further. When the UAV resumes, it either goes to deliver one of the parcels or pick-up an additional parcel when there is payload capacity remaining. The UAV only looks for additional parcels to pick-up that are closer in distance than the nearest delivery destination in distance. Whenever the UAV delivers parcels, it always delivers the parcel with the nearest destination first. This applies to all control policies, which means that the first parcel mainly characterizes the performance of the policies when using multi-load UAVs.

5.4 RESULT ANALYSIS

In this section the results of the simulation experiments for both test cases are analysed. The analysis is performed by considering the effects of the system alternatives on the customer satisfaction, delivery costs and environmental impact KPIs that are also used to measure the performance of existing last mile parcel distribution.

5.4.1 THE HAGUE

In this section the results of the simulation experiments for the test case of The Hague are analysed. The analysis is performed for each KPI and the effects are considered that each of the different simulation setting have on these KPIs.

CUSTOMER SATISFACTION

The customer satisfaction KPI determines the percentage of parcels that have been delivered within 30 minutes to their destination, according to the quantitative KPI of customer satisfaction. In table 5.2 the effects of cruise speed, endurance and multiple-payloads on customer satisfaction will be considered.

In general there are only small differences between the performance of the centralized control policies. Although the differences are not very large, the distance-based policies (FAV/STTD and NAV/STTD) slightly outperform the time-based policies. These small performance differences are explained by the fact that 75% of all distributed parcels originate from the depot. As an example, when a UAV becomes available, there is a 75% probability that the oldest or nearest parcel must be collected at the depot. In case of high vehicle utilization the first available UAV will look for the oldest or nearest

Table 5.2: Results Customer Satisfaction - The Hague

Influence of Cruise speed

	16 m/s	18 m/s	20 m/s
Control policy	*Customer satisfaction [%]*	*Customer satisfaction [%]*	*Customer satisfaction [%]*
FAV/FCFS	90,38	92,10	98,46
FAV/MOD-FCFS	90,42	92,23	98,50
FAV/STTD	90,46	92,45	98,50
NAV/STTD	90,56	92,61	98,50

Influence of Endurance

	15 min	30 min	45 min
Control policy	*Customer satisfaction [%]*	*Customer satisfaction [%]*	*Customer satisfaction [%]*
FAV/FCFS	88,76	90,28	90,38
FAV/MOD-FCFS	89,23	90,39	90,42
FAV/STTD	89,48	90,41	90,46
NAV/STTD	89,18	90,36	90,56

Influence of Multi-load capacity

	1 parcel	2 parcels	4 parcels
Control policy	*Customer satisfaction [%]*	*Customer satisfaction [%]*	*Customer satisfaction [%]*
FAV/FCFS	90,38	90,35	89,98
FAV/MOD-FCFS	90,42	90,32	90,02
FAV/STTD	90,46	90,35	90,05
NAV/STTD	90,56	90,34	90,07

parcel, which must likely be collected at the depot. Whereas under low utilization the UAV will return to the depot under the centralized idle vehicle positioning strategy, which is also the location with a high collection occurrence.

It must also be noted that none of the dispatching policies ever reaches a 100% customer satisfaction, which is a result of a combination between the assumed minimum operational characteristics of the UAV and the demand characteristics, as some of the parcels can never be collected and delivered within the set time window of 30 minutes.

Further as expected, speed has a large influence on customer satisfaction, as parcels can be picked-up and delivered within less time. Remarkably, although there is only a small difference in performance when increasing the speed from 16 m/s to 18 m/s, when the speed is increased to 20 m/s the performance improvement is much higher, which could suggesting that the size of the operating region region plays an role in the relation to speed, as the relative size of the area becomes smaller when the cruise speed increases.
When comparing the customer satisfaction among the different speeds and control policies, for all policies the performance increases similarly when the speed increases.

Increasing the endurance of UAVs has almost no influence on the customer satisfaction. Although UAVs would be capable of sustaining longer flight times between battery changes, the influence is almost neglect able. Presumably, this is caused by the fast battery exchange times in relation to the overall endurance of the UAVs.

When deploying UAVs that are capable of carrying multiple-payloads, customer satisfaction slightly decreases. This can be expected, as it is likely that some parcels have to wait longer before being picked-up or delivered. As a result the overall customer satisfaction decreases, as less parcels are delivered within the set time window.

DELIVERY COSTS

The delivery costs consist of capital costs and operational costs. Both operational and capital costs for The Hague have been summarized in table 5.3 and are further explained below. While capital costs are one-time costs required as an investment for the system and have a certain depreciation time, operational costs are recurring costs on a daily basis. Because equipment of the ATS does not exists, the estimations are based on similar equipment that already exists, such as parcel lockers, and regularly commercially available UAVs.

Table 5.3: Daily capital and operational costs for The Hague

Capital costs				
Costs	*Costs per unit [€]*	*Units*	*Total costs [€]*	*Depreciation costs [€]*
UAV	13.658	215	2.936.470	4.553
Micro-Depots	50.000	367	18.350.000	5.000
Depots	1.000.000	1	1.000.000	100.000
Total costs			22.268.470	109.553
Total daily costs			7.709	

Operational costs			
Costs	*Costs per unit [€]*	*Units*	*Total costs [€]*
Maintenance Infrastructure	1.835.000	1	1.835.000
Maintenance UAVs	587.294	1	587.294
Total costs			2.422.294
Total daily costs			6.636

CAPITAL COSTS

The capital costs for The Hague include the costs for the number of UAVs that must be purchased and the investments required for the infrastructure, including the micro-depots and retrofitting existing depots with docking platforms.

It has been calculated that around 215 UAVs and 367 micro-depots are needed for the infrastructure to support last mile parcel distribution in the operating region of The Hague. (appendix C) Using the costs of the use reference case UAV defined in section 2.4.2 the total investment costs for

the required number of UAVs can be calculated. It is assumed that the UAVs have a depreciation time of 3 years. Further, the investment costs for the (micro-)depots must be calculated. According to (**?**) the average automated parcel locker costs around €38.000 and is depreciated in 7 years. It is estimated that outfitting the parcel locker with additional docking platforms will costs around one third of the original costs, thus the total costs of the micro-depot is estimated to be €50.000. Keeney (2015) has made an estimation that the required capital costs to outfit existing depots will costs around that around €800.000 and is depreciated over a period of 10 years.
In addition the the mentioned infrastructure there are also capital costs required for extra batteries in the system. Because the number of batteries depends on the number of battery exchanges per hour (eg. charging time of a depleted battery takes approximately 60 minutes), the costs are calculated further in the results. The costs of an extra battery is €280 for the reference UAV (**?**).

OPERATIONAL COSTS

The operational costs are recurring costs, that include energy and maintenance costs. Human labour costs are not considered as they are already present in the current operating environment and the system is considered to operate automated without any human intervention. Fuel costs depend on the energy costs per kWh as batteries are drained during operation. According to the energy production costs in the Netherlands are around €0,10 per kWh. Because the total costs depend on the distance covered per combination these costs will be calculated later on. Besides the capital costs investments in the infrastructure, there are also operational costs that arise for maintenance of the infrastructure. Maintenance costs for UAVs are approximately 20% of their purchase value per year, whereas maintenance costs for the remaining infrastructure is approximately 10% per year of the infrastructure investment costs (Keeney, 2015).

The operational costs per parcel have been calculated by multiplying the required average daily energy used by the UAV to cover the transport distances with the costs of energy and adding the daily operational costs divided by the average number of parcels transported per day. The capital costs have been calculated by combing the costs of a battery with the required number of battery exchanges per hour.

In general for all control policies the operational costs slightly vary, where specially the distance based policies have slightly lower operational costs, as the covered distances in the network are kept to a minimum.

Results show that increasing the cruise speed increases the capital costs, as more batteries are required in the system, due to faster need of battery changes. Endurance has the largest influence on the operational costs, as lowering the endurance rapidly increases the number of battery exchanges per hour. Increasing multi-payload capacity for all control policies has almost no influence on both the operational and capital costs. Although the distances would possibly become shorter the UAVs are also carrying heavier payloads.

In general, the largest share of the operational costs is considered to be the high maintenance costs of the infrastructure and UAVs, which requires larger daily volumes to become more cost efficient. Overall the costs of 30 minute delivery are very low, even when considering circumstance that UAVs would have a very low endurance and must exchange batteries more often.

ENVIRONMENTAL IMPACT

The environmental impact of the system is only measured in terms of produced CO2 emission. With battery-powered UAVs being used to transport parcels in the system, the ATS will operate fully electrical and thus no emissions are expelled by the system. Specifically if micro-depots are outfitted with solar panels the system would produce no CO2 emissions.

5.4.2 GOES

In this section the results of the simulation experiments for the test case of The Hague are analysed. The analysis is performed for each KPI and the effects are considered that each of the different simulation setting have on these KPIs.

CUSTOMER SATISFACTION

The customer satisfaction KPI determines the percentage of parcels that have been delivered within 30 minutes to their destination, according to the quantitative KPI of customer satisfaction. In table 5.7 the effects of cruise speed, endurance and multi-payload capacity on customer satisfaction will be considered.

Similar to the test case of The Hague, when comparing the centralized policies in general, the distance-based policies again perform slightly better than the time-based policies. However the maximum attainable customer satisfaction yet again never reaches a 100%. Both the small differences in performance of the centralized control policies and the low level of customer satisfaction are presumably explained by the demand characteristics of the operating region. In Goes around 48% of all distributed parcels must be collected at the distribution center of the shoe retailer and be delivered to the PostNL depot, meanwhile only 37% of all distributed parcels originates at the PostNL depot. As a result most parcels must be transported between the depot and the distribution center of the shoe retailer. Under high vehicle utilization the available UAV has almost 50% change of being located at the PostNL depot and when a parcel arrives it most likely must be collected at the distribution center. Therefore the oldest and/or closest parcel is often located at the distribution center. Thus the UAV must always travel towards the distribution center. Under low utilization the UAVs always return to the depot and wait for new parcels, which again have a high probability of originating at either the depot or the distribution center.

Increasing the cruise speed shows that for all cruise speeds the resulting customer satisfaction improves very fast. Especially when increasing the speed to 20 m/s, the customer satisfaction has practically doubled compared to the 16 m/s cruise speed, allowing the customer satisfaction to reach almost 100% for all centralized distance-based control policies. Again, due to the demand characteristics, a small share of parcels can never be delivered within time, even if there is an UAV immediately available. Endurance has no large influence on the customer satisfaction, although for all policies the customer satisfaction slightly improves, the improvement never larger than 3%-4%.

Results indicate again that UAVs with the capability to carry multiple payloads has a negative influence on customer satisfaction. For all centralized control policies, the customer satisfaction is reduced as the average time in system of parcels increases.

DELIVERY COSTS

The delivery costs consist of capital costs and operational costs. Both operational and capital costs for Goes have been summarized in table 5.6 and are further explained below. While capital costs are one-time costs required as an investment for the system and have a certain depreciation time, operational costs are recurring costs on a daily basis. Because equipment of the ATS does not exists, the estimations are based on similar equipment that already exists, such as parcel lockers, and regularly commercially available UAVs.

CAPITAL COSTS

The capital costs for Goes also include the costs for the number of UAVs that must be purchased and the investments required for the infrastructure, including the micro-depots and retrofitting existing depots with docking platforms.

It has been calculated that around 92 UAVs and 47 micro-depots are needed for the infrastructure to support last mile parcel distribution in the operating region of The Hague. (appendix C) Using the costs similar to those of The Hague the total daily capital costs can be calculated.

OPERATIONAL COSTS

The operational costs are recurring costs, that include energy and maintenance costs. Human labour costs for Goes are also not considered as they are already present in the current operating environment and the system is considered to operate automated without any human intervention. Furthermore, all the operational costs calculations are performed under similar assumptions as in the test case of The Hague.
The operational costs per parcel have been calculated by multiplying the required average daily energy used by the UAV to cover the transport distances with the costs of energy and adding the daily operational costs divided by the average number of parcels transported per day. The capital costs have been calculated by combing the costs of a battery with the required number of battery exchanges per hour.

In general for all control policies the operational costs slightly vary, where specially the distance based policies have slightly lower operational costs, as the covered distances in the network are kept to a minimum.

Results show that increasing the cruise speed increases the capital costs, as more batteries are required in the system, due to faster need of battery changes. Endurance has the largest influence on the operational costs, as lowering the endurance rapidly increases the number of battery exchanges per hour. Increasing multi-payload capacity for all control policies has almost no influence on both the operational and capital costs. Although the distances would possibly become shorter the UAVs are also carrying heavier payloads.

In general, the largest share of the operational costs is considered to be the high maintenance costs of the infrastructure and UAVs, which requires larger daily volumes to become more cost efficient. Overall the costs of 30 minute delivery are very low, even when considering circumstance that UAVs would have a very low endurance and must exchange batteries more often.

ENVIRONMENTAL IMPACT

The environmental impact of the system is only measured in terms of produced CO2 emission. With battery-powered UAVs being used to transport parcels in the system, the ATS will operate fully electrical and thus no emissions are expelled by the system. Specifically if micro-depots are outfitted with solar panels the system would produce no CO2 emissions.

Table 5.4: Results Delivery Costs - The Hague

Influence of Cruise speed

	16 m/s		18 m/s		20 m/s	
Control policy	*Operational costs [€/parcel]*	*Capital costs [€/parcel]*	*Operational Costs [€/parcel]*	*Captial Costs [€/parcel]*	*Operational Costs [€/parcel]*	*Capital Costs [€/parcel]*
FAV/FCFS	3,72	0,67	3,72	0,74	3,72	1,02
FAV/MOD-FCFS	3,72	0,67	3,72	0,74	3,72	1,01
FAV/STTD	3,71	0,66	3,72	0,72	3,73	0,99
NAV/STTD	3,70	0,65	3,71	0,70	3,70	0,98

Influence of Endurance

	15 min		30 min		45 min	
Control policy	*Operational costs [€/parcel]*	*Capital costs [€/parcel]*	*Operational Costs [€/parcel]*	*Captial Costs [€/parcel]*	*Operational Costs [€/parcel]*	*Capital Costs [€/parcel]*
FAV/FCFS	3,70	1,64	3,71	0,90	3,72	0,67
FAV/MOD-FCFS	3,69	1,64	3,71	0,91	3,72	0,67
FAV/STTD	3,69	1,63	3,71	0,90	3,71	0,66
NAV/STTD	3,69	1,63	3,70	0,90	3,70	0,65

Influence of Multi-payload capacity

	1 parcel		2 parcels		4 parcels	
Control policy	*Operational costs [€/parcel]*	*Capital costs [€/parcel]*	*Operational Costs [€/parcel]*	*Captial Costs [€/parcel]*	*Operational Costs [€/parcel]*	*Capital Costs [€/parcel]*
FAV/FCFS	3,72	0,67	3,72	0,67	3,72	0,67
FAV/MOD-FCFS	3,72	0,67	3,72	0,67	3,72	0,67
FAV/STTD	3,71	0,66	3,72	0,67	3,71	0,67
NAV/STTD	3,70	0,65	3,71	0,66	3,70	0,66

Table 5.5: Results Customer Satisfaction - Goes

Influence of Cruise speed

	16 m/s	18 m/s	20 m/s
Control policy	*Customer satisfaction [%]*	*Customer satisfaction [%]*	*Customer satisfaction [%]*
FAV/FCFS	48,84	67,06	98,68
FAV/MOD-FCFS	50,03	67,35	98,73
FAV/STTD	52,50	67,23	98,73
NAV/STTD	52,57	67,55	98,73

Influence of Endurance

	15 min	30 min	45 min
Control policy	*Customer satisfaction [%]*	*Customer satisfaction [%]*	*Customer satisfaction [%]*
FAV/FCFS	45,23	48,14	48,84
FAV/MOD-FCFS	46,21	47,82	50,03
FAV/STTD	50,41	51,36	52,50
NAV/STTD	51,21	52,85	52,57

Influence of Multi-payload capacity

	1 parcel	2 parcels	4 parcels
Control policy	*Customer satisfaction [%]*	*Customer satisfaction [%]*	*Customer satisfaction [%]*
FAV/FCFS	48,84	45,96	44,84
FAV/MOD-FCFS	50,03	47,03	45,57
FAV/STTD	52,50	48,08	46,51
NAV/STTD	52,57	48,34	46,52

Table 5.6: Daily capital and operational costs for Goes

Capital costs				
Costs	*Costs per unit [€]*	*Units*	*Total costs [€]*	*Depreciation costs [€]*
UAV	13.658	92	1.256.536	4.553
Micro-Depots	50.000	47	2.350.000	5.000
Depots	1.000.000	1	1.000.000	100.000
Total costs			3.606.536	109.553
Total daily costs			1.791	

Operational costs			
Costs	*Costs per unit [€]*	*Units*	*Total costs [€]*
Maintenance Infrastructure	235.000	1	235.000
Maintenance UAVs	251.307	1	587.294
Total costs			486.307
Total daily costs			1.332

Table 5.7: Results Delivery Costs - Goes

Influence of Cruise speed

	16 m/s		18 m/s		20 m/s	
Control policy	*Operational costs [€/parcel]*	*Capital costs [€/parcel]*	*Operational Costs [€/parcel]*	*Captial Costs [€/parcel]*	*Operational Costs [€/parcel]*	*Capital Costs [€/parcel]*
FAV/FCFS	4,05	0,58	4,19	0,56	4,21	0,53
FAV/MOD-FCFS	4,02	0,58	4,18	0,56	4,21	0,53
FAV/STTD	4,02	0,57	4,18	0,56	4,21	0,53
NAV/STTD	4,00	0,57	4,17	0,55	4,21	0,52

Influence of Endurance

	15 min		30 min		45 min	
Control policy	*Operational costs [€/parcel]*	*Capital costs [€/parcel]*	*Operational Costs [€/parcel]*	*Captial Costs [€/parcel]*	*Operational Costs [€/parcel]*	*Capital Costs [€/parcel]*
FAV/FCFS	4,04	1,50	4,04	0,82	4,05	0,58
FAV/MOD-FCFS	4,02	1,45	4,02	0,82	4,02	0,58
FAV/STTD	4,01	1,44	4,02	0,82	4,02	0,57
NAV/STTD	3,99	1,42	3,99	0,81	4,00	0,57

Influence of Multi-payload capacity

	1 parcel		2 parcels		4 parcels	
Control policy	*Operational costs [€/parcel]*	*Capital costs [€/parcel]*	*Operational Costs [€/parcel]*	*Captial Costs [€/parcel]*	*Operational Costs [€/parcel]*	*Capital Costs [€/parcel]*
FAV/FCFS	4,05	0,58	3,98	0,58	3,98	0,57
FAV/MOD-FCFS	4,02	0,58	3,97	0,57	3,97	0,57
FAV/STTD	4,02	0,57	3,97	0,57	3,97	0,57
NAV/STTD	4,00	0,57	3,97	0,56	3,96	0,57

6

DISCUSSION

One of the main questions is how well the simulation model represents the actual flight times of the UAVs in practice. Although UAVs are assumed to fly at a constant velocity, in real world circumstances, flight dynamics and weather conditions will have an influence on actual flight times and the required number of battery changes. In addition, the model assumes straight line flight paths between the geographical centres of postal code areas, whereas actual flight path distances between (micro-)depots could be longer, due to their location within the postal code areas and the presence of no fly zones around areas, such as airports.

These actual flight path distances and flight times, could also affect the level of customer satisfaction and the operational and capital costs that have been used as the key performance indicator in this research. It is expected that when incorporating flight dynamics, weather conditions and actual flight path distances into the model , the level of customer satisfaction could very well be much lower compared to the results found by the simulation model. Especially when considering operational cases in which the mean delivery time lies close to 30 minutes. On the other side, the required capital costs and operational costs could be considerably higher, as more batteries would be required and more energy would used per delivery.

Further, the simulation model uses several assumptions in relation to the dimensioning of the system. For (micro-)depots these assumptions include the number of docking platforms, the loading and unloading times and the buffer capacity size. Also, all types of (micro-)depots and UAVs have been considered similar in size, but in practice several types of equipment with different characteristics could be used.

As already mentioned, the demand for the ATS is highly uncertain due to a number of factors, including the customer density in and size of the operating region, but also the distribution of parcel weight and size in relation to the payload capabilities of the UAV. For both test cases a fixed region size has been used combined with the percentage of parcels falling within the requirements for weight. As a result, two very specific test cases have been created, which makes it difficult to determine the performance of the ATS in other operating environments.

From a business perspective it can be questioned if the use of the ATS would be interesting for parcel carriers such as PostNL. To transform existing next-day parcel distribution networks to on-demand networks one of the main conditions is that large retailers move their inventory towards densely populated areas or PostNL provides this storage for their customers. Although the total operational and capital costs per delivery are relatively low compared to existing courier parcel service , the question remains if the added value of on-demand distribution and increase in speed would exceed the possible increase in costs for customers, as only 30% of the customers is willing to pay the additional costs for such services today.

While the discussion has highlighted some of the possible shortcoming in the research, aviation regulations currently prohibit the commercial use of UAVs. As a result, the designed ATS cannot be used in the Netherlands for last mile parcel distribution purposes. Although it can be assumed that in the future this issues will be resolved, it is now considered as the largest barrier for the research outcome.

7

CONCLUSION AND RECOMMENDATIONS

7.1 CONCLUSION

Unmanned Aerial Vehicles (UAVs), also known as drones are aircraft with no human pilot on-board to perform controlling actions to the aircraft. In the past decades the military has been the driving force behind the development of UAV technology, but with the UAV technology becoming more accessible in the past years, the interest of companies for commercial applications of UAVs has been steadily increasing.

PostNL, a Dutch postal and parcel carrier active in the logistics industry, is also interested in the future application of UAV technology in their last mile parcel distribution logistics operations. Despite the recent developments and efforts of several companies, such as Amazon, Google and DHL in researching the application of UAVs for last mile distribution of goods, there remains a lack the knowledge and understanding on integrating UAVs in last mile parcel distribution.

The goal of this research was therefore to design a system, further referred to as the Aerial Transport System (ATS) for last mile parcel distribution. Where engineering Design literature has been used as a reference framework during the design process.

First the current state on last mile parcel distribution was analysed. Existing parcel services are characterised by the offered transit time and limitations in size and weight of parcels. While same-day courier services offer point-to-point transportation , express and regular parcel services use hub and spoke distribution networks to make time and day (un)certain deliveries. In the Netherlands, PostNL also uses a hub & spoke distribution network. In the distribution process, parcels are collected in the afternoon, sorted, transported and cross-docked overnight, sorted for a second time and finally delivered to the final destination in the morning. To measure the performance of the distribution process PostNL uses three KPI's which include customer satisfaction, delivery costs and environmental impact. All sub processes in the distribution process are scheduled in advance and have fixed cut-off times. As a result all these processes lie in the critical path of the distribution process and when a parcel does not reach the cut-off time of the process, it will have to wait until the next day to be distributed. In addition, parcels are pushed towards consumers who have almost no control over, when where or how they receive their parcels and the network is only capable of next-day delivery.

According to future state strategy of PostNL for 2020 , the trends influencing the future environment of last mile parcel distribution are urbanization, sustainability and demand for faster and more customer oriented parcel services. Based on these trends it is expected that the main opportunities for UAVs in the future last mile parcel distribution process lie in same-day and on-demand collection and delivery of parcels in densely populated areas.

The conceptual design of the ATS consists of a functional design for the equipment that includes payload containers, UAVs, docking platforms and (micro-)depots. Payload containers are considered to be parcels with size and weight limitations (as already used today) based on the payload capacity limitations of the UAVs used for transportation. Docking platforms perform loading and unloading of parcels or exchange batteries and (micro-)depots located at collection and delivery points, that have one or more docking platforms and store parcels before being transferred and transported. In this manner a large and dense network of (micro-)depots can be deployed in an urban environment and fixed routes between the (micro-)depots can be used to obtain a closed system. Further, due to the uncertainties in parcel demand, the system is controlled by a centralized dispatching control system, that can use various dispatching policies to make decisions on which parcels are transported by what UAVs.

In the detailed design of the system has been tested in two cases, namely for The Hague and Goes accordingly the most densely populated area and least densely populated areas in the Netherlands. The experiments in the detailed design included alternative dispatching policies for the control system and various values of the speed and endurance, and multi-payload carrying capacity operational characteristics of the UAVs.

Based on the research results the most important design criteria are the speed and endurance of the selected UAV. As these these have the largest impact on customer satisfaction and delivery costs. From the perspective of the control system, distance-based control policies are preferred over time-based policies in both operating environments, as they result in a slightly better performance.

Furthermore it can be concluded that based on the requirements that have been set for UAVs operating in urban areas, and the market exploration of UAVs, there are currently no commercially available UAVs that are capable of handling all parcel demand within the set size and weight limitations of existing parcel carriers. Thus, while with the reference UAV used in the ATS approximately 65% of all parcels in weight could be transported, the remaining share of 35% will still need to be delivered with traditional delivery trucks. Probably a reasonable amount of the remaining share of parcels will also never be transported by an ATS, as there are presumably physical limitations to the maximum payload capacity of UAVs within the size restrictions put upon these vehicles when operating in urban areas.

Finally, the ATS has shown to offer several benefit from a delivery cost versus customer satisfaction perspective and the use of the system would be an interesting value proposition, as delivery within 30 minutes at the costs of 4 to 5 euro's per delivery would could certainly be interesting for some consumers. However, this would include the assumption that the estimated costs represent the real costs of such a system, which can be questioned and that that retailers would move their inventory towards urban areas, which would add additional inventory cost.

7.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Results have shown that the (demand) characteristics, such as spatial distribution of demand, size and customer density within the operating region could have a certain influence on the ATS performance. However, the influence of these characteristics on the systems performance remains unknown for cases that are not similar to the specified test cases . Therefore the effect of placing the ATS in different environments should be further investigated.

In determining where to position idle vehicles, a static idle vehicle positioning strategy for the system has been chosen in this research. Instead dynamic idle vehicle positioning strategies could offer a better performance in terms of faster collection by positioning idle UAVs closer to service areas with a high collection probability. It is therefore recommended to further quantify the influence of the alternative positioning strategies on the systems performance.

While a centralized dispatching control system was chosen to be implemented in the system, potentially a dynamic scheduling control system could deliver a better performance. Especially considering the utilization of UAVs. Therefore it would be recommended to compare the performance of the online dynamic scheduling control system to that of the centralized dispatching control system.

In order to avoid the occurrence of deadlocking in the system, the buffer capacity of the micro-depots was set to unlimited. In practice, micro-depots would have a limited buffer capacity and deadlocking resolution would be required. As this could be done in different ways, such as using alternative control policies or using local decision-making for the micro-depots future research should focus on how to avoid deadlocking in the system while maintaining a sufficient level of customer satisfaction.

Finally, although the model assumes no influence of wind conditions and flight dynamics these aspects will certainly have an influence on the actual performance of these systems. It is recommended to perform real world experiments with actual UAVs under different conditions to incorporate the influences of these aspects into future simulation models and to validate the results of this research.

A

SCIENTIFIC RESEARCH PAPER

Design of an Aerial Transport System for last mile parcel distribution with Unmanned Aerial Vehicles

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In 2013 Amazon publicly announced to be developing a future transportation system to deliver goods to customers within 30 minutes using Unmanned Aerial Vehicles (UAVs), also known as drones. Many dismissed the announcement as a mere marketing stunt, but how realistic is this future actually? Will this emerging technology be the next paradigm shift in the logistics industry? In this paper an Aerial Transport System is designed for last mile parcel distribution with UAVs between businesses and consumers. The potential role and opportunities for UAVs within future last mile parcel are estimated to lie within the context of on-demand parcel distribution in (densely) populated urban areas, taking into account the global trends of continuing urbanization, sustainable goods transportation, the acceleration of online sales and the increasing need of consumers and businesses for faster delivery and more control over where and when they receive their goods. An Engineering Design approach is used, where in the conceptual design phase the function structures and related equipment have been selected, which include, parcels, UAVs, docking platforms and (micro-)depots. Due to the uncertainty in demand, a centralized dispatching control system was selected to be used for control, combined with a central idle vehicle positioning strategy. In the detailed design the performance of system alternatives in terms of control policies and operational characteristics of the UAV have been measured using customer satisfaction and delivery costs as key performance indicators in two test cases, Goes and The Hague. Results show that especially the operational characteristics speed and endurance have a large influence on both customer satisfaction and delivery costs. It can be concluded that the operational characteristics of the UAVs are the most important design parameters for these systems. However, it has been unclear what the effects of varying operating environments and weather conditions or flight dynamics have on the systems performance as these issues have not been taken into consideration with the design. Therefore the influence of these systems should be further assessed.

Additional Key Words and Phrases: Unmanned Aerial Vehicles, Last Mile Parcel Distribution, Aerial Transport System, Design

1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs), also known as drones are aircraft with no human pilot on-board to perform controlling actions to the aircraft. [Eisenbeiss 2004a] In the past decades the military has been the driving force behind the development of UAV technology, due to the distinct advantages that UAVs offer in missions that are considered either too dull, dirty or dangerous for manned aircraft.

With the UAV technology becoming more accessible in the past years, the interest of companies for commercial applications of UAVs has been steadily increasing. in many different industries commercial applications for UAVs can already be found, such as crop dusting in agriculture [Pudelko et al. 2012]. In the film making and photography industry, UAVs allow for unprecedented video recordings and provide a solution to build more accurate terrain maps against lower costs compared to conventional manned aircraft [Eisenbeiss 2004b]. For security and monitoring, UAVs are being used to monitor sensitive areas for fires, illegal logging, poaching and environmental threats such as invasive species [Casbeer et al. 2005]. Another industry where UAVs could be commercially used is the logistics industry. In this industry, UAVs applications include long distance air cargo operations, intra-logistics operations in warehouses or last mile distribution of goods to consumers.When considering the recent developments and efforts of several companies, such as Amazon, Google and DHL in researching the application of UAVs for last mile distribution of goods to consumers, initial short-term opportunities for commercial use of UAVs in the logistics industry are believed to lie in last mile distribution.

PostNL, a Dutch postal and parcel carrier is also active in the logistics industry and is interested in the potential of UAV technology, especially for last mile parcel distribution. However the question is where and how UAV technology can be used in the future last mile parcel distribution operations for the company. As most previous research on last mile parcel distribution with UAVs only concerns single aspect of these systems, such as vehicle design, vehicle navigation and localization and vehicle co- ordination. This paper will use an integrated design perspective and has the objective to analyse the current state on last mile parcel distribution including the characteristics of existing parcel distribution process of PostNL and design a system, further referred to as the Aerial Transport System (ATS), which uses UAVs and possibly other equipment.

2. RESEARCH METHODOLOGY

Engineering Design theory serves as a reference framework throughout the paper to come to a comprehensive conclusion. First, design requirements and system boundaries are formulated by analyzing the current state on last mile parcel distribution and taking trends affecting the future state of last mile parcel distribution into consideration. These design requirements and system boundaries serve as input for the conceptualization phase, where the PROPER-model and steady-state model from the Delft Systems Approach are used to describe the static function structure of the system and assign the equipment to these functions. Further, literature on control systems is reviewed and an appropriate control system is selected based on the type of control system needed within the system requirements and boundaries. For the detailed design, a discrete-event simulation model is developed based on the conceptual design of the ATS and two test cases are used to study the time-dependent behavior of alternative system configurations.

3. CURRENT STATE ON LAST MILE PARCEL DISTRIBUTION

Parcel services are characterized by the high volume of small and low weight parcel shipments. Depending on the offered transit time (e.g. the time between pick-up and delivery) these services can be categorized into same-day courier services, time- and day definite express services or time- and day undefined regular parcel services. Many of these services use hub & spoke distribution networks to cost efficiently move parcels with many origins and many destinations.

3.1 Parcel Distribution Process Description PostNL

PostNL also operates a hub & spoke network, called the New Logistics Infrastructure (NLI). The distribution process in the NLI,starts with the collection of parcel in the afternoon, where after the parcels are sorted, transported and cross-docked overnight, and sorted again before finally delivered to the final destination in the morning.

All these processes are scheduled in advance and have fixed cut-off times to ensure that parcels can reach the subsequent processes on-time. As a result all these processes lie in the critical path of the distribution process and thus when a parcel does not reach the cut-off time of the process, it will have to wait until the next day to be distributed. In addition, due to the scheduled processes, there exists a minimum transit time for parcels which cannot be further reduced and therefore most of these networks are currently only capable of next day delivery.

To measure the performance of the distribution process PostNL uses three different KPI's:

(1) Customer Satisfaction
(2) Delivery Costs

(3) Environmental Impact

Customer Satisfaction is often expressed in terms of how a product or service performs in perspective to the expectations of customers for the product or service. Customer Satisfaction can therefore be considered as a qualitative KPI, but can be expressed as a quantitative KPI when only using the number of deliveries performed within the expected time frame as the main PI.

Another KPI used by PostNL is the delivery costs. Setting up large distribution networks, such as the NLI have a significant impact on the financial position of the company. The investments required to set up these distribution networks are composed of both capital costs and operational costs, which can ultimately be translated into costs per parcel.

The last KPI concerns the environmental impact of the parcel distribution operations on the external environment. PostNL is increasingly focusing on more sustainable operations, striving to reduce their environmental impact by lowering the energy consumption of their buildings, small trucks, vans and large trucks. Therefore the environmental impact is based on the amount of emission of types, such as NO2, and PM(x), and CO2 the distribution process causes.

4. FUTURE STATE ON LAST MILE PARCEL DISTRIBUTION

According to future state strategy of PostNL for 2020 [PostNL 2015], the trends influencing the future environment of last mile parcel distribution are urbanization, sustainability and demand for faster and more customer oriented parcel services.

Based on these trends it can is expected that future last mile parcel distribution in urban areas will play a more prominent role, as more consumers will live in (densely populated) urban areas due to ongoing urbanization. Combined with the acceleration of online sales parcel volumes collected and delivered within these urban areas are also expected to increase. Hence sustainability of delivery services will become more important, as local governments will presumably take measures to reduce congestion and emissions caused by increasing transportation movements in urban areas.

Meanwhile the acceleration of online sales is driven by the changes in the needs and behavior of both retailers and consumers. In most developed countries existing regular parcel services already offer standard next day delivery. A next logical evolution for many larger online retailers is the move towards same-day and on-demand delivery to compete with existing brick-and-mortar retailers.

Based on these trends it is expected that the main opportunities for UAVs in the future last mile parcel distribution process lie in same-day and on-demand collection and delivery of parcels in densely populated areas.

5. CONCEPTUAL DESIGN OF AN AERIAL TRANSPORT SYSTEM FOR LAST MILE PARCEL DISTRIBUTION WITH UAVS

Designing an automated transport system, such as the ATS, is often difficult, due to the high level of interaction and system dynamics, but also because the design involves at least three different aspects; the infrastructure of the operational system, the equipment used within the operational system and the control system that is responsible for the logistic decisions.[Versteegt and Verbraeck 2006] In the conceptual design of the ATS, the equipment and its processes combined with interaction with a control system are designed. The infrastructure is considered in the detailed design by using two test case environments.

5.1 Equipment

The systems equipment is composed of payload containers, UAVs, docking platforms and (micro-)depots. Payload containers are considered to be parcels with size and weight limitations (as already used today) based on the payload capacity limitations of the UAVs used for transportation. Docking platforms perform loading and unloading of parcels or exchange batteries and (micro-)depots located at collection and delivery points, that have one or more docking platforms and store parcels before being transferred and transported. In this manner a large and dense network of (micro-)depots can be deployed in an urban environment and fixed routes between the (micro-)depots.

5.2 Control System

The control system focuses on the coordination among vehicles in terms of scheduling, dispatching and routing, ensuring fast and efficient operation of the system independently of the number of vehicles used [Vis 2006]. If these requirements are not guaranteed, the overall performance of the system will decline, become less efficient and generate less profit or operate at higher costs [Vivaldini 2015]

For complex systems, such as the ATS most often off-line vehicle scheduling control systems are implemented to decide when, where and how a vehicle should act to perform given a certain demand. [Le-Anh and De Koster 2006] Most of these scheduling control systems however assume demand information to be known in advance, but in practice environments, demand is often much more stochastic of nature and exact information is often only known at a very late instant. With parcel demand strongly fluctuating on a daily basis, and the requiring on-demand allocation there is no planning horizon available for a scheduling approach, making an off-line scheduling control system impractical. Instead on-line control systems, such as dynamic scheduling or dispatching systems can be used.

Although a dynamic vehicle scheduling control system is more efficient compared to a dispatching control system, these scheduling algorithms would require too much processing time and take a long time to develop. Instead simple dispatching systems can be used.

Dispatching control systems can be divided into either decentralized and centralized control systems. While decentralized control systems are very simple and robust in areas with communication limitations as they only use local information to make decisions, centralized control systems are more efficient as all information is available to a single entity. As there are no immediate communication limitations for the ATS in its environments, a centralized dispatching system will be used in the final concept. Figure X shows the relation between the equipment and the control system.
The centralized dispatching control system can use different combinations of dispatching policies to determine which UAV must be assigned to what parcel or vice versa. For the centralized dispatching control system, the three First-Come-First Serve, Modified-First-Come-First Serve and the Shortest-Travel-Time-Distance vehicle-initiated dispatching policies are combined with the two First Available Vehicle and ”Nearest Available Vehicle workstation-initiated dispatching policies [Egbelu and Tanchoco 1984]. These dispatching policies have been selected, as they are frequently used in literature and are focused on reducing the waiting time of parcels as much as possible, which relates to the primary objective of the system and serves to increase customer satisfaction.

6. DETAILED DESIGN: TEST CASES THE HAGUE AND GOES

simulation model is developed based on the conceptual design explained in the previous chapter. Simulation experiments with the model are performed for two test case operating environments: The Hague and Goes. The Hague, is one of the most congested and densely populated areas in the Netherlands, where demand is concentrated in a small part of the operating environment. Meanwhile Goes has a much lower population density and demand is more spread across the operating environment.

6.1 Simulation Experiments

With the simulation model in total 28 experiments are performed. Each of these experiment is replicated a number of times for a certain run duration. Depending on the test case a different number of replications are performed based on the confidence interval method [Law 2007].

The first four experiments are used are used to compare the difference between the four control policies selected to be used by the centralized control system. Due to large differences in operational characteristics between existing UAVs, a number of experiments is performed to determine the influence of these characteristics. The characteristics of the UAV that influence the performance of transportation applications including speed and endurance have been selected to be used. Where the speed is varied from 16 m/s, 18 m/s to 20 m/s and endurance is varied from 15 min, 30 min to 45 min. Further, one could assume that UAVs could transport multiple parcels at once, therefore the multi-load criteria are also included, and ranges from 1, 2 or 4 parcels at once.

6.2 Simulation Results

Simulation results show that in both operating environments, UAVs with higher speeds are preferred compared to UAVs with longer endurance in terms of customer satisfaction. Furthermore, little difference exists in the performance between the dispatching policies , although distance-based policies slightly outperform time-based policies.

In terms of delivery costs, the distance-based dispatching policies lead to somewhat slightly lower costs. Further, endurance has a large influence on the capital costs, as with decreased endurance, UAVs need to exchange batteries more often.

7. DISCUSSION

One of the main questions is how well the simulation model represents the actual flight times of the UAVs in practice. Although UAVs are assumed to fly at a constant velocity, in real world circumstances, flight dynamics and weather conditions will have an influence on actual flight times and the required number of battery changes. In addition, the model assumes straight line flight paths between the geographical centers of postal code areas, whereas actual flight path distances between (micro-)depots could be longer, due to their location within the postal code areas and the presence of no fly zones around areas, such as airports. These actual flight path distances and flight times, could also affect the level of customer satisfaction and the operational and capital costs that have been used as the key performance indicators.

Parcel demand for the ATS is highly uncertain due to a number of factors, including the customer density in and size of the operating region, but also the distribution of parcel weight and size in relation to the payload capabilities of the UAV. For both test cases a fixed operating region size has been used combined with the percentage of parcels falling within the requirements for weight. As a result, two very specific test cases have been created, which makes it difficult to translate the results to other operating environments.

While the discussion has highlighted some of the possible shortcoming in the research, aviation regulations currently prohibit the commercial use of UAVs. As a result, the designed ATS cannot be used in the Netherlands for last mile parcel distribution purposes. Although it can be assumed that in the future this issues will be resolved, it is now considered as the largest barrier for the research outcome.

8. CONCLUSION

Based on the research results the most important design criteria are the speed and endurance of the UAV. As these these have the largest impact on customer satisfaction and delivery costs. Furthermore, it can be concluded that from the perspective of the control system, that distance-based control policies are preferred over time-based policies in both operating environments, as they result in a slightly better performance.

Furthermore it can be concluded that based on the requirements that have been set for UAVs operating in urban areas, and the market exploration in UAVs, there are currently no commercially available UAVs that are capable of handling all parcel demand within the set size and weight limitations of existing parcel carriers. Thus, while with the reference UAV used in the ATS approximately 65% of all parcels in weight could be transported, the other 35% will still need to be delivered with traditional delivery trucks. Probably a reasonable amount of the remaining share of parcels will also never be transported by an ATS, as there are presumably physical limitations to the maximum payload capacity of UAVs within the size restrictions put upon these vehicles when operating in urban areas.

9. FUTURE RESEARCH

Results have shown that the (demand) characteristics, such as spatial distribution of demand, size and customer density within the operating region could have a certain influence on the ATS performance. However, the influence of these characteristics on the systems performance remains currently unknown and their effect should therefore be further investigated.

In determining where to position idle vehicles, a static idle vehicle positioning strategy for the system has been chosen in this research. Instead dynamic idle vehicle positioning strategies could offer a better performance in terms of faster collection by positioning idle UAVs closer to service areas with a high collection probability. It is therefore recommended to further quantify the influence of the alternative positioning strategies on the systems performance.

Finally, although the model assumes no influence of wind conditions and flight dynamics these aspects will certainly have an influence on the actual performance of these systems. It is recommended to perform real world experiments with actual UAVs under different conditions to incorporate the influences of these aspects into future simulation models and to validate the results of this research.

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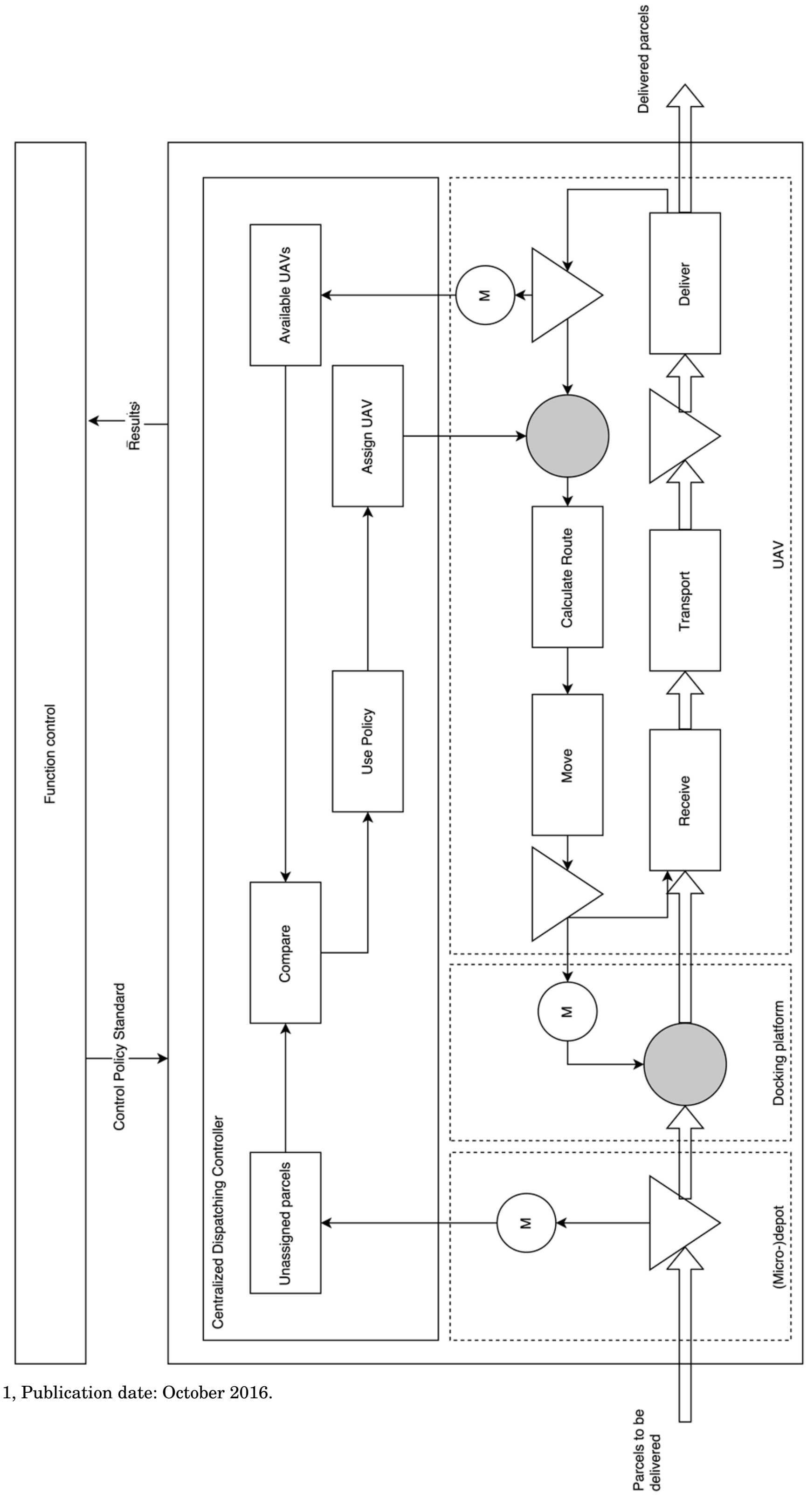


Fig. 1. Overview Centralized Dispatching Control Stucture

B

RECENT MARKET DEVELOPMENTS IN LAST MILE PARCEL DISTRIBUTION WITH UNMANNED AERIAL VEHICLES

This chapter summarizes the recent developments and efforts of different parcel carriers, retailers and other companies from the United States, Australia, Switzerland and Germany in exploring the potential of UAVs for last mile distribution of goods. All of the recent developments summarised below walk a fine line between being a potential new logistics paradigm or a simple publicity and marketing stunt. Nevertheless it is interesting to see what efforts are being undertaken and from which point of view these companies explore this new technology.

AMAZON

On December 1, 2013 Amazon founder and CEO Jeff Bezos, announced his companys plans to develop an automated transport system capable of delivering goods to customers within 30 minutes after ordering, with UAVs (CBS, 2013).

Amazon Prime Air, as the system is called, would be capable of delivering parcels from Amazon warehouses to customers living within a 15 kilometre radius of the warehouse. Altough the UAVs would only be capable of carrying parcels of up to 2.2 kilograms, according to Amazon around 86% of their shipments would fall within this weight limitation. In 2015 Amazon released a new video showing a new prototype of one of its UAVs under development, which shares features of both rotary wing and fixed wing aircraft.

Amazon Prime Air

AUSTRALIAN POST

In April 2016, Australian Post has began conducting trials of rural UAV deliveries in south-east Melbourne at Dandenong South. The use of UAVs is envisioned for rural customers given that they currently buy online 3x more per capita than their metropolitan counterparts, and for some Australians, their mailboxes are miles away from their front doors, meaning this would present a perfect opportunity for delivery drivers to remotely test pilot the drones closer to the customers homes from the nearest road.

The trials consisted of using UAVs to deliver parcels to 50 locations two times per week with the precondition that customers specifically agree to receive their parcels by UAV in order to avoid any privacy concerns that might arise. The trials were backed by the Australian Civil Aviation Safety Authority (CASA) which upheld the rule that a 30 meter distance should be kept at all times from all humans and buildings. Currently, UAVs in Australia cannot fly over urban areas due to regulations. Nevertheless, Australia Post has the goal of having their delivery UAV experiments up by the end of this year.

Australian Post UAV

According to Australia Post chef executive UAVs are still in the very early stages of technology, but believes that over the next 5 to 10 years there would be an enormous amount of change as in e-commerce and online sales, it’s all about customer convenience. If you were shopping and wanted something really quickly, what’s the best way when you’ve got traffic and a situation where you need it right now? You could potentially use UAVs to get it.

DEUTSCHE POST DHL

In December 2013 the German parcel carrier Deutsch Post DHL launched a research project into transportation of goods with UAVs. The research was performed in cooperation with the Institute of Flight System Dynamics at RWTH Aachen University and Microdrones GmbH.

Parcelcopter DHL

The first test flight involved a multi-rotor UAV, referred to as the "Parcelcopter", which was flown manually over a river in Bonn, Germany. Not soon thereafter in 2014 the company performed additional test flights with an enhanced version of the UAV capable of transporting a payload of 1.2 kg autonomously over 12 kilometres across the open sea from Nordreich, Germany to the Island of Juist (DHL, 2014).

In 2016, DHL resumed the test flights and completed a 3 month test in the Bavarian mountains with a new version of the Parcelcopter (Soeteman, 2016). The version was specially designed to fly at high altitudes, dealing with fluctuating weather and temperature conditions and handle up to 500 meters differences in elevation while in flight. Furthermore, loading and unloading of the UAVs was automated by using a Skyport, which isa combination of a modified Packstation parcel locker with a docking platform. In total 130 autonomous loading/unloading cycles were completed during the trial, with the UAV covering 8 km of mountain terrain within 8 minutes of take-off, a trip that would have taken 30 minutes by car.

Skyport DHL

The Skyport, which weighs 14.5 tons, measures 5 x 5 x 3.5 meters and can handle up to two UAVs which automatically align to a 3 x 3 meter landing pad. It has been described as a small post office with a small docking platform on top of it, with the entire system working automatically without human intervention. When parcels are inserted, they are loaded into the Parcelcopter and approximately 2 minutes later, the roof of the Skyport opens allowing the UAV to fly off and deliver its goods to their destination.

GOOGLE

In 2014, Google unveiled *Project wing*, a research project to develop an autonomous parcel delivery UAV for both disaster relief and commercial delivery of goods. A video was released, showing delivery field trails of the first prototype in the outback of Australia (Barr, Bensinger, 2014). While the design was discontinued for unknown reasons, a year later its successor was presented, which is said to reach speeds of up to 100 km/hr Opam (2015).

SWISS POST

In July 2015, Swiss Post started testing the use of UAVs for delivery of goods as part of a joint venture which includes Swiss WorldCargo and Matternet (Swiss Post, 2015). The goal was to investigate the specific use cases of UAV technology and examine the cost-effectiveness of UAVs for logistic transportation applications. Not specifically for mail and parcels, but also for emergency situations such as the delivery of emergency relief supplies or for high priority shipments such as laboratory samples.

In these trials only the UAVs without payload were tested, however the company plans to perform new test flights including payloads in 2016 on pre-set routes authorized by the Swiss Civil Aviation Authority.

At this point in time, Swiss Post aims to use the UAVs to build up their own experience and increase their knowledge in order to get an advantage over the competition when UAVs can be deployed within the regulatory frameworks, of which the believes that will be reached by 2020.

WALMART

In 2015, Walmart the worlds largest retailer asked regulators for permission to perform test flights with UAVs for home delivery, pick-up and checking of warehouse inventories, indicating its plans to compete with Amazon in using UAVs to fill and deliver online orders (Abrams, 2016).

In its large warehouses, the company wants to experiment with the use of UAVs to check inventory. Where at present Walmart employees manually scan pallets of goods with hand-held scanning devices in aisles that are packed nearly to the ceiling, UAVs could be used to mimic the path of a person in a forklift who might be inspecting labels while taking 30 images per second reducing the inventory checking process from a month to a single day.

Furthermore, according to Walmart, 70% of the population in the United States lives within five miles of its retail stores , which creates a unique opportunity to serve customers with UAVs. The retailer wants to test UAVs for grocery pick-ups and confirm whether UAVs could deliver parcels to retails stores or customer homes in small residential neighbourhoods after obtaining permission from those living in the flight path.

C

SIMULATION MODEL

This appendix contains an elaborate description on the simulation model that has been build and used during this research. First it covers the usage of the TOMAS software package for discrete event/process simulation and the basic set up of the simulation/model. Then section C.3 describes the generic model and its functioning by use of a process description language, describing all processes, attributes and methods used by the modelled objects. Thereafter section C.4) covers the validation and verification of the model and the final set up for both the test cases of The Hague and Goes are given in section C.5.

C.1 TOMAS FOR DELPHI

The system is modelled using the process descriptions of the equivalent equipment defined in section 4.2.1) during the conceptual design phase. These process descriptions have been discussed with a simulation expert and provide the basis for an unambiguous translation to the software environment. This process-oriented approach has already been implemented in several simulation languages and packages such as Simula, PROSIM, MUST and TOMAS (Veeke et al., 2008).

In this research the Tool for Object-oriented Modelling and Simulation (TOMAS) software package is used as it is object-oriented, supports both modelling and simulation of logistic and transport processes and has been developed to be used in combination with a systems approach (Veeke, Ottjes, 1999). In general TOMAS can be considered as a toolbox that can be used in a standard Delphi-environment.

C.2 MODEL & SIMULATION SET UP

The simulation experiments performed with the simulation model build using TOMAS should represent a correct and realistic system. It is therefore important to first prepare the simulation in terms of the required run time, warm up time, run replications followed by verification and validation of the simulation model. In this section the selected methods used to set up these aspects of the simulation model are further explained.

RUN LENGTH AND WARM-UP PERIOD

Before performing simulation experiments the run length of the simulation needs to be determined. The run length should be long enough to present all possible events and let the simulation come to a steady state. Therefore a long runtime of 12 weeks was selected for the system.

One of the objectives of discrete event simulation is to estimate the steady-state means of the simulation output. Because each simulation run starts with an empty input set, it requires a certain amount of time, also known as the initial transient, before a steady-state is reached, assuming that the output reaches a steady-state. The required period of time is also referred to as the warm-up period.

One of the simplest and most general methods to determine the length of the warm-up period is by means of a graphical procedure developed by Welch (1981). Welch's procedure is based on making a number of independent replications of the simulation where the run length is large enough to eventually let the simulation run reach a steady-state. From this graphical representation the warm-up period was determined to lie at 2 weeks, giving a simulation runtime of 14 weeks.

RUN REPLICATIONS

Replications of simulation runs are needed to reduce the effects of variation on the model. Every individual replication run is performed with a different seed and therefore delivers a different output.

According to (Law, 2007) there are three methods that can be used to determine the number of replications; the Rule of Thumb method, which states that simulation experiments must be replicated 3 - 5 times, a simple Graphical method where the cumulative mean of a chosen output variable for multiple replications is plotted and the number of replications is visually selected from a graph and the Confidence Interval method, which uses a predefined estimate on the tolerated error for the true mean for the simulation model. Because both the Rule of Thumb and Graphical methods are subjective and do not use any measured precision in determining the number of replications, Law (2007) recommends to use the Confidence Interval method to determine the required number of replications.

According to Law (2007) when using the confidence interval method, the half width of the confidence interval for any PI should be smaller than a predefined percentage of the cumulative mean. For the ATS is was decided that a 95% certainty interval would suffice and thus the half width of the confidence interval should be no larger than 5% of the cumulative mean. In case a value exceeds this limit, an extra replication is added and the model is run again. This process is repeated until all PIs are within the limit.

VERIFICATION & VALIDATION

Verification and validation are needed before the results of the simulation can be used and conclusions can be drawn. According to Sargent (2012) verification determines if the model is right and operates as intended, whereas validation is used to determine if the right model has been build.

Sargent (2012) proposes several verification methods, including comparing the models output to the output of similar models, using an interactive debugger or graphical interface to trace the state of the simulation taken by the model and examining the model output for reasonableness under limiting conditions (i.e. degenerate testing).

Another technique is when possible, be run under special assumptions for which results can also be obtained by analysis. One of the analytic methods that can be used to obtain these results is queueing theory (Law, 2007). By simulating the system as an existing queuing model with either deterministic and/or exponential arrival and service times the results of the simulation can be compared to the results calculated for queuing theory. In the verification, both the D/D/1 and M/D/1 queuing models will be used as these can be easily calculated.

Validation is the process of determining the degree to which the simulation model is an accurate representation of the real world from the perspective of the intended uses of the model. Because system does not exist in the real world today, operational validation of the system cannot be performed.

NUMBER OF UAVS

To ensure that all tasks in the system are performed within time, sufficient UAVs have to be available. However overestimating the number of UAVs can lead to high costs as they are generally expensive, whereas underestimating the number of UAVs can influence the systems performance. Therefore it is important to determine the minimum number of UAVs required in system.

According to Vis (2006) there are several factors affecting the required number of vehicles, such as the number of units transported, the number and locations of pick-up and delivery points, the vehicle capacity and the vehicle dispatching policy used. These factors should thus be taken into consideration when determining the required number of UAVs.

For the design of Automated Guided Vehicle Systems both simulation and analytical methods are commonly used to determine the minimum required number of vehicles. Analytical methods include simple mathematical models, queuing models, statistical approaches, multi-criteria decision modelling and network-flow modelling approaches (**?**).

In this research the inital minimum required number of UAVs for each test case is calculated using a simple mathematical model proposed by Egbelu (1987). The method is based on the complete transport process of the vehicles, by estimating the empty travel time and loaded travel time between the pick-up and delivery locations, but also includes the idle waiting time, failure rate and charging time.

C.3 MODEL PROCESS DESCRIPTION LANGUAGE

The simulation model that has been build based on the developed conceptual design is further outlined in this section. All the different elements, their attributes, processes and methods are explained comprehensively in the process description language.Ries

PARCEL

Parcels are transported by UAVs from their origin to their destination. They are generated by the Parcel Generator, which assigns all attributes and enters the Parcel to the origins Micro-Depot My-

ParcelsQ. For simplicity all Parcels are assumed to be of uniform weight and size.

ATTRIBUTES

Origin	Micro-Depot from where parcel must be transported
Destination	Micro-Depot to which parcel must be transported
ReleaseTime	Time when Parcel entered the system
DueTime	Time the Parcel should be delivered (ReleaseTime + TimeWindow)
registerCustomerSatisfaction	Method: registers the customer satisfaction

PROCESS AND METHODS

Although Parcels are inactive elements, they have the *registerCustomerSatisfaction* method, which is used when the Parcel has been delivered at the destination Micro-Depot.

registerCustomerSatisfaction method description

registerCustomerSatisfaction method

```
Remove Parcel from AllParcelsQ
If TNow > DueTime then
        Register average too late time of Parcel
Register CustomerSatisfaction
Destroy parcel
```

PARCEL GENERATOR

The Parcel Generator is responsible for creating new Parcels, assigning attributes to them and adding them to the MyUnassignedParcelsQ of the Control System and the MyNewParcelsQ of the origin (micro-)depot. The inter arrival times of Parcels are generated according to a Poisson process using exponentially distributed inter arrival times. When multiple (Micro)-Depots are located in the origin and/or destination Postal code Area, the destination/origin (Micro)-Depot is uniformly sampled from all (Micro-)Depots located in the Postal code Area.

ATTRIBUTES

PROCESS	General process of the DemandGenerator

PROCESS AND METHODS

ParcelGenerator process description

Process

```
Repeat until end simulation
    Sample InterArrivalTime
    Wait for InterArrivalTime
    Create new Parcel
    Set ReleaseTime
    Set DueTime
    Uniformly sample origin and destination Stations from the origin and destination Area’s
    MyLoadingUnloadingStationsQ
    Add Parcel to AllParcelsQ
    Add Parcel to AllNewParcelsQ
    Add Parcel to Control System MyUnassignedParcelsQ
        Add Parcel to the origin Station MyParcelsQ
        Add Parcel to Control System MyUnassignedParcelsQ
Interrupt simulation
Register all statistics in output file
```

UAV

UAVs are used to transport Parcels from their origin to their destination. For simplicity, a homogeneous fleet of UAVs is assumed, meaning all UAVs have similar vehicle characteristics. In practice, a heterogeneous fleet of UAVs could be used with different sizes, endurance’s and speeds that can be assigned to different transport requests based on weight, size, flight distance and weather conditions.

ATTRIBUTES

MySpeed	Constant flight speed
MyEndurance	Flight time based on the assigned average range and constant flight speed.
MyRemainingEndurance	Remaining flight time
MyOrigin	Micro-Depot where UAV is located
MyDestination	Micro-Depot where UAV must fly to.
MyParcels	Parcels carried by the UAV
MyAssignedParcels	List of assigned parcels
MyRouteQ	Flight route consisting of flightpaths

getRoute	Method: determine flightpath of UAV
performFlight	Method: executes flight from origin to destination
findNearestChargingLocation	Method: find nearest available ChargingDepot

	from current Origin
• *findNearestHoldingLocation*	Method: find central HoldingDepot from current Origin
• *PROCESS*	General process of the UAV

PROCESS AND METHODS

The UAV has several methods which are used in the UAVs process. The *getRoute* method selects the path(s) that are used by the *performFlight* method. Because all paths are straight lines from origin to destination service areas the method only selects a single path. However, in the future this method could be expanded to include flight dynamics or charging locations into the routing process instead of directly flying to its destination.

performFlight method description

performFlight method

```
Repeat until MyRouteQ is empty
    Select first Path from MyRouteQ
    Enter AllInFlightQ
    Calculate total flight time
    Hold flight time
    Set MyRemainingEndurance
    Add flight distance to total flight distance
    Remove Path from MyRouteQ
Enter MyDestinationStations MyVehiclesQ
Set MyOrigin as MyDestination
```

getRoute method description

getRoute method

```
For all Paths in AllPathsQ
    Select first Path in AllPathsQ
    If StartArea = MyOriginStation's Area and EndArea = MyDestinationStation's Area then
        Add Path to MyRouteQ
```

The *findNearestChargingLocation* and *findNearestHoldingLocation* methods are used when the UAV needs to change a battery or becomes idle when it has no assignments. While both methods are almost similar, the findNearestChargingLocation method chooses the nearest (Micro-)Depot, whereas the findNearestHoldingWarehouse always returns the Depot that is attributed as the central holding location for idle UAVs.

findNearestChargingLocation method description

findNearestChargingLocation method

```
Set distance to Infinite
For all ChargingWarehouses in AllChargingWarehousesQ
    Select first ChargingWarehouse
    Get distance between MyOrigin and ChargingWarehouse
    Calculate flight time to ChargingStation
    Get length MyLoiteringUAVsQ and MyVehiclestTravellingTowardsQ of ChargingStation
    Calculate waiting time at ChargingStation
    Add flight time and waiting time to EstimatedServiceTime
    If EstimatedTime < ShortestServiceTime then
        Select ChargingWarehouse as nearest station
        Set new ShortestServiceTime
Set MyDestination to origin of nearest ChargingWarehouse
```

To calculate if the UAV has enough endurance left to perform its assigned parcels, the method *calculateRequiredEndurance* is used. The method determines the flight times for pick-up, delivery and finally to a charging station and adds the average platform times. Variation in flight, service and waiting times is incorporated in the required endurance in terms of a safety factor.

calculateRequiredEndurance method description

calculateRequiredEndurance method

```
Set requiredEndurance = 0
Select first assignment from MyAssignedParcelsQ
    Add average flight time from MyOrigin to Parcel Origin to requiredEndurance
    Add average PlatformPreparationTime and PlatformLoadingTime to requiredEndurance
    Add average flight time from Parcel Origin to Destination to requiredEndurance
    Add average PlatformPreparationTime and PlatformUnloadTime to requiredEndurance
    Add average flight time from Parcel Destination to nearest ChargingWarehouse to requiredEndurance
Return requiredEndurance
```

UAV process description

Process

```
Repeat
    If MyAssignedParcelsQ > 0 then
        If Loaded then
            Read MyDestination from first Parcel in MyParcelsQ
            getRoute
            performFlight
            Enter MyLoadedVehiclesQ at MyDestination Station
            Activate Station and Wait for Platform

        Else then
            calculateRequiredEndurance
            If RequiredEndurance > MyRemainingEndurance then
                Return all assigned Parcels from MyAssignedParcelsQ to UnassignedParcelsQ
                findNearestChangingStation
                getRoute
                performFlight
                Enter MyNeedChangingVehiclesQ at MyDestination Station
                Activate Station and wait for Platform
            Else then
                Read Destination from MyAssignedParcelsQ
                getRoute
                performFlight
                Enter MyLoiteringVehiclesQ at MyDestination Station
                Activate Station and wait for Platform
    Else if MyEndurance < EnduranceThreshold then
        findNearestChargingStation
        getRoute
        performFlight
        Enter MyVehiclesQ at MyDestination Station
        Activate Station and wait for Platform
    Else if not Holding then
        findNearestHoldingStation
        getRoute
        performFlight
        Enter MyVehiclesQ at MyDestination Station
        Acativate Station and wait for Platform
    Else wait for new assignment
```

(MICRO-)DEPOT

The (Micro-)Depots are located in Postal code Areas. As mentioned they have a number of Docking Platforms for automated loading, unloading of Parcels and changing of batteries. In the simulation model, different types of (Micro-)Depots can be defined based on their number of Docking Platforms, such as a regular depot or micro-depot.

ATTRIBUTES

MyType	’Depot’ or ’micro-depot’
MyArea	Postal code Area where (Micro-)Depot is located
MyPlatformsQ	Queue with all Docking Platforms
MyIdlePlatformsQ	Queue with all idle Docking Platforms
MyUAVsQ	Queue with all UAVs
MyLoiteringUAVsQ	Queue with all loitering UAVs
MyNeedChargingUAVsQ	Queue with all UAVs that need to change their battery
MyLoadedUAVsQ	Queue with all loaded UAVs
selectPlatformTask	Determine the Docking Platform task
PROCESS	General process of the (Micro-)Depot

PROCESS AND METHODS

The *SelectPlatformTask* method (figure **??**) is used to assign UAVs to available Docking Platforms and determine the task that must be performed by the Docking Platform. Instead of a Fist Come-First Serve assignment method, priority is given to battery changing. This due to the fact that loaded UAVs are assumed to already have used more energy during their flight and because loaded UAVs use more energy during their hovering state, due to the added weight of their payload.

(Micro-)Depot process description

Process

```
Repeat
    Wait until activated by UAV
    Repeat while MyUAVsQ is not empty
        selectPlatformTask
        If PlatformTask = load
            Select first Docking Platform from MyIdlePlatformsQ
            Remove Docking Platform from MyIdlePlatformsQ
            Select first UAV from MyLoadedUAVsQ
            Remove UAV from MyUAVsQ
            Assign UAV to Docking Platform
            Set MyTask of Docking Platform to load
            Active Docking Platform
        Else if PlatformTask = unload
            Select first Platform from MyIdlePlatformsQ
            Remove Docking Platform from MyIdlePlatformsQ
            Select first UAV from MyLoiteringUAVsQ
            Remove UAV from MyUAVsQ
            Assign UAV to Docking Platform
            Set MyTask of Docking Platform to unload
            Active Docking Platform
        Else if PlatformTask = charge
            Select first Docking Platform from MyIdlePlatformsQ
            Remove Docking Platform from MyIdlePlatformsQ
            Select first UAV from MyNeedChargingUAVsQ
            Remove UAV from MyUAVsQ
            Assign UAV to Docking Platform
            Set MyTask of Docking Platform to unload
            Active Docking Platform
        Else
            Wait for available Docking Platform
```

DOCKING PLATFORM

Docking Platforms are used for loading, unloading or changing of batteries and provide a secure area where the UAV can take-off and land. Although the detailed design of platforms for each type of Station would be different the they are modeled as a generic object part of each type of Station and can perform every type of task that is assigned to them.

ATTRIBUTES

- MyTask Task assigned to the Docking Platform by the Warehouse

• MyWarehouse	(Micro-)Depot to which the Docking Platform belongs
• MyUAV	UAV assigned by the Platform
• *PROCESS*	General process of the Docking Platform

PROCESS AND METHODS

Docking Platform process description

Process

```
Repeat
    Wait until activated by MyWarehouse
    Leave MyWarehouse MyIdlePlatformsQ
    PlatformPreparationTime.Sample
    If MyTask = load then
        Retrieve Parcel from MyWarehouse MyNewParcelsQ
        PlatformLoadingTime.Sample
        Add Parcel to MyUAV MyParcelsQ
        Resume UAV
    Else if MyTask = unload then
        PlatformUnloadingTime.Sample
        Remove first Parcel from MyUAV MyParcelsQ
        Use Parcels registerCustomersSatisfaction method
        Resume UAV
    Else if MyTask = charge then
        PlatformChargingTime.Sample
        Set UAV MyRemainingEndurance = MyEndurance
        Resume UAV
    Else if MyTask = park then

    Enter MyWarehouse MyIdlePlatformsQ
    Suspend
```

CONTROL SYSTEM

Control System is responsible for assigning available UAVs to Parcels that must be transported. Based on the literature review of assignment methods in section **??**, a centralized dispatching control system was chosen to be implemented into the simulation model.

ATTRIBUTES

• MyAvailableUAVsQ	Queue with available UAVs
• MyUnassignedParcelsQ	Queue with Parcels that have to be transported
• MyPolicy	Control Policy used by Control System
• *PROCESS*	General process of the System Control

PROCESS AND METHODS

Control System process description

Process

```
Repeat
    While MyUnassignedParcelsQ > 0 and MyAvailableVehiclesQ > 0
        If Prioriy then
            For all Parcels in MyUnassignedParcelsQ
                Select Parcel

                calculateEstimatedHandlingTime

            Sort MyUnassingedParcelsQ on all Parcels PickUpTimeLeft

        Select first Parcel from MyUnassignedParcelsQ

        Get origin selected Parcel

        Find closest UAV to origin from MyAvailableVehiclesQ

        Assign Parcel to UAVs MyAssignedParcelsQ

        Activate UAV
```

POSTAL CODE AREA

An Postal Code Area represents a subregion in the overall operating region of the ATS. These Postal Code Areas can be of different sizes and can contain different numbers of (Micro)-Depots. Furthermore, all Postal Code Area's are interconnected with bidirectional Flight Paths of a certain length.

ATTRIBUTES

MyLoadingUnloadingStationsQ	Queue with all LUS in Service Area
MyChargingStationsQ	Queue with all CS in Service Area
MyHoldingStationsQ	Queue with all HS in Service Area
MyVehiclesQ	Queue with all UAVs in Service Area
MyDeliveredParcelsQ	Queue with Parcels delivered in Service Area

FLIGHTPATH

A Flightpath either represents the straight line distance between the centers of two Postal Code Areas. These Flight path's are assumed to be of infinite capacity in terms the number of UAVs that can travel along these paths as they could fly above each other. This assumption reduces the possibility of deadlock or collisions with UAVs.

ATTRIBUTES

StartArea	Postal Code Area where Flightpath starts
EndArea	Postal Code Area where Flightpath ends
Distance	Length of the Flightpath

C.4 VALIDATION AND VERIFICATION

In this section the verification and validation process of the simulation model is described together with the methods used during the process.

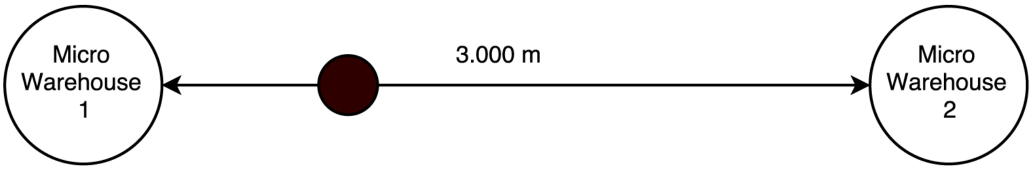
VERIFICATION - DELPHI DEBUGGER

The simulation model has been extensively verified throughout the development process using the debugging interfaces of Delphi and Tomas. Because no graphical representation of the simulation model has been developed the tools offered by both Delphi and Tomas have been used to debug the program. For example, the Tomas trace function allows the developer to follow every event occurring during run-time. This ensures that all the right events take place and they follow in the correct order. Further, the Delphi debugging function has been used to follow the order in which the code is executed.

VERIFICATION - SIMPLIFIED CALCULATIONS

Existing mathematical models from queuing theory are used to verify the output of the simulation model. A simplified system layout (figure **??**) and input parameters are chosen for which the utilization of UAVs and the expected time and number of parcels in system and queue can be calculated with use of these mathematical models.

In the simplified layout the micro-depots are inter connected with flight paths.



Graphical representation of simplified system layout for simple calculations

Besides the simplified layout a number of input parameters have been changed compared to the parameters used in the simulation runs for the test cases:

- Runtime: 8760 hours
- No of UAVs: 1
- UAV speed: 10 m/s
- UAV endurance: Infinite
- Platform loading time: 0 seconds
- Platform unloading time: 0 seconds
- Platform charging time: 0 seconds
- Control policy: First-Come-First Served (FCFS)

Two verification cases have been created by combining these input parameters with different distributions for the inter arrival times of parcels and the service times of docking stations. In the first case both the inter arrival times and service times are deterministic (D/D/1 system according to Kendall's notation). In the second case the inter arrival times are exponentially distributed and the service times remain deterministic (M/D/1 system).

Case 1: D/D/1

In case 1, the inter arrival time of parcels is deterministic with an arrival rate of $\lambda = 6$ parcels/hour. Because the platform preparation, loading and unloading times have been set to zero and the UAV is travelling with a constant speed of $v_c = 10$ m/s, the service times are also deterministic with a service time of $\frac{6000}{10} = 600$ seconds = 10 minutes per parcel and a service rate of $\mu = 6$ parcels/hour. As a result, the time and number of parcels waiting in queue for service should be zero. Furthermore, as parcels can be transported immediately when they arrive their time in system should be $\frac{3000}{10} = 300$ seconds = 5 minutes and the number of parcels in system should be 0.5, as they leave the system when the UAV still has to return to area 1. Further, because the UAV is always busy, its utilization should be $\rho = 1.00$.

Because both the inter arrival times and service times are deterministic there is no randomness in the model and it only has to be run once. Comparing the calculated results to the simulations output it can be seen that the simulation performs as expected, with all of the output values being equal to the calculated results.

Verification results for the D/D/1 system with $\lambda = 6$ and $\mu = 6$

	Calculated result	**Simulation result**
UAV utilization	1.00	1.00
Mean number of parcels in system	0.5	0.5
Mean time parcel in system [min]	5	5
Mean number of parcels in queue	0	0
Mean time parcel in queue [min]	0	0

Case 2: M/D/1

In case 2, the inter arrival times of parcels is exponentially distributed with a mean arrival rate of $\lambda = 4$ parcels/hour. The service times remain fixed at 600 seconds with a mean service rate of μ_q = 6 parcels/hour for the parcels in queue and 300 seconds or with a mean service rate of $\mu_s = 12$ parcels/hour for the parcels in system. Because the arrival process of parcels is stochastic, the simulation has been run 10 and a 100 times with different Tomas seeds.

Verification results for the M/D/1 system with $\lambda = 4$ and $\mu = 6$

	Calculated result	**Simulation result**	
		10 runs	100 runs
UAV utilization	0,67	0,67±0,00	0,67±0,00
Mean number of parcels in system	1,00	0,99±0,02	1,00±0,02
Mean time parcel in system [min]	15,05	14,91±0,33	14,98±0,26
Mean number of parcels in queue	0,67	0,66±0,02	0,67±0.02
Mean time parcel in queue [min]	10,05	9,91±0,33	9,98±0,26

Both the calculations and the sample mean and standard deviation of all simulation runs are displayed in table **??**, show that the simulation model performs as expected. Also increasing the number of runs directly affects the accuracy of the simulation models output.

VERIFICATION - DEGENERATE TESTING

The behaviour and output of the simulation model should also be validated in case of degeneracy. Degeneracy happens when a limiting case or extreme condition in the system occurs. For example when the arrival rate is higher than the service rate, whereby the number of parcels waiting for services increases over time (Sargent, 2012). Below the behaviour and output of the system have been validated for a number of predetermined degenerate cases.

Unstable system

One of the underlying assumptions in the previous calculations has been that the system always reaches a steady-state. However when the arrival rate becomes higher than the service rate ($\lambda > \mu$)

the system will become unstable. It is expected that in the unstable system the number of parcels waiting for service in queue will increase to infinite over time. To determine if this happens a verification case has been created with an exponential distributed arrival rate of $\lambda = 10$ parcels/hour and a deterministic service rate of $\mu = 6$ parcels/hour. As a result, every hour 4 parcels should be added to the overall queue length in the simulation.

Verification results for unstable M/D/1 system with $\lambda = 10$ and $\mu = 6$

Runtime [hrs]	**Calculated result** No. of delivered parcels	**Simulation result** No. of delivered parcels 10 runs	 100 runs
8760	35.040	34.992±226	0

Again the simulation has been run 10 and a 100 times with different Tomas seeds. The expected number of parcels in queue of the unstable system (table **??**) are almost the equal to the calculated results.

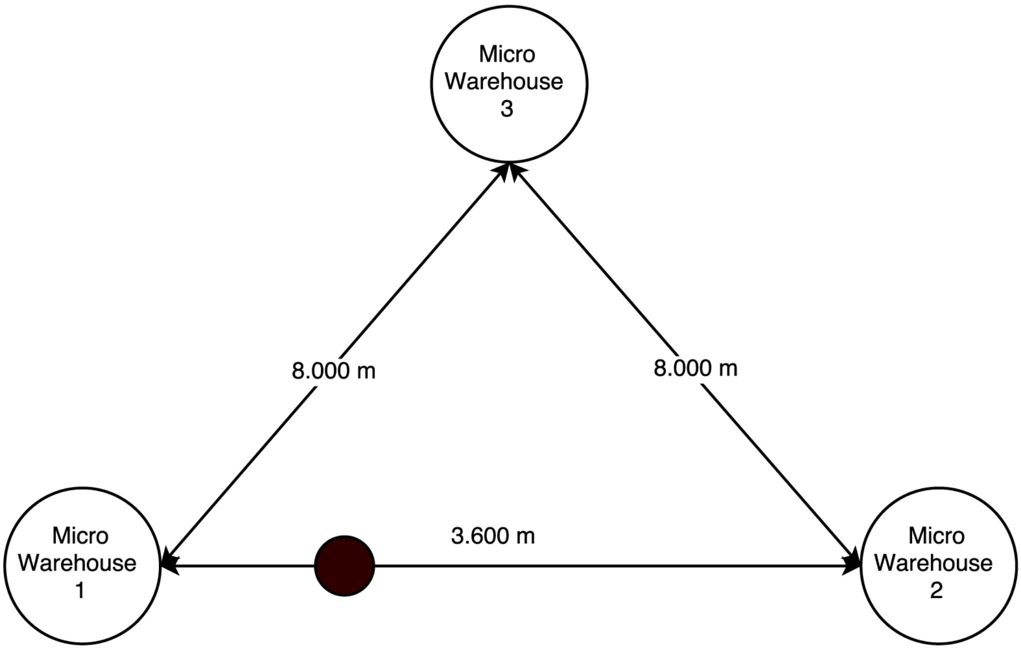
Limited endurance

Another limiting conditions occurs when UAVs do not have enough endurance to reach one or multiple micro-depots in the system. For verification of this case a new simplified system layout has used as presented in figure **??**. All parcels are generated at micro-depot 1 and their destinations are equally distributed between micro-depot 2 and 3. While almost all input parameters are kept similar to the defined input parameters in section C.4, only the endurance of the UAV has been changed and set to 13 minutes. As a result the UAV should be capable of transporting all parcels between micro-depot 1 and micro-depot 2 but does not have enough endurance to reach micro-depot 3. Therefore all parcels for micro-depot 3 should be rejected by the UAV and remain at micro-depot 1. Again parcels arrive with exponentially distributed inter arrival times with an arrival rate of $\lambda = 4$ parcels/hour. While the service times remain deterministic the service rate becomes $\mu = 5$ parcels per hour, because the service time will include flying to and from the charging station after every delivery. When running the simulation for 8760 hours this would mean that an average of 35.040 parcels should be generated of which 50% can be transported. On average this would mean 17.520 parcels should be delivered.

Verification results for limited endurance using M/D/1 system with $\lambda = 4$ and $\mu = 6$

Runtime [hrs]	**Calculated result** No. of delivered parcels	**Simulation result** No. of delivered parcels 10 runs	 100 runs
8760	17.520	16.969±83	16.719±77
8760	50%	47%	49%

Simulation results show that the number of delivered parcels is much lower compared to the calculated number of parcels to be delivered. However the percentage of parcels delivered of the total



Graphical representation of simplified system layout for limited endurance testing

generated parcels for 10 runs is on average 47% and for 100 runs 49%. The difference between the calculated results and the simulation results can be partially explained by the fact that both the inter arrival time and the destinations are sampled in the simulation.

VALIDATION

Verification of the model shows that the simulation model behaves as expected even in degenerate cases. All calculated results lie within the expected output results. Although the simulation model has been verified, validation of the simulation model cannot be performed as this system or a similar system does not yet exist.

C.5 MODEL SET UP: THE HAGUE AND GOES

In this section all basic input settings that have been used in the simulation experiments for the test cases of Goes and The Hague are shortly covered. These settings include the demand across all postal code areas, the number of (micro-)depots per postal code area, the number of UAVs and the settings of the UAVs.

NUMBER OF REPLICATIONS

The number of replications per test case have been determined using the Confidence Interval Methods. All simulations were initially run 5 times. For the simulation of Goes an additional 3 replications were needed to reach results that where within the confidence interval boundaries that ware set for the design. For The Hague, the simulation required 13 replications to reach the desired results.

NUMBER OF UAVS

Before evaluating the alternative dispatching policies and operational characteristics, the minimum required number of UAVs needs to be determined. The initial number of UAVs for both test cases were calculated using the simple mathematical procedure of (Egbelu, Tanchoco, 1984). For the calculations peak demand in an average month was used, as this prevents dimensioning the system with under or over capacity.

Number of UAVs

	The Hague	Goes
Number of UAVs	215	92

(MICRO-)DEPOT AND UAV CHARACTERISTICS

The speed, endurance and payload characteristic of the UAVs are based on capabilities of the reference case UAV from section 2.4.2.

- Cruise speed: 16 m/s
- Climb/descend rate: 10 m/s
- Endurance: 45 minutes
- Maximum payload capacity: 4 kilograms
- Total weight (without payload): 10,4 kilograms
- Drag coefficient: 0.9
- Front surface area: 1,8 m^2

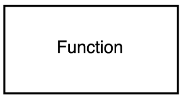
The number of docking platforms located at the depot and (micro-)depot have been estimated based on the size of the buildings. While micro-depot are assumed to operate in small areas, they will probably only have a single platform, whereas regular depots have enough room to accommodate up to 100 or more docking platforms. By running initial simulation runs with infinite docking platforms at the depot, it was determined that 100 platforms would be sufficient to handle all demand. Further, the loading, unloading and exchange times have been based on existing exchange mechanisms found in literature (Suzuki et al., 2011).

Simulation settings - station characteristics

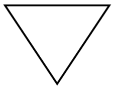
	Depot	Micro-Depot
No. of Docking Platforms [-]	100	1
Unloading time [min]	2	2
Loading time [min]	2	2
battery changing time [min]	0,5	0,5

D

Symbols

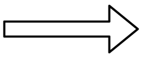


Function block
Black-box containing a (sub)system where elements undergo a transformation.



Buffer
Inventory and/or queue where no transformation takes place.

Information flow
Supporting information flows including measurements, orders and other.



Aspect flow
Flow of elements going trough the system.

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