Master Thesis Research

A value analysis of unmanned aircraft operations for the transport of high time-value cargo

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In order to speed up the development and integration of cargo UAS, it is necessary to analyze and quantify the value that UAS can add in the commercial transport of cargo. Up to now, no such quantitative research is performed. The current research tries to fill this void by contributing to an increased understanding of the value adding capabilities of cargo UAS. By means of a value analysis, this research compares the value of cargo UAS in the commercial transport of air cargo to that of conventional cargo aircraft for specific future demand scenarios. Research findings show that unmanned or less manned cargo aircraft are especially suited to anticipate on the future demand for the transport of high time-value commodities. The most promising market opportunities emerge when there is a relatively small demand for high time-value cargo transport on long distance routes. Especially in the situation of long distance routes and small freight flows, the costs for transportation are high in relation to the value of the product. It is this market segment where cargo UAS can deliver maximum additional value over conventional cargo aircraft, given that the airline adapts its operations to facilitate the utilization of cargo UAS specific capabilities.

I. Introduction

UNMANNED aircraft have taken a huge flight over the past few years due to specific benefits they can offer over manned aircraft. Currently, the main application is for defense missions that are considered either too dull or too dangerous for manned aircraft. Due to issues with safety, lack of infrastructure, legislation and certification, the commercial use of unmanned aircraft has been very limited (Dolan & Thompson II, 2013). Despite these challenges which will need to be overcome for unmanned aircraft to be used commercially on a large scale, the potential cost-savings and productivity gains could make a promising case for the application of unmanned aircraft in a commercial setting. For the near future the human fear factor will likely prevent the idea of a passenger airline without an on-board pilot sitting behind the controls (MacSween-George, 2003). Thus, a logical first step towards large-scale commercial implementation of unmanned aircraft systems (UAS) would be to fly completely unmanned cargo aircraft.

It is a credible prediction that UAS will be commercially used for the transport of cargo. In terms of technical feasibility, UAS could easily be deployed to carry cargo. In fact, the military already uses an unmanned platform for resupply missions in remote locations (Eshel, 2012). However, civil cargo transport is different from military cargo transport. Where frontline resupply missions are dangerous, civil transport missions are not. Therefore arguments of elimination of risking human lives do not apply to the application of UAS in civil cargo transportation. Cargo UAS need to prove themselves to be value adding in some other way before their commercial application becomes interesting for cargo airlines.

It is not self-evident how much value can be created by the commercial operation of UAS for the transport of cargo. Neither is it clear where exactly this value is added. This information is, however, crucial for a speeded-up development and integration of cargo UAS. Both manufacturers and operators (airlines) are unlikely to support the development of commercial cargo UAS if it is unknown how, and if, they could benefit from this development. As a consequence fewer resources are put into test flights and other proofs of concept that are needed to prove that UAS are reliable and safe alternatives to manned aircraft and are able to operate in commercial airspace. This is needed in order to gain acceptance of the general public, aviation constituencies and civil aviation authorities and with this acceptance would come the development of international rules and regulations.

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What is needed is a way to analyze and, where possible, quantify the value that UAS can add in the commercial transport of cargo. The current research directly addresses this need. By means of a value analysis, it compares the value of cargo UAS in the commercial transport of air cargo to that of conventional cargo aircraft for specific future demand scenarios and identifies market segments and routes that are especially promising for unmanned cargo operations.

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>$A$</td>
<td>aircrew costs per block hour [$/hour]</td>
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<tr>
<td>$C_{a/c}$</td>
<td>aircraft depreciation costs [$/week]</td>
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<tr>
<td>$C_{aircrew}$</td>
<td>aircrew costs [$/week]</td>
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<tr>
<td>$C_{airport usage}$</td>
<td>airport user charges [$/week]</td>
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<tr>
<td>$C_{cargo}$</td>
<td>cargo related costs [$/week]</td>
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<td>$C_{fuel}$</td>
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<tr>
<td>$C_{handling}$</td>
<td>costs for cargo handling [$/week]</td>
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<tr>
<td>$C_{inventory}$</td>
<td>loss of cargo value during transport [$/week]</td>
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<tr>
<td>$C_{maintenance}$</td>
<td>maintenance costs [$/week]</td>
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<td>$C_{transport}$</td>
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<tr>
<td>$C_{warehouse}$</td>
<td>costs for cargo storage [$/week]</td>
</tr>
<tr>
<td>$d_{AB}$</td>
<td>flight leg distance between airports A and B [mile]</td>
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<tr>
<td>$f$</td>
<td>flight frequency [week$^{-1}$]</td>
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<tr>
<td>$FC$</td>
<td>fuel consumption [gallon]</td>
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<tr>
<td>$H_{consolidation}$</td>
<td>charge for the consolidation of cargo [$/m^3]$</td>
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<td>$H_{load/unload}$</td>
<td>charge for loading and unloading cargo [$/m^3]$</td>
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<tr>
<td>$MAT_{airframe}$</td>
<td>airframe and systems maintenance materials cost per block hour [$/hr]$</td>
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<tr>
<td>$MAT_{engine}$</td>
<td>engine maintenance materials cost per block hour [$/hr]$</td>
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<tr>
<td>$MHR_{airframe}$</td>
<td>number of airframe and systems maintenance man-hours per block hour [-]</td>
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<tr>
<td>$MHR_{engine}$</td>
<td>number of engine maintenance hours per block hour [-]</td>
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<tr>
<td>$MTOW$</td>
<td>maximum takeoff weight</td>
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<td>$P_{a/c new}$</td>
<td>aircraft new price [$]</td>
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<td>$P_{fuel}$</td>
<td>fuel price [$/gallon]</td>
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<tr>
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<td>freight flow between airports A and B [ton/week]</td>
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<td>airport charge rate</td>
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<td>$R_{labor}$</td>
<td>aircraft maintenance labor rate per man-hour [$/hr]$</td>
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<td>$\rho$</td>
<td>commodity density [ton/m$^3$]</td>
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<td>commodity value density [$/ton]$</td>
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<td>warehouse rent [$/m^3]$</td>
</tr>
<tr>
<td>$t_{block}$</td>
<td>block time [hour]</td>
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<tr>
<td>$t_{wait}$</td>
<td>average cargo waiting time before transport [hour]</td>
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<tr>
<td>$t_{0.5}$</td>
<td>half-time [hour]</td>
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<tr>
<td>$U$</td>
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<td>$V_{cargo,0}$</td>
<td>value of the cargo right before arrival at the airport [$]</td>
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<tr>
<td>$V_{shipping premium,0}$</td>
<td>maximum shipping premium charged for same-day shipping services [$]</td>
</tr>
<tr>
<td>$W$</td>
<td>aircraft depreciation rate [%/day]</td>
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### II. Methodology

A logistics cost model was developed that is able to compare the value of air transport operations in a value analysis for various demand and operational characteristics, including the use of cargo UAS. Hereto, value is expressed in terms of logistics costs. The methodology that is adopted throughout the research to arrive at a measure of value in terms of logistics costs is explained in more detail below. First, the boundaries of the research are defined by the research scope.

#### A. Scope

In the determination of the value of air cargo transport services, only transport operations are taken into account. This is a common practice in logistics systems analysis (Daganzo, 1999). The performance of the transport operations is assumed not to be affected by costs related to support activities, firm infrastructure or technology development. In addition the scope is limited to airside (airport to airport) operations. It assumes a simplified logistics problem linking one origin and one destination. Given that only airside operations are considered, the origins and destinations considered in this research are airports. Logistics operations considered...
are direct flights or single flight legs from an origin A to a destination or stopover B that do not include intermediate stopovers. These direct flights serve to meet a demand for cargo transport from origin A to destination B.

Within the air cargo market there are different air cargo service providers that can be differentiated based on their mode of logistic operations. The three main groups of cargo carriers are: combination carriers, all-cargo carriers and integrators. This study specifically looks at the all-cargo and integrator market, while combination carriers are left out of consideration. Combination carriers are passenger airlines that also carry cargo using the lower hold capacity of passenger aircraft. These airlines often give priority to passenger services and regard their cargo business as a byproduct of their passenger business. The incurred costs of cargo operations for combination carriers are difficult to separate from the costs tied to their passenger operations because both are transported in the same aircraft. All-cargo carriers and integrators use all-cargo aircraft, where all operational costs can be attributed to the transport of the cargo. Leaving out combination carriers makes the subsequent value analysis much more transparent.

The value analysis is applied to demand scenarios where the transported goods have quick decay times. This means that the goods are high time-value goods that require short transport times, such as perishables and express freight. The fact that these goods require fast transportation makes them interesting for the air cargo market and for consideration in this research.

B. Operationalization of value and cargo UAS

This research choses a cost approach to express value, much analogous to a cost-benefit analysis. This means that customer satisfaction (the benefits) and costs related to a certain logistics operation are expressed in terms of monetary value. The sum of all costs and benefits determines the value of the product or operation. Hereby, benefits are regarded as negative costs (factors that drive down logistics costs). The value analysis then encompasses a cost comparison of transport options. As opposed to passengers, goods have no personal preferences or feelings, which makes the best transport choice the choice with the lowest logistics cost. The option with the lowest logistics cost is said to have the highest value for the customer. In the context of cargo UAS, this means that a cargo UAS adds value with respect to conventional cargo aircraft if it can reduce transport costs made by these conventional cargo aircraft. The amount of value added corresponds with the amount of saved costs.

A simple cost-based comparison has the problem of cost allocation. Costs are always measured with regard to a certain stakeholder. But it is hard to say how changes in the air cargo operations affect the individual actors, as this has to do with the division of cost and benefits over the different actors. This research therefore quantified and analyzed the value of a logistics operation through its total logistics cost, which is the sum of all cost incurred by cargo transport from origin to destination. The total logistics cost can be determined accurately, no matter which costs are undertaken by what actor.

For the value analysis, six conventional freighter aircraft were selected and compared with cargo UAS. As an operationalization of cargo UAS, the situation was considered that conventional cargo aircraft are operated without an onboard aircrew. Instead, a ground station operator will take a supervisory role and oversees the flight. In the context of this research the level of automation is chosen to be fully automatic, meaning that the operator is completely left out of the decision process. Research has shown that in the case of fully autonomous UAS operators can control up to 12 vehicles simultaneously while operator workload and performance stay within acceptable levels (Cummings & Guerlain, 2007). Although this operationalization foregoes several aspects that enable UAS to differentiate themselves from their manned counterparts, it makes possible the use of existing and substantiated data for value calculations. Also the situation was considered where the aircrew consists of only a single pilot that will take the controls in case of emergency. In addition to the removal of aircrew from conventional freighter, a cargo UAS concept was taken into consideration: the BoXair (BoXiaR Engineering Corporation, 2011).

C. Modeling approach

The research objective requires that the total logistics costs that arise from the transportation of cargo through the air be modeled. Specifically the model must enable the analysis of current and future demand scenarios and be able to compare manned with unmanned cargo logistic costs. Hereto the model has to provide solutions to a (one-to-one) logistics optimization problem. Namely, given a specific set of input variables that are dependent on demand scenario and aircraft type, the model has to find the logistics operation that minimizes total logistics cost and maximizes value. This corresponds with the efforts of the cargo airline and other actors in the air transport chain to optimize their logistics operations. For example, airlines use flight-planning models to determine the most cost-effective aircraft routing in flight networks (Delling, Pajor, Wagner, & Zaroliagis, 2009) and fleet planning models to select the most cost-effective aircraft to fly those routes (Wang & Li, 2013). Moreover, airlines make choices on freight consolidation and routing that makes their shipping strategy as cost-effective as possible (Campbell, 1990).
The economic ordering quantity (EOQ) model is used to specify the logistics operation, which minimizes total logistics cost and maximizes value, in terms of shipment volume and flight frequency. The EOQ model is a classic production scheduling and inventory management model. The EOQ model assumes a fixed cost for each order placed (the ordering costs) and a cost for each unit held in storage, referred to as holding costs. EOQ is defined as order quantity that minimizes total inventory holding costs and ordering costs. Although the EOQ model sees common application in inventory management, it can also be applied to minimize total logistics cost for shipping volume and flight frequency. In this case, order quantity is analogous to shipment volume, the cargo quantity that is transported on a single aircraft. The ordering costs should in this respect be seen as all costs that are involved with the operation of the aircraft. In the remainder of this research, these costs are referred to as transportation costs. The holding costs are analogous to the cargo related costs that are borne from storage and handling.

The minimum total logistics cost corresponds to the sum of transportation and cargo related costs at the optimum shipment volume. Once a specific logistics operation, which is constraint to a specific set of inputs (market demand, aircraft type), is optimized for total logistics cost, it can be compared with other operations that are subject to different constraints. The inputs of the logistics operation with the lowest (minimized) total logistics cost are said to add the most value.

III. Market Analysis

The value of different transport options can only be examined in relation to market specific cargo demand. Because commercial cargo UAS will operate in future markets, as they are not yet operational, it is necessary to look at their value adding capabilities in a future market. For this purpose, a market trend analysis was performed to yield predictions in air cargo demand. This trend analysis considers both developments in current demand as well as predictions in market demand based on characteristics of future logistic developments.

Before market trends were analyzed, three demand components were selected to effectively map air cargo demand: distance over which the goods are transported, the amount of goods transported (freight flow) and the type of goods transported (commodity type).

The distance component of air cargo demand describes the various routes in terms of distance between different origins and destinations. As an aggregation level the logistical centers of global economic regions are chosen as representatives of the collection of possible origins and destinations within these regions. Airfreight flow is the component that expresses the amount of cargo that is transported between origin and destination within a certain time frame. With global economic regions chosen as the geographic aggregation level, the origins and destination coincide with the logistical centers of these regions. The amount of cargo transported between or within these regions is expressed in tonnage per year. Furthermore, time aggregation is performed on a yearly basis to exclude seasonal influences, leading to yearly average freight flows between particular regions. The freight flows have to be corrected to exclude the belly cargo share, as belly cargo is excluded from the scope of this research. The physical condition of the transported goods, or commodity type, drives the demand for certain transport modes and services. Commodity type was therefore taken into account as one of the components that are necessary to effectively map airfreight demand.

To establish current demand for airfreight, current yearly freight flows were extracted from Boeing, Airbus and the Seabury database (Airbus, 2008; Boeing, 2008; Seabury Group, 2010). Due to data availability, 2008 freight flows between the 12 most important global economic regions are taken as the current freight flows. This includes some intra regional freight flows for the largest internal markets. The advantage of taking 2008 as a base year for current cargo flows is that large variability in demand due to the following years of economic crisis will not cloud predictions.

By plotting yearly average freight flows between global economic regions against the flight leg distances between these regions’ logistical centers, one is able to identify the current market opportunities in terms of flight distance. Figure 1 shows that the routes that are currently most frequently serviced have either a distance that is less than 2000 miles (for internal markets) or a distance that lies between 4000 and 6000 miles (freight flows between North America, Europe and Asia).

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Asia including the PRC). Over the course of the global economic crisis of the last few years the perishable market remains a constant strength and even continued to grow due to rising consumer demand for cut flowers, exotic fresh seafood and counter-seasonal vegetables. The demand for traditional express traffic also continues to rise, despite of the economic crisis. Both developments indicate that indeed the physical product condition and marketing considerations make up the most important drivers of current air cargo service demand. On the other hand, a market decline is seen for products that are not subject to decay and for which improvements in supply chain management make marketing considerations of less importance for the selection of transport mode.

Future demand predictions made based on Airbus’ Global Market Forecast (Airbus 2008) show that in 2030, the three most important market opportunities for cargo UAS are on the 0-1000, 5000-6000 and 7000-8000 miles ranges. Most of the freight flow growth in these sectors is caused by the predicted economic developments in Asia, and specifically the PRC, which has an anticipated growth rate of 9.2% per year. To understand what the increased demand looks like in terms of commodity type and what services are needed this demand, a look was given at the main characteristics of future logistics development. One of these characteristics is the continuing change towards production strategies that need international cooperation. In this light, logistics systems need to improve their efficiency and reliability of goods delivery. Airfreight thus has an opportunity to play a key role in this development. However, continuing improvements in supply chain management lead to a gradual shift of lower value, time-sensitive products to be transported by sea to cut on transport costs. Therefore, air transport should especially prove its value in offering specialized delivery services for delicate (perishable) products. Another characteristic of future logistics development is the continuing rise of e-commerce. The advance of e-commerce and web shops makes that delivery time becomes an important selling point that drives customer demand. Express services are perfectly adapted to the requirements that e-commerce imposes on airfreight and are expected to become a major presence in future market.

IV. Logistics Cost Model

A logistics cost model was developed that is able to compare the value of one-to-one air transport operations for various demand and operational characteristics, including the use of cargo UAS. Hereto, value is expressed in terms of logistics costs. It was proposed that a cargo UAS is able to add value with respect to conventional cargo aircraft if it can reduce the total logistics cost of conventional cargo aircraft transport operations. The model itself distinguishes two main cost components that together define a logistics cost function: transportation costs and cargo related costs. The cost components of the logistics function are dependent on the model inputs, which can be categorized in three categories: demand parameters, operational variables and aircraft characteristics. Once the model and its inputs are specified, in an effort to limit the operational variables, optimal flight frequencies are obtained through the minimization of logistics costs for shipment volume. The model and all its components are schematically depicted in Fig. 1. The model inputs and the components of the logistics cost function are now explained in more detail. The last part of this section pays attention to the EOQ model that minimizes total logistics cost and maximizes value.

Figure 2. A schematic rending of the logistics cost model and its breakdown into separate components.
A. Model inputs

A total logistics cost follows from the logistics cost function, which is dependent on several input parameters. One of these inputs is the demand for air cargo services. To perform a representative analysis on the value of cargo UAS, this demand corresponds to the demand for airfreight in future markets that follows from the demand predictions of the market trend analysis. To arrive at a quantitative representation of demand, airfreight demand is parameterized into five demand parameters: freight flow, distance between origin and destination airport, commodity density, commodity value density and commodity half-time. The total logistics cost total logistics cost is calculated per week for the air transport of a given freight flow $q_{AB}$ from origin A to destination B over distance $d_{AB}$. To specify the type of goods transported, the freight flow is said to consist of freight of a certain, unified commodity type with density $\rho$ value density $\rho_{value}$ and half-time $t_{0.5}$. Commodity density and value density were derived from earlier research performed by Carlier (2011) and Van de Reyd and Wouters (2005). The latter parameter refers to the time it takes for a shipment to fall to half its quality in the case of perishables. Half-time with respect to express shipments is defined as the increase in delivery time in which the shipping fee that the customer is willing to pay is reduced to half the original shipping fee. It is the commodity characteristic that drives the speed of devaluation of the cargo. This loss of physical value and loss of opportunity of the goods while being transported is referred to as inventory costs. Commodity half-times were derived from the Online Cargo Handbook (BTM Surveys, 2013) and Amazon shipping rates (Amazon, 2014).

Three operational parameters were specified as inputs of the logistics cost function: aircraft type, aircraft utilization and flight frequency. The operational variables are dependent on how the cargo airline runs its operations once the routes on which cargo is transported are determined. The cost of a logistics operation is highly dependent on the type of aircraft that is used to transport the cargo. With the right choice of aircraft type, meaning selecting the aircraft that best fits the operations it needs to perform, the airline is able to let the air cargo chain save considerably on transport and logistics costs. The choice of aircraft type and its effect on logistics cost is especially relevant looking at the research objective. The research objective requires the comparison of cargo UAS with conventional cargo aircraft to see which aircraft is able to keep total logistics costs the lowest on specific routes and for specific market segments. To do this, six conventional cargo aircraft were selected to serve as comparison material. Aircraft utilization is another important operational parameter that has to be taken into account as it drives the aircraft depreciation costs per block hour. It is defined as the average number of block hours an aircraft logs during each 24-hour period. Common utilization rates were derived from the industry (Cargolux, 2013; van der Pluijm & van den Berg, 2013). The last operational parameter considered was flight frequency. The airline is able to choose the flight frequency and consequently shipment volume on a certain route. Shipment volume is the volume of cargo transported by a single aircraft from origin to destination. The flight frequency for a given aircraft type is dependent on the shipment volume $Q$ and the weekly freight flow between origin A and destination B. This dependency is captured by the following equation:

$$f = \frac{q_{AB}}{Q}$$

The cargo aircraft that are compared in the subsequent value analysis have to be defined in terms of their operational characteristics. These aircraft characteristics form the last inputs of the logistics cost function. The aircraft characteristics that were considered cover aircraft specific payload, range, fuel consumption, average speed, maintainability, aircrew salary and new value. Aircraft specific payload and range for the different aircraft models was derived from payload-range diagrams provided by the respective OEM’s (Boeing, 2011; Brinkley Aviation, 2010). In the determination of range and payload, the density of the cargo was taken into account as the maximum shipment volume has both a weight as well as a volume constraint. Aircraft specific fuel consumption, average aircraft speed and block time $t_{block}$ were predicted by means of regression analyses performed on operational data from the U.S. Department of Transportation traffic database (Bureau of Transportation Statistics, 2013). The aircraft’s maintainability, defined as the ease with which the aircraft can be maintained to stay airworthy, was obtained by applying a costing method that was verified from operational data (Roskam, 1990). The aircrew salary is necessary to arrive at an expression for aircrew costs in the logistics cost function. A dynamic per hour aircrew pay rate was therefore derived (Transport Studies Group, 2008). This per hour rate consists of a base rate (Pilot Jobs Network, 2013) and a marginal rate due to overtime made by the flight crew in case of delays. Last, aircraft new values were obtained from various sources (Boeing, 2013; Park & Rothman, 2012; Aviation Today, 2006(1); Aviation Today, 2006(2); Coddington, 1993; Phelan, 2002) in order to calculate the costs related to aircraft depreciation. Namely, the costs of aircraft depreciation are proportional to the aircraft new value.
B. Definition of the logistics cost function

To arrive at an expression for total logistics costs, all cost components that contribute to the logistics costs made by the cargo transport chain have to be included in the logistics cost function. These cost components are driven by the demand, operational and aircraft characteristics that were discussed in the previous section. As was mentioned earlier on, two main cost components are distinguished: transport costs and cargo related costs.

1. Transportation costs

Transportation costs include all costs that are involved with the operation of the aircraft. These costs are usually borne by the airline and consist of airport and airspace user charges, aircrew costs, fuel costs, aircraft depreciation costs and maintenance costs. By adding the individual cost components, the following expression for transportation costs is found:

$$C_{transport} = C_{airport usage} + C_{aircrew} + C_{fuel} + C_{Aircraft depreciation} + C_{maintenance}$$

Each of the cost components that make up the transportation costs can be defined separately. Airport user charges are dependent on a large number of factors. Think of landing and takeoff charges; ground handling charges (excluding cargo handling); security charges and parking charges. Dependent on the characteristics of the aircraft, these charges can vary widely. However, the most important factor in the amount the airport will charge the operator for usage is the maximum take off weight (MTOW). For the purpose of this study, a simplified airport user charge structure is adapted, that is solely dependent and directly proportional to MTOW:

$$C_{airport usage} = R_{airport} \cdot M_{MTOW} \cdot f$$

Although simplified, the cost structure in eq. 3 that is only based on MTOW is a fairly reliable reproduction of airport user charges. Major international airports like Schiphol maintain landing and takeoff charges that are directly proportional to MTOW. Also handling charges and parking charges are proportional to weight (Schiphol Amsterdam Airport, 2013).

Aircrew costs are an important input of the logistics cost function, given the fact that the function will be used to compare manned with unmanned aircraft economic performance. It is therefore critical to get a good estimate of aircrew costs for each given route. Earlier on it was mentioned that, despite its dependency on many factors, aircrew salary could be accurately converted to per-hour rates that differ for different aircraft types and with route distance. With these per-hour rates, crew costs are defined as the product of aircrew hourly salary and the total operational hours or block time. This leads to the following expression for weekly aircrew costs:

$$C_{aircrew} = A \cdot t_{block} \cdot f$$

Fuel costs account for up to 50 percent of the total variable transportation costs born by the airline (van der Pluijm & van den Berg, 2013) and make up a large part of total logistics costs. The fuel costs of one origin-to-destination flight can be calculated by multiplying aircraft fuel consumption by the fuel price. The total weekly fuel costs for that same flight leg are obtained by multiplying the fuel costs for one flight by the number of flights per week. This leads to the following expression for fuel costs:

$$C_{fuel} = P_{fuel} \cdot FC \cdot f$$

Aircraft are depreciating assets. The costs associated with this depreciation must be taken into account, as they are part of the transportation costs. The two major reasons for aircraft depreciation are a physical deterioration of individual aircraft over time and a growing obsolescence due to the introduction of new technologies and improvements in operating costs. As long as an aircraft is maintained properly, its structural life is indefinite. However, the value of an aircraft is tied to the net present value of all the future cash flows that can be generated from the operation of the aircraft. Over its lifetime an aircraft progressively requires more maintenance with associated increases in cost of labor, parts and down time. This increases absolute operating costs. Due to the introduction of new aircraft types that are more economic in their operations, relative operating costs of older aircraft types increase as well. When an aircraft can no longer generate a positive discounted cash flow, its economic life ends and the only thing that is left is its residual (or scrap) value (Hallerstrom, 2010). To arrive at an expression for depreciation costs, the aircraft new value is multiplied by the daily depreciation rate \(W\) obtained from a regression analysis on a scatterplot of aircraft current market value (CMV) against aircraft age (Kelly, 2008). As aircraft utilization \(U\) determines the number of operational hours over which the costs related to aircraft depreciation are spread out, this product is multiplied by the block time of a flight times the flight frequency, divided by the aircraft utilization. This leads to the following expression for weekly aircraft depreciation costs accounted to the total block time necessary to transport the weekly freight flow:
The last cost component included in the transportation costs is the cost for maintenance. In general it can be stated that the more flight hours and cycles and aircraft makes, the earlier it is in need of service. The ease with which the aircraft can be maintained to stay airworthy is defined by a set of maintainability metrics that express the "per block hour" maintainability of different aircraft types. The differences in maintainability between aircraft types cover the influence of aircraft type on per-hour maintenance costs. The maintainability metrics also cover aircraft age and engine maturity as factors that influence aircraft maintainability. To move from per-hour maintainability to a total weekly maintenance cost for all flight movements on route AB, the total block hours flown on this route have to be included in the expression for maintenance cost. Hereto the cost of maintenance is broken down in labor and material costs for engine and airframe (including systems):

\[ C_{\text{maintenance}} = C_{\text{lab,airframe}} + C_{\text{lab,engine}} + C_{\text{mat,airframe}} + C_{\text{mat,engine}} \] (7)

Each of the cost components in eq. 7 is dependent on one of the maintainability metrics of maintenance man-hours per block hour (\(MHR_{\text{airframe}}\) or \(MHR_{\text{engine}}\)) or maintenance materials cost per block hour (\(MAT_{\text{airframe}}\) or \(MAT_{\text{engine}}\)). The labor costs for engine and airframe maintenance are found using the following expressions:

\[ C_{\text{lab,airframe}} = MHR_{\text{airframe}} \cdot R_{\text{labor}} \cdot t_{\text{block}} \cdot f \] (8)

\[ C_{\text{lab,engine}} = 1.3 \cdot MHR_{\text{engine}} \cdot R_{\text{labor}} \cdot t_{\text{block}} \cdot f \] (9)

The labor rate \(R_{\text{labor}}\) is chosen similar to the on used by Roskam (1990), adjusted for inflation. To include the labor due to cycle-dependent wear of engine components, a factor 1.3 is added in eq. 9 that accounts for these labor costs. Next, the costs of maintenance materials are calculated from the maintenance materials cost per block hour maintainability metrics. These costs cover the cover the maintenance materials usage for airframe and systems and for the engines. The respective costs are expressed as follows:

\[ C_{\text{mat,airframe}} = MAT_{\text{airframe}} \cdot t_{\text{block}} \cdot f \] (10)

\[ C_{\text{mat,engine}} = 1.3 \cdot MAT_{\text{engine}} \cdot t_{\text{block}} \cdot f \] (11)

Again, a factor 1.3 is included in eq. 11 that accounts for labor due to cycle-dependent wear of engine components.

2. Cargo related costs

Cargo related costs are all costs that come with the storage and handling of the cargo, including the cargo loss of value during transport. These costs are generally heard by the shipper, the forwarder and the ground-handling agency. The cargo related costs that are taken into account by the total logistics cost model are: Warehousing costs, inventory costs and cargo handling costs. The summation of these cost components provides the following expression for cargo related costs:

\[ C_{\text{cargo}} = C_{\text{warehouse}} + C_{\text{inventory}} + C_{\text{handling}} \] (12)

Goods that are waiting at the airport for air transport need to be stored. This brings about storage costs that cover the rent for the warehouse space, the machinery needed to store the items in place plus any maintenance costs directly related to the provision of storage space. These maintenance costs cover things like security and utility costs. Warehouse rent is dependent on the amount of cargo that needs to be stored on the warehouse floor and the time it needs to be stored away. The volume of the cargo hereby determines the space that needs to be reserved in the warehouse, which makes that warehousing costs are directly proportional with cargo volume. Cargo volume is determined from the cargo freight flow between origin and destination and the density of the transported commodity type. This results in the following expression for warehousing (storage) costs, with \(S\) the warehouse rent in $ per m\(^3\) of cargo per hour taken similar to the on used in the research of Hsu and Wang (2013):

\[ C_{\text{warehouse}} = S \cdot \frac{QA}{\rho} \cdot t_{\text{wait}} \] (13)
The flight frequency determines the average waiting time for the cargo at the origin. Namely, delivery time decreases when flight frequency increases, as goods spend less time waiting at the origin airport. Assuming a uniform distribution with regards to cargo arrival times at the origin, one arrives at the following expression of the waiting time:

\[ t_{\text{wait}} = \frac{168}{2 \cdot f} \]  

(14)

Inventory costs represent the loss of opportunity and the loss of physical value of the goods while being transported. During transport, goods cannot be used and may physically decay, thereby loosing value. As was mentioned earlier, this process is referred to as devaluation. In the calculation of inventory costs, a distinction is made between the devaluation of perishable commodities and the devaluation of express shipments. In the devaluation of perishables, the loss in value depends on the quality decay of the commodity over time. The exponential nature of the decay process and the dependency of the product’s value on the state of decay make that the devaluation of perishables is likely to go faster at the beginning than at the end of the product’s life. As goods become less valuable, the speed of devaluation will then decrease. The simplest way to model a devaluation function that meets this characteristic is with an exponential function. The devaluation over the time the cargo is in transport is represented by the value at the start of the devaluation period (when it arrives at the origin) \( V_{\text{cargo,0}} \) minus the value of the cargo at the end of the devaluation period (when it arrives at the destination). This provides us the following expression for inventory costs:

\[ C_{\text{inventory}} = V_{\text{cargo,0}} \left( 1 - e^{-k(t_{\text{block}} + t_{\text{wait}})} \right) \]  

(15)

The constant \( k \) is dependent on the on the type of commodity that is shipped. It was mentioned earlier that different commodities have different quality decay rates, with half time as the parameter that determines the speed of decay. Taken that decay in quality corresponds to a proportionate decay in product value, the half times for product decay and product value are similar. The value of the constant \( k \) can then be determined from the commodity half times. The following equation applies:

\[ k = \frac{\ln(2)}{t_{0.5}} \]  

(16)

With express shipments, the delivery time does not influence the quality of the product (although it might influence the desirability of the product). It is therefore not correct to assume that the goods devaluate over time at a rate that corresponds to the innate worth of the goods, as this is likely to overestimate the inventory cost. What devaluates though is the premium of express shipment \( V_{\text{shipping premium,0}} \) that can be charged to the customer. It is shown from Amazon shipping rates (Amazon, 2014) that the decrease in shipping rates with longer delivery times approximated follows a decreasing exponential function. The same equation as eq. 15 can then be used to calculate the inventory costs that result from the devaluation of the shipment premium:

\[ C_{\text{inventory}} = V_{\text{shipping premium,0}} \left( 1 - e^{-k(t_{\text{block}} + t_{\text{wait}})} \right) \]  

(17)

Cargo handling is considered to be all actions performed on the cargo outside the aircraft. Cargo handling costs consist of costs borne from unit loading device (ULD) consolidation, which includes packaging, and ULD loading and unloading, which include moving the ULD to the aircraft. Of course, these operations are reversed at the destination. Generally speaking, handling costs are directly proportional to the cargo volume. Total weekly handling costs of the cargo volume on route AB can therefore be expressed by the following equation:

\[ C_{\text{handling}} = \frac{q_{AB}}{\rho} \left( H_{\text{load/unload}} + H_{\text{consolidation}} \right) \]  

(18)

The charge for loading and unloading of cargo \( H_{\text{load/unload}} \) and the charge for cargo consolidation \( H_{\text{consolidation}} \) are taken similar to the one used in the research of Hsu and Wang (2013) at $50 respectively $10 per m³.

3. The logistics cost function

By adding up all the transportation and cargo related cost components an expression is obtained for the total logistics cost. This expression can be seen as a logistics cost function whose value depends on the value of all demand, operational and aircraft related inputs.
The expression for total logistics cost in Equation 52 can be used to calculate the total logistics cost involved with meeting the transport demand on a certain freight route. This cost is shared amongst all actors of the transport supply and demand chain. All players in the transport chain will try to maximize the value of their operations by choosing optimal values of the operational parameters that will minimize total logistics costs and therefore maximize profits for the chain. These profits can then be divided amongst the actors. When looking at the cargo airline, it can organize its operations in such a way that their service adds the most value. It can do this by altering the operational variables. The other variables lay with the customer (demand parameters) or the organization of the transport chain. One of the operational variables that airline can influence is the main subject of this research: the selection of aircraft type, and specifically the selection of unmanned cargo aircraft over their manned counterparts. The aircraft should be selected that is able to maximize transport value on a specific route.

\begin{equation}
C_{\text{logistics}} = R_{\text{airport}} \cdot M_{\text{MTOW}} \cdot f + A \cdot t_{\text{block}} \cdot f + \\
P_{\text{fuel}} \cdot FC \cdot f + W \cdot \frac{t_{\text{block}}}{U} \cdot P_{A/c \text{ new}} + \\
(M_{HR_{\text{airframe}}} \cdot R_{\text{labor}} + 1.3 \cdot M_{HR_{\text{engine}}} \cdot R_{\text{labor}} + \\
M_{AT_{\text{airframe}}} + 1.3 \cdot M_{AT_{\text{engine}}}) \cdot t_{\text{block}} \cdot f + \\
+ S \cdot \frac{q_{AB}}{\rho} \cdot t_{\text{wait}} + \frac{q_{AB}}{\rho} (H_{\text{load/unload}} + H_{\text{consolidation}}) \\
+ V_{\text{cargo,0}} (1 - e^{-k(t_{\text{block}} + t_{\text{wait}})}) \tag{19}
\end{equation}

The expression for total logistics cost in Equation 52 can be used to calculate the total logistics cost involved with meeting the transport demand on a certain freight route. This cost is shared amongst all actors of the transport supply and demand chain. All players in the transport chain will try to maximize the value of their operations by choosing optimal values of the operational parameters that will minimize total logistics costs and therefore maximize profits for the chain. These profits can then be divided amongst the actors. When looking at the cargo airline, it can organize its operations in such a way that their service adds the most value. It can do this by altering the operational variables. The other variables lay with the customer (demand parameters) or the organization of the transport chain. One of the operational variables that airline can influence is the main subject of this research: the selection of aircraft type, and specifically the selection of unmanned cargo aircraft over their manned counterparts. The aircraft should be selected that is able to maximize transport value on a specific route.

C. Minimization of total logistics cost

It was mentioned in the methodology that the economic ordering quantity (EOQ) model is used to specify the logistics operation, which minimizes total logistics cost and maximizes value, in terms of shipment volume and flight frequency. By defining total logistics cost as a function of shipment volume, an optimal shipment volume or economic ordering quantity (EOQ) is found that minimizes total logistics cost. This way shipping volume is eliminated as an independent variable of the model, making total logistics cost only a function of the demand parameters and aircraft type. Comparison of aircraft types for various demand scenarios then becomes possible.

If a linear expression is assumed for holding and inventory cost, an expression for optimal shipment volume as a function of inventory and transportation costs is easily found. However, given the exponential decay of perishables and the potential importance of this process for the outcomes of this research, such an assumption would not fully reflect the characteristic of high time value cargo in terms of optimal shipment volume and flight frequency. Therefore the exponential devaluation of the cargo over time was taken into account in optimization for shipment volume. Exponential instead of linear inventory costs does complicate the process of optimizing ordering quantity for minimal total logistics cost. In the appendix, an analytical expression is derived for optimized shipment volume used to find the optimal shipment volume from the logistics cost function.

V. Value Analysis

The value of a logistic operation is quantified and analyzed through the total logistics cost of that operation. With the total logistics cost model outlined in the previous chapter the value of air cargo transport services can be assessed in a quantitative manner and compared for different aircraft types and market segments. This enables us to answer the main research questions on how much additional value cargo UAS add in the commercial transport of air cargo compared to conventional cargo aircraft for specific future demand scenarios and which market segments and routes are especially promising for unmanned cargo operations. First, a value comparison is made between manned and unmanned cargo aircraft. Through comparison, a statement can then be made about the selection of the optimal aircraft given a certain market demand. In addition, this section looks at general market opportunities for cargo UAS and at the design specifications cargo UAS should have to best anticipate on these opportunities.
A. Future demand scenarios

Based on the demand predictions following from the market trend analysis, multiple future demand scenarios were selected for analysis to compare the performance of cargo UAS with conventional freighters. The scenario where the aircrew is limited is only to a single pilot is taken into account as well. Table 1 shows the outcomes of the logistics cost model for different demand scenarios.

On intra-regional (internal EU, PRC and North American markets), short distance routes, cargo UAS perform well in terms of added value if the transported cargo has a high time-value and the freight flow is relatively small in size, as is the case with point-to-point transport. For example, the transport of express goods on an average intra EU route with a transport demand of 100 tons per week will yield an almost 5% decrease in TLC of unmanned over manned aircraft operations. This is equal to a $25000 value increase. The absolute value increase is larger for large freight flows. However, the value of unmanned aircraft as a percent of the TLC of the manned cargo aircraft case is largest for small freight flows.

The added value of cargo UAS over conventional cargo aircraft is around 2% of the total cost of logistics operations on EU-Asia and EU-PRC routes with a freight flow demand varying from 500 tons (into PRC/Asia) to 900 tons (into EU) of high time-value perishable or express goods per week. Dependent on the exact commodity type transported, the absolute added value ranges from $95000 up to $136000. In terms of the absolute added value, cargo UAS have more potential in the transport of cut flowers such as tulips than in the transport of express goods. The latter commodity is less time-sensitive and therefore requires fewer flights between origin and destination. The potential savings on aircrew costs are therefore lower.

On the very long distance route between North America and the PRC, the aircrew costs increase as a relief aircrew is necessary. The potential for cargo UAS to save on logistics cost and add value thus increases. This increase is again highest for commodities with a large rate of devaluation. For example, a cargo UAS is able to add $155000 of value if it is used for the transport of 500 tons of express goods per week on a 7250 miles long PRC-North America route. This is equal to almost 3% of the total cost of the logistics operations. The absolute added value of cargo UAS operations becomes even higher if the transport demand increases. This effect can however be attributed to economies of scale. Namely, the added value of cargo UAS over conventional freighters as a percentage of TLC decreases with increased freight flow sizes.

B. Optimal aircraft selection

For each specific cargo route, the airline will select the aircraft that results in the lowest possible total logistics cost and thus delivers maximum value. The optimal choice of aircraft depends on the demand and operational parameters and on the characteristics of the aircraft available for comparison and follows directly from the logistics cost model. If all conventional freighters are made unmanned (by removing the aircrew and replacing it with the presence of a ground operator) and compared in terms of value added, the optimal aircraft selection will deviate from the optimal aircraft selection in case conventional freighter are operated. More specific, the optimal cargo UAS will be smaller than the optimal conventional freighter would be under similar demand scenarios. This is explained by the fact that the reduced transportation costs (due to a reduction in aircrew costs) of cargo UAS makes it more attractive to increase the flight frequency between origin and destination airport. This flight frequency increase reduces inventory costs caused by goods waiting for transport at the airport of origin. Reducing waiting time at the expense of higher transport costs is especially interesting in the case commodities are transported that are highly time sensitive and thus devaluate quickly.

When the optimal flight frequency of manned cargo aircraft is compared to their unmanned counterparts for a large range of freight flows and distances, this increase in flight frequency is indeed observed. Also this change is larger for the transport of high time-value cargo than for the transport of low time-value cargo. The average percentage change in optimal flight frequency for the transport of express goods was found to be 2.4% while this increase was only 0.6% for the transport of clothing. The percentage change was defined against the optimal flight frequency for conventional freighters. The flight frequency increase simultaneously reduces the necessary payload capacity of the aircraft as shipment volume decreases (with increased flight frequency). Therefore, the unmanned equivalent of the conventional cargo aircraft will be able to deliver the best value on longer distance routes with larger freight flows and in particular freight flows with high time-value commodities compared to conventional freighters. Apparently, in some cases the choice of aircraft changes when the choice concerns cargo UAS instead of conventional, manned freighters. Moreover, if the airline starts operating cargo UAS, it should take into account that the operation of these aircraft requires (slight) changes in operation in terms of flight frequency and shipping volume to fully utilize the value adding capabilities of cargo UAS.

C. The Boxair cargo UAS concept

The Boxair is a cargo UAS concept that has a fuselage that can house standard 40 feet aluminium containers and has an interchangeable equipment bay. The performance of the Boxair UAS concept was analyzed separately. On short trade routes, the Boxair has an edge over both manned as well as the unmanned versions of the conventional freighters in terms of value. This fact is illustrated by fig. 3, which shows the added value of
### Scenario

#### Demand characteristics

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Commodity type</th>
<th>Distance (mi)</th>
<th>Freight flow (ton)</th>
<th>Conventional</th>
<th>Single pilot</th>
<th>Unmanned</th>
<th>Conventional</th>
<th>Single pilot</th>
<th>Unmanned</th>
</tr>
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<tr>
<td>Intra regional express</td>
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<td>750</td>
<td>100</td>
<td>458000</td>
<td>11000 (2.3%)</td>
<td>22000 (4.8%)</td>
<td>F27-500</td>
<td>F27-500</td>
<td>F27-500</td>
</tr>
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<td>2000</td>
<td>4347000</td>
<td>37000 (0.9%)</td>
<td>76000 (1.7%)</td>
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<td>727-200F</td>
<td>727-200F</td>
</tr>
<tr>
<td></td>
<td>Express</td>
<td>1000</td>
<td>100</td>
<td>530000</td>
<td>12000 (2.3%)</td>
<td>25000 (4.7%)</td>
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</tr>
<tr>
<td></td>
<td>Express</td>
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<td>2000</td>
<td>4903000</td>
<td>46000 (0.9%)</td>
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<tr>
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<td>604000</td>
<td>16000 (2.6%)</td>
<td>32000 (5.3%)</td>
<td>F27-500</td>
<td>F27-500</td>
<td>F27-500</td>
</tr>
</tbody>
</table>

| EU-Asia and EU-PRC | Cut flowers | 5500          | 500               | 5366000      | 64000 (1.2%) | 102000 (1.9%) | MD-11F       | MD-11F       | MD-11F    |
|                   | Cut flowers | 6000          | 500               | 5635000      | 65000 (1.2%) | 104000 (1.9%) | MD-11F       | MD-11F       | MD-11F    |
|                   | Express      | 5500          | 500               | 4655000      | 59000 (1.3%) | 95000 (2.0%)  | MD-11F       | MD-11F       | MD-11F    |
|                   | Express      | 5500          | 900               | 7187000      | 80000 (1.1%) | 120000 (2.0%) | MD-11F       | MD-11F       | MD-11F    |
|                   | Express      | 6000          | 500               | 4902000      | 62000 (1.3%) | 99000 (2.0%)  | MD-11F       | MD-11F       | MD-11F    |
|                   | Express      | 6000          | 900               | 7589000      | 86000 (1.1%) | 136000 (1.8%) | MD-11F       | MD-11F       | MD-11F    |

| South America-EU | Perishables   | 5750          | 500               | 2339000      | 43000 (1.8%) | 68000 (2.9%)  | MD-11F       | MD-11F       | MD-11F    |
|                  | Perishables   | 5750          | 1000              | 4002000      | 60000 (1.5%) | 94000 (2.4%)  | 777-200F     | 777-200F     | 777-200F  |
|                  | Perishables   | 5750          | 2000              | 6992000      | 119000 (1.7%) | 188000 (2.7%) | 777-200F     | 777-200F     | 777-200F  |
|                  | Clothing      | 5750          | 500               | 1569000      | 30000 (1.9%) | 47000 (3.0%)  | 777-200F     | 777-200F     | 777-200F  |
|                  | Clothing      | 5750          | 1000              | 2720000      | 59000 (2.9%) | 94000 (3.5%)  | 777-200F     | 777-200F     | 777-200F  |
|                  | Clothing      | 5750          | 2000              | 5021000      | 119000 (2.4%) | 188000 (3.7%) | 777-200F     | 777-200F     | 777-200F  |

| PRC-North America | Clothing     | 7250          | 500               | 5561000      | 110000 (2.0%) | 155000 (2.8%) | MD-11F       | MD-11F       | MD-11F    |
|                  | Clothing     | 7250          | 1000              | 9749000      | 137000 (1.4%) | 207000 (2.1%) | 777-200F     | 777-200F     | 777-200F  |
|                  | Clothing     | 7250          | 2000              | 17040000     | 2540000 (1.4%) | 362000 (2.1%) | 777-200F     | 777-200F     | 777-200F  |
|                  | Clothing     | 7250          | 500               | 1936000      | 64000 (3.3%)  | 90000 (4.7%)  | 777-200F     | 777-200F     | 777-200F  |
|                  | Clothing     | 7250          | 1000              | 3530000      | 129000 (3.7%) | 181000 (5.1%) | 777-200F     | 777-200F     | 777-200F  |
|                  | Clothing     | 7250          | 2000              | 6716000      | 2590000 (3.9%) | 362000 (5.4%) | 777-200F     | 777-200F     | 777-200F  |

**Table 1. Outcomes of the logistics cost model for different demand scenarios.**

The above commodity types are operationalized by their demand parameters as follows:

- Express goods: $t_{0.5} = 106$ hours, $\rho = 0.16$ ton/m$^3$, $\rho_{value} = 60000$ $/ton$;
- Cut flowers (tulips): $t_{0.5} = 39$ hours, $\rho = 0.20$ ton/m$^3$, $\rho_{value} = 30000$ $/ton$;
- Perishables (bananas): $t_{0.5} = 167$ hours, $\rho = 0.20$ ton/m$^3$, $\rho_{value} = 30000$ $/ton$;
- Clothing: $t_{0.5} = 750$ hours, $\rho = 0.16$ ton/m$^3$, $\rho_{value} = 50000$ $/ton$. 

12
the Boxair concept over both the manned and unmanned versions of the conventional freighters for the transport of two different commodity types. Its operational efficiency due to increased fuel economy, simplicity of design, decreased loading and unloading times and higher utilization rates make that the Boxair adds considerable value in the transport of bananas and apparel. However, the Boxair is only able to add value in the transport of less time-sensitive commodities. In case the transported commodity is highly time-sensitive, the Boxair is unable to deliver added value over conventional freighter alternative due to its low cruise speed. The Boxair has a specified average cruise speed of 210 miles/hour, which is significantly lower than that of conventional cargo aircraft.

Low cruise speeds are advantageous for fuel efficiency and thus reduces transportation costs. However, with lower cruise speeds, the transport time increases. In the case of high time-value commodities, this means that cargo related costs increase considerably.

D. Market opportunities for cargo UAS

The ability of cargo UAS to unlock new markets based on the value they can add over conventional cargo aircraft in proportion to the value of the transported product was taken into consideration. In general, new market opportunities for airfreight due to cargo UAS operations will present themselves if cargo UAS enable the cargo to be delivered in less time, or if cargo UAS enable the cargo to be transported at lower cost. It was shown that the most promising market opportunities emerge when there is a relatively small demand for high time-value cargo transport on long distance routes. Especially in the situation of long distance routes and small freight flows, the costs for transportation are high in relation to the value of the product (see fig. 4). It is this market segment where cargo UAS can deliver maximum additional value over conventional cargo aircraft.

It is also possible to look at the above research question in the opposite way: what are desirable UAS characteristics given a specific market opportunity? If cargo UAS characteristics are tailored to market opportunities, the ability to act on these market opportunities improves. The Boxair concept for example was designed for short distance operations, increased fuel efficiency and high utilization. This makes the Boxair suited for air transport of low time-value cargo on regional routes. However, if it faces the predicted increase in transport demand for high time-value cargo, the design focus should be on increasing its cruise speed. Namely, cruise speed has a much higher impact on added value than

![Figure 3. The added value of the Boxair concept over both the manned and unmanned versions of the conventional freighters for the transport of two different commodity types over 500 miles.](image)

![Figure 4. Surface diagram showing the added value of cargo UAS as a percentage of cargo value for the transport of perishables.](image)
fuel economy in the transport of high time-value cargo. For the unmanned versions of the conventional freighters, it was found that cruise speed and fuel economy are the aircraft characteristics that have the most influence on the aircraft’s value adding capabilities. Designing solely for increased fuel economy without regard of cruise speed has adverse effects on the usefulness of the aircraft for the transport of high time-value cargo. Maintainability should also be taken into account in the design of a cargo UAS.

VI. Conclusion

One of the things this research shows is that cargo UAS are capable of adding value over conventional cargo aircraft, especially in demand scenarios that include the transport of time sensitive cargo. This added value can reach up to 5% of the total logistics cost in predicted demand scenarios and could even be higher in other scenarios. If airlines start operating UAS, this additional value will in some way be distributes among the members of the transport chain. The final customer or consignee could benefit from lower transport costs if the airline lowers it rates to gain a competitive edge. The consignee could also benefit from more frequent flights and better, direct connections that will lead to decreased transport times. The consignee therefore incurs less inventory costs due to devaluation of cargo. Last, the airline could benefit from lower transportation costs if it doesn’t offset the lower costs by lowering its rates. If the airline flies on direct routes and more frequent between destinations, it can even ask premiums due to the better service offered.

A few percent of the total logistics cost does not look like a large benefit of unmanned operations. However, the airline industry is known to have low profit margins. Airlines commonly have a profit margin in the region of 1% (The Economist, 2014). In terms of Porter’s five forces analysis, this low profit margin is explained by large bargaining power of both customers and suppliers and a large competitive intensity among incumbents. The profit of cargo airlines is even lower, if they are already able to make a profit. The potential to have a 5% value increase could therefore lead to radical changes in the air cargo transport industry. For example, routes that could not be operated on before could now become economically viable to operate.

Another thing that follows from the research is that the operation of UAS that are specifically designed to be unmanned can add extra value over unmanned conventional aircraft. Namely, a cargo UAS can be kept simple, small and light, as it does not need all the equipment and facilities necessary to accommodate an aircrew. This research already showed that the Boxair cargo UAS concept is able to add this extra value for certain demand scenarios due to its specific design characteristics. However, the design of cargo UAS should be tailored to the demand they are likely to face in order to maximize their value adding capabilities. This means that cargo UAS design decisions need to be made from a perspective of future developments in air transport demand. The industry thus needs to look further than the traditional business models as most value can be created outside the current markets. This can include routes that have economic potential but do not have the proper transport infrastructure, or routes that are currently serviced by other modes of transport. Once the future demand is known, aircraft characteristics need to be identified that are considered value driving in meeting this demand. The UAS should then be designed based on these characteristics.

Although this research looked specifically at the value adding capabilities of cargo UAS in future markets, the total logistics cost model that was developed in research also enables the analysis of current transport operations. In the determination of an optimal aircraft selection based on demand characteristics, it was shown that the optimal aircraft selection that followed from the research did not correspond to the aircraft selection of KLM on a similar route with similar demand. This could mean that KLM makes a decision to operate a certain aircraft based on criteria other than the criterion of maximum value creation. A motive could be to reduce short-term costs by operating the aircraft that are already available to the airline, instead of operating the aircraft that performs best value-wise. This also means that taking a value perspective and considering the entire transport chain in the decision to select an aircraft to service a particular route, can improve current operations.

But it is not only KLM that operates older, non-optimal (in terms of value creation) aircraft. The DOT air traffic database that was used in the determination of some of the aircraft operational characteristics shows us that the operation of 30 to 40 year old aircraft like the DC-10 and the Boeing 727 is still common among cargo airlines. These aircraft are used for reasons of cost accounting, but it is unlikely that in this process, the costs and benefits of the entire chain are considered. So again, taking a total value perspective could lead to different decisions that improve current operations. However, it is not only the airline that can make this decision. The entire transport chain should collaborate to find a fair distribution of both costs as well as benefits among the individual actors. This means that operations need to be integrated for maximum efficiency. The fact that the integrated express market remains strong throughout the economic crisis while the airline cargo market does everything to stay alive might just be an indication of the validity of this statement.
Appendix

In this appendix an expression is derived for optimized shipment volume, indicated by $Q_{opt}$. With eq.1 and eq. 14, the total logistics cost of eq. 19 can be expressed in terms of shipment volume. This gives the following equation:

$$C_{logistics} = \frac{C_1}{Q} + C_2 \cdot Q + C_3 - C_4 \cdot e^{C_5 \cdot Q}$$ (20)

Where:

$$\begin{align*}
C_1 &= (R_{airport} \cdot M_{MTOW} + A \cdot t_{block} + R_{fuel} \cdot FC + W \cdot \frac{t_{block}}{u} \cdot P_{A/C_{new}} + (MHR_{airframe} \cdot R_{labor} + 1.3 \cdot MHR_{engine} \cdot R_{labor} + MAT_{airframe} + 1.3 \cdot MAT_{engine}) \cdot t_{block}) \cdot q_{AB} \\
C_2 &= \frac{S \cdot B4}{\rho} \\
C_3 &= \frac{q_{AB}}{\rho} (H_{load/unload} + H_{consolidation}) + V_{cargo,0} \\
C_4 &= V_{cargo,0} \cdot e^{-k \cdot t_{block}} \\
C_5 &= -k \cdot \frac{B4}{q_{AB}}
\end{align*}$$ (21)

To determine at what ordering quantity the total logistics cost is at its minimum, the total logistics cost function in eq. 20 needs to be partially differentiated with respect to the shipment volume and set to 0:

$$\frac{\partial}{\partial Q} C_{logistics} = -\frac{C_1}{Q^2} + C_2 - C_4 \cdot C_5 \cdot e^{C_5 \cdot Q} = 0$$ (26)

If eq. 26 is solved for $Q$, the optimal shipment volume, or economic ordering quantity, is found. However, this equation is not easily solvable for $Q$. Although a numerical approach could be chosen to solve for shipment volume, it is decided to find an algebraic expression for $Q$ that can be directly inserted into the logistics cost function. This way, there is no need for more complex computer programs that use (sometimes time consuming) numerical solving methods and the model is able to retain its relative simplicity.

The exponential part of eq. 26 can be approximated by the following Taylor series:

$$e^{C_5 \cdot Q} = \sum_{n=0}^{\infty} \frac{(C_5 \cdot Q)^n}{n!} = 1 + C_5 \cdot Q + \frac{(C_5 \cdot Q)^2}{2!} + \frac{(C_5 \cdot Q)^3}{3!} + \cdots$$ (27)

Inserting the first two terms of the Taylor series in eq. 26 gives the following third-degree polynomial:

$$-C_4 + (C_2 - C_4 \cdot C_5) \cdot Q^2 - C_4 \cdot C_5^2 \cdot Q^3 = 0$$ (28)

One of the roots of this cubic function is the economic order quantity $Q_{opt}$. The roots of the cubic function therefore need to be determined. To this end, eq. 28 is rewritten as:

$$a \cdot Q^3 + b \cdot Q^2 + c \cdot Q + d = 0$$ (29)

Where:

$$a = -C_4 \cdot C_5^2$$ (30)
\[ b = C_2 - C_4 \cdot C_5 \]  \hspace{1cm} (31)

\[ c = 0 \]  \hspace{1cm} (32)

\[ d = -C_1 \]  \hspace{1cm} (33)

Equation 29 can be reduced to a depressed cubic by performing a Tschirnhaus transformation, substituting \( Q \) by:

\[ x = \frac{b}{3a} \]  \hspace{1cm} (34)

The following equation then follows:

\[ x^3 + px + q = 0 \]  \hspace{1cm} (35)

Where:

\[ p = \frac{3ac-b^2}{3a^2} \]  \hspace{1cm} (36)

\[ q = \frac{2b^3 - 9abc + 27a^2d}{27a^3} \]  \hspace{1cm} (37)

By using Cardano’s method for solving the roots of a depressed cube, we arrive at the following set of solutions:

\[ x = \{ A + B, \omega A + \bar{\omega} B, \bar{\omega} A + \omega B \} \]  \hspace{1cm} (38)

Where:

\[ A = 3^{\frac{1}{3}} \left( -\frac{q}{2} + \sqrt{\left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3} \right) \]  \hspace{1cm} (39)

\[ B = 3^{\frac{1}{3}} \left( -\frac{q}{2} - \sqrt{\left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3} \right) \]  \hspace{1cm} (40)

\[ \omega = e^{2\pi i/3} \]  \hspace{1cm} (41)

If the expressions under the square root in eq. 39 and eq. 40 are positive, the first solution \( A + B \) is real. The other two solutions are therefore automatically complex. However if the expression under the square root is negative, we get a complex number under the cubic root. This is the case for the combinations of values of \( p \) and \( q \) that follow from the domain of the logistics cost function. As a result, \( A \) and \( B \) are each other’s complex conjugates of the form:

\[ a + ib = \sqrt{a^2 + b^2} \cdot e^{i\varphi} \]  \hspace{1cm} (42)

\[ a - ib = \sqrt{a^2 + b^2} \cdot e^{-i\varphi} \]  \hspace{1cm} (43)

Where:

\[ \varphi = \arctan \left( \frac{b}{a} \right) \]  \hspace{1cm} (44)

\[ e^{i\varphi} = \cos(\varphi) + isin(\varphi) \]  \hspace{1cm} (45)
Inserting eq. 42 and eq. 43 into eq. 39 and eq. 40, and using eq. 44, finds an expression for \(A\) and \(B\).

\[
A = \sqrt[3]{\left(-\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3} \cdot e^{\frac{i}{3} \arctan \left(\frac{2 \sqrt{\left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3}}{q}\right)}
\]

\[
B = \sqrt[6]{\left(-\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3} \cdot e^{-\frac{i}{3} \arctan \left(\frac{2 \sqrt{\left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3}}{q}\right)}
\]

Because \(A\) and \(B\) are complex conjugates of each other, all three solutions given by eq. 39 are real. The solutions are found by adding the real parts of the complex numbers, which is the same as multiplying the real part of one of the complex conjugates by two.

\[
x = A + B = 2 \cdot \text{Re}(A)
\]

\[
x = \omega A + \bar{\omega} B = 2 \cdot \text{Re}(\omega A)
\]

\[
x = \bar{\omega} A + \omega B = 2 \cdot \text{Re}(\bar{\omega} A)
\]

As the ordering quantity \(Q\) was transformed to \(x\), the solutions need to be transformed back to \(Q\). This can be done by substituting the following expression:

\[
x = Q + \frac{b}{3a}
\]
Note that only one of the solutions is the solution that corresponds with the economic ordering quantity. The other two roots are either negative, or are a result of the linear approximation of the exponential function. The root represented by eq. 50 is therefore discarded as a solution of the optimization problem, leaving eq. 49 as the only real solution. Therefore we find the following algebraic expression for $Q_{eq}$:

$$Q_{eq} = 2 \sqrt[3]{-\frac{q}{2} + \left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3} \cdot \cos\left(-\frac{2\pi}{3} + \frac{1}{3} \arctan\left(\frac{2 \cdot \left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3}{q}\right)\right)$$

When $p$, $q$, $a$ and $b$ in eq. 52 are substituted by their original expressions in terms of the cost components of the logistics cost function, an expression of optimal shipment volume is found that is dependent on aircraft type and transport demand. The optimal shipment volume corresponds to the shipment volume for which the sum of all transportation and cargo related costs are minimal. At this point, there is a minimum in total logistics costs.

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