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THE AIR CARGO CARRYING POTENTIAL OF THE AIRBUS A350-900XWB AND BOEING 787-9 AIRCRAFT ON THEIR ULTRA-LONG-HAUL FLIGHTS: A CASE STUDY FOR FLIGHTS FROM SAN FRANCISCO TO SINGAPORE

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The introduction of the Airbus A350-900 (A359) and the Boeing B787-9 (B789) have enabled airlines to operate ultra-long-range services. Using a mixed methods research design, this study has examined the air cargo-carrying potential of Singapore Airlines Airbus A350-900XWB (A359) and United Airlines Boeing B787-9 (789) aircraft on their ultra-long-haul San Francisco to Singapore and the Singapore to San Francisco air routes. The qualitative data was analysed using document analysis, and the air cargo payload was modelled by simulation. The air cargo-carrying potential of the two aircraft types was significantly influenced by enroute weather. In the event of eastbound winds, the Singapore Airlines Airbus A350-900XWB air cargo payload was 16.9 tonnes and the United Airlines Boeing 787-9 was 11.5 tonnes, when these flights had a full passenger payload. In the case of westbound winds with a full passenger payload, the Singapore Airlines Airbus A350-900XWB air cargo payload was 13.1 tonnes and the United Airlines Boeing 787-9 was 7.9 tonnes. When there were no winds on the air routes, the Singapore Airlines Airbus A350-900XWB offered 15.0 tonnes and the United Airline Boeing 787-9 offered 9.7 tonnes of air cargo payload, respectively.

Keywords: air cargo; air cargo capacity; airlines; ultra-long-range flights; payload-range envelopes; passenger transportation; simulation

1. Introduction

The transportation of goods/freight by the air cargo mode for commercial purposes plays a significant role in the global economy and in many firms' supply chain management and logistics strategies. Air cargo is defined as 'anything carried in an aircraft except for mail or luggage carried under a passenger ticket and baggage check but including baggage shipped under an airway bill or shipment record' (Hui *et al.*, 2004). In 2016, the world's airlines transported 52 million tons of cargo, representing over 35 per cent of world trade by value (International Air Transport Association, 2018). Air cargo not only has a socio-economic significance for globalization, but also plays a significant role in airlines' revenue streams (Budd and Ison, 2017), generating an estimated 9.5 percent of total global airline revenues in 2016 (International Air Transport Association, 2017). In the world air cargo industry, air cargo capacity is provided by full-service network (FSNC) or combination passenger airlines, that is, airlines that carry passengers on the main deck and air cargo in their passenger aircraft lower lobe belly-holds and by dedicated all-cargo carriers, such as Cargolux Airlines and Nippon Cargo Airlines (NCA), as well as the integrators, for example, FedEx and United Parcel Service (UPS) (Baxter and Bardell, 2017).

Baxter and Bardell (2017) have noted that the aircraft fleet composition and route networks are regarded as two of the most critical elements of an airline's business model. The world's major full-service network carriers (FSNCs) usually structure their route networks according to the hub-and-spoke principle (Goedeking 2010; Holloway, 2016; Schmidt and Gollnick, 2016). Under such a strategy, airlines link together smaller peripheral cities via their hub airports to optimise both passenger and air cargo connectivity. Many FSNCs also structure their route networks on short haul, medium-haul, and long-haul services (Baxter and Bardell, 2017). The Boeing B787-9 (ICAO aircraft code, B789) and the Airbus A350-900 (ICAO aircraft code, A359) passenger aircraft entered commercial service in 2011 and 2015, respectively (Aircraft Commerce, 2016). These next generation aircraft have provided airlines with the ability to operate ultra-long-haul flights (ULR). An ultra-long-haul flight is defined as ultra-long-range

(ULR) as any non-stop flight carrying an economically meaningful payload of passengers and air cargo over a distance in excess of 7,000 nautical miles (Baxter and Bardell, 2017).

The focus of this study is on assessing the ability of the Airbus A350-900XWB and Boeing 787-9 aircraft to carry a meaningful air cargo payload on the ultra-long-range (ULR) services provided by Singapore Airlines (IATA Code SQ) and United Airlines (IATA Code UA) on their air routes from Singapore (IATA Airport Code SIN) to San Francisco (IATA Airport Code SFO) and from San Francisco (SFO) to Singapore (SIN). The SIN to SFO non-stop air route is ranked as the world's fourth longest ultra-long-haul route (Australian Aviation, 2016). United Airlines commenced non-stop Boeing 787-9 services from SFO to SIN on June 1, 2016. This service is presently the longest scheduled Boeing 787-9 flight operated by any airline and at the time of the current study was the longest scheduled flight operated by any U.S. carrier, at 8,446 nautical miles (United Airlines, 2017a). Singapore Airlines commenced daily A350-900XWB services from Singapore (SIN) to San Francisco (SFO) on 23 October 2016 (Singapore Airlines, 2016). Thus, the selection of the Singapore (SIN) to San Francisco (SFO) ULR air route provides, for the first time, the opportunity to empirically examine the air cargo-carrying ability of the two latest next generation aircraft in one of the most important world air cargo markets. The study also examines the impact that prevailing winds will have on the commercial payload offered by the A350-900XWB and Boeing 787-9 aircraft when deployed on the ultra-long-range San Francisco (SFO) to Singapore (SIN) and Singapore (SIN) to San Francisco (SFO) sectors.

The remainder of the paper is organized as follows. The literature review presented in Section 2 commences with a summary on the full-service network carrier's recent adoption of ULR flights and their impact for the transportation of air cargo. This is followed with an overview of the airline route networks, the importance of belly-hold cargo for FSNCs, and a review of the civil aircraft payload/range envelope. The research method underpinning the study is described in Section 3. The empirical results of the case study are presented in Section 4. A summary and discussion of the key findings follow in Section 5.

2. Background

2.1. Airline ultra-long-haul network strategy – key concepts

In the global airline industry, airlines have strategically focused on optimizing the performance of their jet-powered aircraft and, as such, have implemented wherever technically and commercially feasible, non-stop services. As noted by Baxter and Bardell (2017), during the 1970's, ULR were understood to mean any non-stop flight distance which more than 5,000 nautical miles in length is. The ability to operate flights of such stage lengths was made possible following the commercial service entry of the first generation of wide-bodied "*jumbo*" jets such as the Boeing B747 and the McDonnell-Douglas DC-10-30 series aircraft (Baxter and Bardell, 2017).

However, as noted earlier, nowadays it is more appropriate to define ultra-long-range (ULR) as any non-stop flight carrying an economically meaningful payload of passengers and air cargo over a distance more than 7,000 nautical miles in length. The emerging trend for airlines to offer ULR services satisfies a niche market requirement for both air travellers and air cargo shippers. Such customers are increasingly placing a higher focus on the ability for an airline to provide the shortest possible journey time from their origin to their destination. In addition, by eliminating enroute intermediate stopovers, passenger facilitation is simplified by avoiding the requirement for transit documentation, and new opportunities are offered for time-sensitive, and often, highly perishable, air cargo transportation. These services therefore benefit the economies of the states of origin and destination (Baxter and Bardell, 2017).

Ultra-long range (ULR) services are now being offered by Emirates Airline, Qatar Airways, Qantas Airways, Singapore Airlines, and United Airlines. These airlines all follow the conventional "full service network carrier" (FSNC) business model. Hence, they are airlines that focus on providing a wide range of both pre-flight and onboard services, including different travel classes, and connecting flights via their hub(s) (Ehmer *et al.*, 2008). These airlines ULR services that are scheduled to depart from and arrive back at their major hub airport to optimize both passenger and air cargo connectivity. This ULR strategy also enables these airlines to optimize the available passenger and air cargo origin-and-destination (O&Ds) markets. However, more importantly, to operate such long-range services, these airlines require aircraft with the ability to carry a favourable economic payload of both passengers and cargo over the distance to ensure profitability (Baxter and Bardell, 2017). This is because when an aircraft's mission length increases, it may be required to operate with a reduced payload. That is, the airline will trade-off extra fuel for commercial payload to enable the aircraft to complete the flight on a non-stop basis (Aircraft Commerce, 2012; Cook and Billig, 2017) thereby incurring a lost revenue opportunity.

2.2. Full service network carriers ultra-long-haul network strategy

Every airline is endowed with a unique route structure, traffic catchment area, cost base, productivity levels and management skills that are the result of its path and pace of historical development, strategic intent, the characteristics of its home and regional markets, and the international regulatory system (Baxter, 2016). The way the airline links various nodes (the spatial dimension) and coordinates flight schedules (the temporal dimension) defines the airline's network (Burghouwt, 2016). An airline's route network is therefore a collection of origins-and-destinations (O&Ds), often called city pairs. If a single city-pair is regarded as one product of the airline, then, the larger the airline route network, the greater is its range of products. Route networks are therefore a factor in differentiating airlines (Kleymann and Seristö, 2016). Accordingly, the addition of extra routes, whether by inaugurating new city-pairs or by entering one of the world's major strategic alliances, is primarily how airlines satisfy passengers' preferences for an extended network (Oum and Yu, 2001).

Most large, scheduled full service network airlines, and some low-cost carriers (LCCs), typically operate a form of hub-and-spoke route network (Baxter and Bardell, 2017; Franke, 2018). With a hub-and-spoke route network, hub airports are linked by a high frequency of services using relatively large aircraft. Smaller, nearby airports are connected (the "spokes") to the large hub airports using smaller aircraft (Wensveen, 2015).

It is also important to note that as the numbers of passengers increase on a route, it becomes possible for airlines to deploy larger aircraft types and/or offer a more frequent service. Furthermore, in the airline industry, there are "thin" routes, that is, routes with a small number of passengers per day, and "dense" routes, where there are substantial numbers of passengers per day. Typically, dense air routes receive a point-to-point (P2P) service, whilst thin routes are combined using the hub-and-spoke route network system (Morrison, 2007).

2.3. The importance of belly-hold cargo for the full-service network carriers

In the global air cargo industry, slightly under half of world air cargo traffic is carried in the lower deck belly holds of passenger aircraft (Boeing Commercial Airplanes, 2016). This arrangement, in which passengers are carried on the aircraft's main deck, and air cargo is carried below in the lower deck "belly hold" compartments, is referred to as a combination aircraft (Cook and Billig, 2017; Morrell, 2016). Importantly, the design of passenger aircraft is dictated by passenger requirements, space for air cargo transportation is what is left over in the otherwise unusable space below the main passenger deck of the aircraft that is not required for the stowage of passengers' luggage and that exists simply due to the aerodynamic requirements for a tubular shape for the aircraft fuselage (Tretheway and Andriulaitis, 2016, p. 138).

The introduction of wide-bodied passenger aircraft, such as the Boeing B747 in the 1970s resulted in a substantial increase in space available to carry cargo in the lower deck or belly-hold compartments (Morrell, 2016). Combination airlines air cargo capacity may come in the form of narrow bodied, single-aisle aircraft, such as, the Airbus A320 or Boeing B737NG aircraft, or wide-bodied, twin aisle aircraft, such as the Boeing B787-9 aircraft. Other wide-bodied aircraft include the Airbus A350-900, Boeing B777-300ER and B747-8 aircraft as well as the Airbus A330, A350-900XWB and the A380 aircraft.

The combination airline air cargo product is offered to generate additional revenue on already-scheduled passenger services (McKnight, 2010; Morrell, 2016). Combination airlines principally offer point-to-point (airport-to-airport) services on a wholesale basis, relying on international freight forwarders for pick-up and delivery, sales to shippers and customer service. Because the aircraft belly hold space that represents much of their air cargo capacity is a co-product of passenger service, combination airlines air cargo services have a low marginal cost. Thus, these airlines usually offer lower prices than those of the integrated carriers (Tretheway and Andriulaitis, 2016). The carriage of air cargo consignments in the lower lobe belly holds of their passenger aircraft enables airlines to reduce their costs as they are not incurring the expense of operating dedicated freighter aircraft. This is because belly hold cargo unit costs are lower than those for a dedicated freighter aircraft (Doganis, 2010).

2.4. Civil jet aircraft performance: payload/range envelope

A key performance parameter of an aircraft within the operational environment of the airline industry is the aircraft's range (Russell, 2003). Specifically, the range relative to an aircraft payload lift capability is essential understand. The maximum distance that an aircraft can fly, given a certain amount of fuel in the tanks, is referred to as the aircraft's range (Horonjeff *et al.*, 2010). The aircraft payload is the useful load that may be carried – passengers, air cargo, or mail (Clark, 2017; Sadraey, 2013). Several factors affect this performance, such as takeoff and landing performance limitations in combination with aerodrome considerations (runways length, weather, etc), but more directly by the certified maximum takeoff weight (MTOW). The payload lift capability can be used to lift or carry some combination of payload and fuel, the aggregate of which is limited (Padilla and Wittenberg, 2009). An aircraft's fuel is often limited by volume or by the aircraft's maximum ramp weight. There are many factors that influence an aircraft's range, among the most important being its payload. Generally, as the range increases the payload decreases, with a weight trade-off occurring between the required fuel to operate the service and the payload which needs to be carried (Horonjeff *et al*., 2010). The primary means of assessing the overall performance of a civil aircraft is from its payload-range diagram, which provides an envelope showing how payload capacity varies with flight range. Full details are available from other sources (Belobaba, 2016; Clark, 2017; Schmitt and Gollnick, 2016) and only a brief description is presented here. A typical payload-range diagram is shown in Figure 1 in which the range is plotted on the abscissa and the payload on the ordinate (see Appendix 1 for the key aircraft weight definitions).

The origin of the vertical axis (payload) corresponds to the aircraft's Operating Empty Weight (OEW). The horizontal line AB is fixed at the Maximum Zero Fuel Weight (MZFW) of the aircraft. In the region AB, the difference between the MZFW and the OEW equals the payload capacity; since the fuel tanks are only partially filled in this region the full payload can be transported for these ranges; and range is increased simply by increasing the fuel quantity. The gross weight of the aircraft (OEW + payload + fuel) increases along line segment AB but remains less than the maximum value (MTOW), except at point B which corresponds to the maximum payload at MTOW, although there is still fuel capacity (Schmitt and Gollnick, 2016). Point B also corresponds to the maximum range at maximum payload, which Morrell (2016) identifies as the point of maximum efficiency. Between points B and C, the range can only be increased by exchanging fuel weight for payload weight, i.e. payload is offloaded whilst fuel is added, thus maintaining the MTOW, utilizing the aforementioned available fuel capacity. Point C occurs when the fuel tanks are completely full, a limit that is set by the aircraft's fuel tank capacity. Along the line segment CD, further increases in range can be achieved by progressively reducing the payload since no additional fuel can be accommodated. In this region the aircraft's TOW is less than the MTOW. For commercial use the region CD is unimportant and uneconomic, which explains why the range corresponding to point C is referred to as the maximum range, rather than point D. At Point D there is no payload remaining and the corresponding range is referred to as the ferry range of the aircraft which is its maximum possible flight range when flown empty (Baxter and Bardell, 2016). It is, however, structurally possible to add additional fuel capacity (in unused cargo areas etc) to achieve the ultimate range, which corresponds to the point E, although impractical.

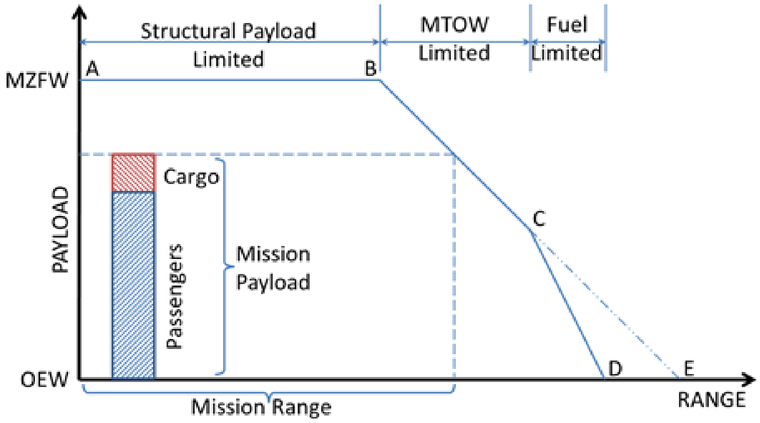

Figure 1. Civil aircraft payload/range envelope

For a typical desired mission range, the maximum payload that can be carried is easily determined from the payload range diagram (Fig. 1). From the desired mission range value, a line is projected vertically upwards until it intersects the envelope. A horizontal line is then projected horizontally back from this point to the vertical axis, indicating the available maximum payload. For a given mission this payload will likely comprise of both passengers and cargo; ideally facilitating a full complement of passengers in the airline's chosen seating configuration, plus some additional cargo, as indicated schematically in Figure 1. All ULR flights will occur in the MTOW limited region of the payload range diagram since there is no current civil aircraft designed to operate with a maximum payload for ranges greater than 8,000 nautical miles. Clearly, the aircraft offering the most promising ULR performance will be those for which the range for maximum efficiency (B) is closest to the desired mission range. However, it may not be possible to attain the desired range without imposing considerable payload restrictions which in turn will impact an airline's ambition to offer a particular level of service. Ultimately all these variables are governed by the payload-range characteristics of a given aircraft type (Baxter and Bardell, 2016).

2.5. The Airbus A350-900XWB and Boeing 787-9 aircraft: a brief overview

The Boeing 787 family includes the 787-8, 787-9 and the 787-10 models (Aircraft Commerce 2006, 2015). The B787-8 entered commercial service in October 2011 with Japan-based All Nippon Airlines (Norris, 2015) whilst the B787-9 entered commercial service in 2014 (Aircraft Commerce, 2014). The Boeing 787 is a mid-sized aircraft, seating between 220-280 passengers, depending upon the operators desired seating configuration (Aircraft Commerce, 2012). The two variants of the Boeing B787 family, the -8 and -9, broadly have seating capacities that could enable them to replace aircraft types ranging from the Boeing B767-300 to the Airbus A340-200/300 (Aircraft Commerce, 2010). The 787-10 is the largest variant of the B787 family and is anticipated to enter commerce service in 2018 (Aircraft Commerce, 2014). A key objective of the B787 design was the ability of the aircraft to offer the same unit cost per available seat mile (CASM) as larger aircraft types, and thereby making it economically viable for the 787 to operate over many city pairs or origins-and-destinations (O & Ds) that are only likely to produce small volumes of traffic (Aircraft Commerce, 2010). Due to the B787-9 long-range capability (Table 1), the aircraft can connect almost any two airports in the world, with few operating and performance restrictions. The extensive long-haul capability provides operators with significant and valuable flexibility in planning their route network and flight schedules. The B787 aircraft is made of 50 per cent carbon fibre reinforced plastic (CFRP) and other composites, and 20 per cent aluminium. The use of the CFRPs and aluminium has made the aircraft lighter than previous generation aircraft (Aircraft Commerce, 2009).

Table 1. Boeing 787-9 key specifications. Source: data derived Boeing Commercial Airplanes (2015, 2018)

Specification	General Electric Engines	Rolls Royce Engines
Typical seating configuration (2 class layout)	290	290
Range (km)	14,140	14,140
Maximum zero fuel weight (tonnes)	181.4	181.4
Maximum landing weight (tonnes	192.7	192.7
Maximum take-off weight (tonnes)	254.0	254.0
Maximum fuel capacity (litres)	126,372	126,372
Lower deck belly and bulk hold capacity (m^3)	175.2	175.2

When Boeing committed to developing the 7E7 (now the B787), Airbus formally launched the Airbus A350, which was derived from the Airbus A330-200/-300, in response (Flottau, 2016; Qiu, 2005). The Airbus A350 was therefore originally based on the same fuselage and fuel capacity as the A330-200/-300. The major difference between the A350 and the A330 was the use of carbon fibre in the A350's wing structure. Also, the Airbus A350 used the General Electric (GE) (GENX) engines. Originally, the Airbus A350-900 had the same fuselage as the Airbus A330-300 and was offered with the same maximum take-off weight (MTOW) (Qiu, 2005). The A350-900 standard 300 three class seating configuration places the aircraft as a direct competitor for the Boeing B777-200ER and the Boeing 787-10 when the latter aircraft was launched (Hill *et al*., 2017). Originally the A350 was adapted from the Airbus A330-200/-300 with aircraft sharing the same eight abreast fuselage cross-section and material composition. Following further discussions with customers and intense competition from the Boeing 787, in 2006, Airbus announced a new aircraft design: the A350XWB (extra wide body). The A350 XWB aircraft features a wide fuselage cross-section, a brand-new wing and flight deck, and a greater use of composite materials. The A350 has become the first Airbus widebody aircraft to adopt a new wider fuselage cross-section (Aircraft Commerce, 2006). This has provided the aircraft with a wider external cabin width of 234 inches, and an internal cabin width of 208 inches (Aircraft Commerce, 2009; Wall, 2006; Wall and Mecham, 2006). This permits a standard economy class configuration of nine-abreast seating (Aircraft Commerce, 2015).

The Airbus A350XWB family now comprises the A350-800, -900 and -1000. The sole engine option for these aircraft is the Rolls Royce Trent XWB (Aircraft Commerce, 2015). (The -800 is the shortest variant and -1000 the largest variant of the aircraft). The first Airbus A359 was scheduled to be delivered to Qatar Airways in late 2014 (Flottau, 2016; Kingsley-Jones, 2014). The aircraft entered commercial service with Qatar Airways on the 15th January 2015 (Kingsley-Jones, 2015). The Airbus A350XWB is half plastic and has composite wings, tail, fuselage and other primary infrastructure. Overall the breakdown in the materials used in the aircraft approximates to 50 per cent composite, 20 per cent aluminium, 15 per cent titanium and five per cent other materials (Marsh, 2015). The key specifications and operational characteristics of the Airbus A350XWB are presented in Table 2.

Table 2. Airbus A350-900XWB key specifications. Source: data derived from Airbus SAS (2018)

Specification	Value
Typical seating configuration (2 class layout)	325
Range (km)	15,000
Maximum zero fuel weight (tonnes)	192.0
Maximum landing weight (tonnes	205.0
Maximum take-off weight (tonnes)	280.0
Maximum fuel capacity (litres)	141,000
Lower deck belly and bulk hold capacity (m^3)	172.4

3. Research method

The research undertaken in this study used a mixed methods research design (Arora and Mahankale, 2013; Creswell, and Plano Clark 2017; Krishnaswamy *et al.*, 2009) that was broadly exploratory in nature (Yin, 2017). The study utilized an inductive approach that combined both qualitative and quantitative methods (Leavy, 2017; McNabb, 2017). The qualitative and quantitative data for this study was obtained from a range of documents, including the Airbus SAS and Boeing Commercial Airplanes aircraft characteristics for airport planning manuals and the Singapore Airlines and United Airlines websites. Qualitative data was also gathered from leading air transport and airport industry-related magazines, and press articles. The study therefore used secondary data analysis to investigate the research problem. The three principles of data collection suggested by Yin (2017) were followed in this study: the use of multiple sources of case evidence, creation of a database on the subject, and the establishment of a chain of evidence.

The empirical data collected for the case studies was examined using document analysis. Document analysis is often used in case studies and focuses on the information and data from formal documents and company records (Andrew *et al.*, 2011). The documents collected for the study were examined according to four criteria: authenticity, credibility, representativeness and meaning (Fulcher and Scott, 2011; Scott, 2014; Scott and Marshall, 2009). Prior to conducting the formal analysis of the documents gathered in the study, the context in which the documents were created was determined and the authenticity of the documents was assessed (Payne and Payne, 2004). Authenticity involves an assessment of the collected documents for their soundness and authorship. Scott and Marshall (2009, p.188) note that ‘soundness refers to whether the document is complete and whether it is an original and sound copy. Authorship relates to such issues as collective or institutional authorship. In this study the primary source of the case study documents was the Airbus SAS *A350 Aircraft Characteristics: Airport and Maintenance Planning Manual* (2017), and the Boeing Commercial Airplanes *B787 Airport Characteristics for Airport Planning Manual* (2015). The documents were available in the public domain. The credibility criterion concerns the accuracy and sincerity of a document. The representativeness criterion involved an assessment of the availability and survival of the documents gathered. The fourth criterion, meaning, is a most important matter and occurs at two levels. The first is the literal understanding of a document, by which is meant its physical readability, the language used and whether it can be read, as well as the date of the document (Scott, 2004).

Following the recommendations of O’Leary (2004), the qualitative document analysis process in the present study was undertaken in six distinct phases as follows (Table 3):

Table 3. Phases and tasks in the study’s document analysis process. Source: Adapted from O’Leary (2004, p. 179)

Phase	Task
1	This phase involved planning the types and required documentation and their availability
2	The data collection involved gathering the documents and developing and implementing a scheme for the document management
3	Documents were reviewed to assess their authenticity, credibility and to identify any potential bias
4	The content of the collected documents was interrogated, and the key themes and issues were identified
5	This phase involved the reflection and refinement to identify and difficulties associated with the documents, reviewing sources, as well as exploring the documents content
6	The analysis of the data was completed in this final phase of the study

The quantitative methodology utilized as part of this exploratory study was a simulation. Dooley (2002) suggested that a simulation method is utilized to answer the question “what if?” The purpose of the simulation in this work is to compare the "performance" difference between two different aircraft operating between a given city pair, that is, from Singapore (SIN) to San Francisco (SFO) and from San Francisco (SFO) to Singapore (SIN). Axelrod (1997) lists performance as one of the key uses of simulation-based research. This work utilized a discrete event simulation (Law and Kelton, 2000), which is appropriate to situations in which variables only change a finite number of times (in the case of this work, there are only two options for the aircraft type, and two flight directions).

Specifically, for the simulation, a single city pair was used as the case study; that is, Singapore (SIN) to San Francisco (SFO). It is important to note that the prevailing winds (from west to east) affect the performance of aircraft; which here will result in additional time aloft heading west, and a reduced time aloft heading east. As previously noted, two different aircraft from competing airlines were considered in the study, the Airbus A350-900XWB of Singapore Airlines, and the Boeing 787-9 of United Airlines. The test matrix for the simulation is therefore, 1 city pair, 2 directions, and 2 aircraft, giving 4 possible combinations.

The payload range diagram is based on Breguet's range equation for a jet powered aircraft (Law and Kelton, 2000),

$$R = \frac{v}{TSFC}\frac{L}{D}\ln\frac{W_{\text{int}}}{W_{final}}. \tag{1}$$

Here *TSFC* is the thrust specific fuel consumption, a property of the engine describing how efficiently thrust is developed in terms of the mass of fuel consumed (kilograms per second) relative to the resultant thrust developed in Newtons. Next, *L*/*D* is the lift to drag ratio, and is effectively the aerodynamic efficiency in terms of how much lift is generated relative to the resultant drag. The terms within the natural logarithm (ln) are 1) the initial weight (W_{int}), effectively the takeoff weight of the aircraft (in Newtons), and 2) the final weight (W_{final}), effectively the landing weight of the aircraft (also in Newtons). The difference between these two weights is the weight of the consumed fuel ($W_{fuel} = W_{int} - W_{final}$). The range (*R*) can be defined as the air range, if *v* is the true airspeed of the aircraft. However, it is far more useful to define *R* as the ground range (R_g), which requires *v* to be the ground speed. The relationship between the ground speed (v_g) and the airspeed (*v*) is the wind speed (v_w). As such we can redefine the ground range as (Anderson, 2005).

$$R_g = \frac{v_g + v_w}{TSFC}\frac{L}{D}\ln\frac{W_{\text{int}}}{W_{final}}. \tag{2}$$

The relative wind speed is a highly variable quantity, which varies as a function of latitude, longitude, and altitude, as well as time of day, and season. However, since conclusions are being drawn regarding long term impacts of aircraft selection on route profitability, an annual wind average will result in an average effect on the payload range performance. The route from Singapore (SIN) to San Francisco (SFO) was used to determine the relevant latitudes and longitudes of interest for the wind vector. An altitude corresponding to 250 millibar was chosen (corresponding to a cruise altitude). Monthly wind data for the corresponding latitudes, longitudes, and altitude was sourced from the Climate Data Library (Columbia University, 2017). The data had a resolution of 2.5 degrees in latitude and longitude and was provided as meridional and zonal values corresponding to longitudinal and latitude components, respectively. These component values were then averaged to give the average wind vector.

To determine the impact of wind on the payload range diagram, the following procedure was utilized:

1. Determine range of payload range diagram critical points (B, C, and D),
2. Utilizing the weights of the respective aircraft, calculate the L/D/TSFC constant for each critical point,
3. With the average wind speed calculate the new critical points, and
4. Plot new payload range diagrams.

The key parameters for the case aircraft which were utilized in the simulation are given in Table 4.

Table 4. Phases and tasks in the study's document analysis process. Source: Airbus data sourced from (George, 2015); Boeing Commercial Airplanes (2015)

Aircraft	**Mass (kg)**				**M_{cruise}**
	Payload	**Fuel**	**OEW**	**MTOW**	
Airbus A350-900	60,528	113,036	135,172	275,002	0.85
Boeing 787-9	52,587	101,456	128,850	254,011	0.85

4. Results

4.1. Singapore Airlines: a brief overview

Singapore Airlines (IATA Airline Code: SQ) was established on 28 January 1972. This followed the emergence of Singapore as a Republic that was independent of the Federation of Malaysia; consequently, this resulted in the division of Malaysia-Singapore Airlines (MSA) into two individual airlines that became the national flag carriers of Singapore and Malaysia, respectively. SQ launched operations on 1 October 1972, serving the same international destinations that had been previously served by Malaysia-Singapore Airlines (MSA). The airline used a fleet of Boeing B707 and Boeing B737 aircraft (Chant, 1997).

On 2 April 1973, Singapore Airlines commenced daily services between Singapore and London, and this was followed shortly thereafter when on 31 July, the airline commenced a major expansion program following the delivery of its first widebody aircraft type, the four turbo-fan powered Boeing B747-212B aircraft. This was followed quite soon by another widebody aircraft, the McDonnell-Douglas DC10-30. These aircraft were deployed on the airline’s medium-and-high density air routes. On 20 December 1980, SQ received its first Airbus A300B4-203 aircraft; this aircraft complemented the airlines Boeing B747-212B and McDonnell Douglas DC10-30 aircraft (Chant, 1997).

Currently, Singapore Airlines operates a modern passenger fleet of over 100 aircraft. The Singapore Airlines Group, which comprises the wholly-owned subsidiaries SilkAir, Scoot, Tiger Airways (which operates as Tigerair) and SIA Cargo, has a combined fleet of almost 180 aircraft. The airlines combined passenger network covers 131 destinations in 35 countries. The Singapore Airlines Group carried over 31 million passengers in the 2016/17 financial year (Singapore Airlines, 2017).

At the time of the current study, Singapore Airlines operated a fleet of 11 Airbus A350-900XWB aircraft and had a further 56 on order (Singapore Airlines, 2017). On ultra-long-haul services, such as the Singapore (SIN) to San Francisco (SFO) route, the aircraft are operated in a 3-class seating configuration (Table 5).

Table 5. Singapore Airlines Airbus A350-900XWB passenger cabin configuration. Source: Singapore Airlines (2018)

Cabin Class	Number of seats
Business Class	42
Premium Economy Class	24
Economy Class	187

4.2. United Airlines: a brief overview

In 1930, United Airlines (IATA Airline Code: UA) was formed following the merger of four airlines. Capital Airlines was taken over. In 1973, UA was the sole International Air Transport Association (IATA) member to carry more than 30 million passengers. The airline also had the largest fleet at the time (370) (Taylor and Young, 1975). During the early 1960s, United Airlines needed to upgrade its medium-haul aircraft fleet. The airline decided to acquire the Boeing B727-22 aircraft, which entered commercial service on 6 February 1964. United Airlines also became the first United States-based airline to order the Boeing B737. The first Boeing B737 aircraft was delivered on 29 December 1967 (Chant, 1997).

The next major aircraft type ordered by United was the Boeing B747-122, which was deployed on long-haul operations. The first Boeing B747-122 aircraft was delivered on 30 June 1970 (Chant, 1997). Later widebody aircraft operated by United Airlines include the Airbus A320, Boeing B757, B767 and 777 aircraft. Currently, United Airlines operates services to 338 destinations, of which 216 are United States cities. The airline serves 122 destinations. United Airlines has a mainline fleet of 744 aircraft and a regional fleet of 507 aircraft (United Airlines, 2018a).

As at December 31, 2017, United Airlines owned and operated a fleet of 21 Boeing 787-9 aircraft (United Airlines, 2018b). These aircraft are operated on a variety of long-haul routes in which they are configured with a two-class cabin configuration (Table 6) consisting of 48 (J) Business Class seats, 88 premium economy, and 116 (Y) Economy Class seats (United Airlines, 2018c).

Table 6. United Airlines Boeing 787-9 passenger cabin configuration. Source: United Airlines (2018c)

Cabin Class	Number of seats
United Polaris^{SM} Business Class	48
United Economy Plus®	88
United Economy®	116

4.3. Simulation results

Figure 2 shows the route between Singapore (SIN) in South East Asia to San Francisco (SFO) located on the west coast of the United States of America. The map was produced using Google Maps (Google Maps, 2018), which gave the distance between the city pair as 13,596.09 km, measured from airport to airport. Overlaid on top of the map is the wind vectors. The wind vectors were available at latitude increments of 2.5 degrees, and the longitude increments were adjusted to 3.4375 degrees (calculated by using a weighted average of the 4 or 5 constituent longitudinal values with 2.5-degree increments). The average wind vector was calculated to have components of 6.84 ms^{-1} and -1.21 ms^{-1}, corresponding to the zonal and meridional components, respectively.

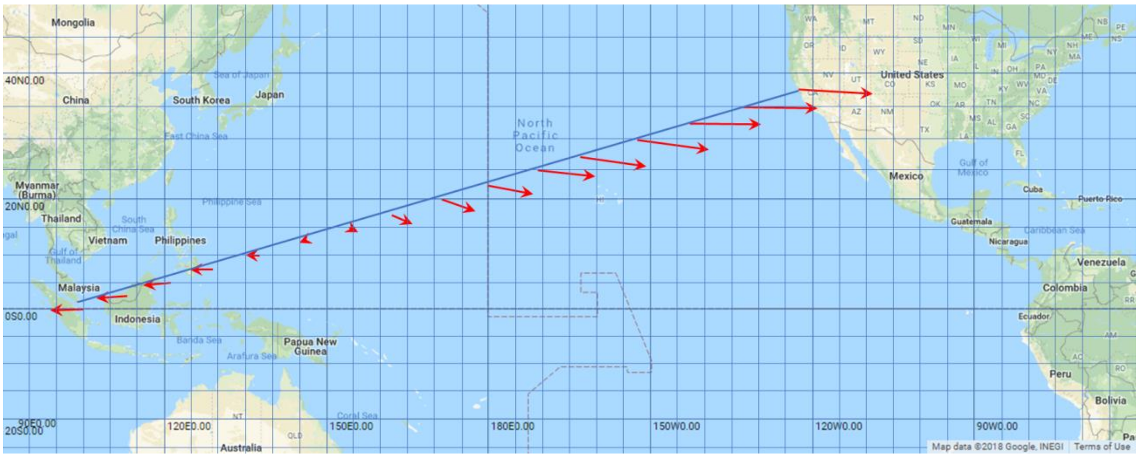

Figure 2. Route between Singapore (SIN) and San Francisco (SFO) and the annual average wind vectors at the 2.5-degree latitude increments, referenced to the tail end. Note: The SFO wind vector is 21ms. Map data ©2018 Google Maps (2018)

Figure 3 shows the resultant payload range diagram for the Airbus A350-900XWB aircraft. Three curves are included, the first of which is the published payload range diagram of the Airbus A350-900XWB aircraft. In addition to this are the two resultant payload range diagrams that results from the east bound and west bound annual wind average. Marked on the payload range diagram is the corresponding range between Singapore (SIN) and San Francisco (SFO). This mission range intersects with the raw payload range curve at 39.1 tonnes, while including the annual average wind the values are 37.1 tonnes and 40.9 tonnes for the westbound and eastbound flights, respectively. Using the typical value of 95 kg per passenger with baggage and a full passenger payload (European Aviation Safety Agency, 2009), the passenger payload is 24.0 tonnes, leaving an excess cargo payload of 13.1 tonnes and 16.9 tonnes for the westbound and eastbound flights, respectively. If there are no prevailing winds in either direction of the flight, then the available air cargo payload with a full passenger load is 15.0 tonnes. If we include the Singapore Airlines annual load factor of 79% (Singapore Airlines, 2017), the expected passenger payload becomes 19.0 tonnes, leaving an excess cargo payload of 18.2 tonnes and 21.9 tonnes for the westbound and eastbound flights, respectively. When flights are operated with an average load-factor and there are no winds enroute then the available air cargo payload is 20.1 tonnes. These results are summarized in Table 7.

Figure 4 shows the resultant payload range diagram for United Airlines Boeing 787-9 aircraft. Again, three curves are included, the published payload range of the Boeing 787-9 and the two resultant payload range diagrams that result from the eastbound and westbound annual wind average. The Singapore and San Francisco mission range intersects with the raw payload range curve at 33.7 tonnes, while including the annual average wind the values are 31.8 tonnes and 35.4 tonnes for the westbound and eastbound flights, respectively. Using the typical value of 95 kg per passenger with baggage (European Aviation Safety Agency, 2009), the passenger payload is 23.9 tonnes, leaving an excess cargo payload of 7.9 tonnes and 11.4 tonnes for the westbound and eastbound flights, respectively. If there are no prevailing winds in either direction of the flight, then the available air cargo payload with a full passenger load is 9.7 tonnes. If we include the United Airline Annual Pacific load factor of 80.2% (United Airlines, 2017b), the expected passenger payload becomes 19.2 tonnes, leaving an excess cargo payload of 12.6 tonnes and 16.2 tonnes for the westbound and eastbound flights, respectively. In the event that a flight is operated with an average passenger load and there are no winds on the air route, then the available air cargo payload is 14.5 tonnes. These results are summarized in Table 7.

4.4. Comparison of the air cargo-carrying potential Airbus A350-900XWB vis-à-vis Boeing 787-9

All of the relevant air cargo carrying parameters are summarised in Table 7. As can be seen, the payload potential of the Singapore Airlines Airbus 350-900XWB aircraft is always slightly greater than the United Airlines Boeing 787-9 aircraft, particularly when there are no prevailing wind penalties. Specifically, the Singapore Airlines Airbus 350-900XWB on average offers 5.5 tonnes more than United Airlines Boeing 787-9. Based on the current air cargo proxy yield ($0.375/tonne/km) (Boeing Commercial Airplanes, 2016), and the distance (13,596.09 km) then there could be an additional $27,900 in revenue potential when the aircraft operates daily services. This equates to an annual revenue potential of $USD 20.3 million.

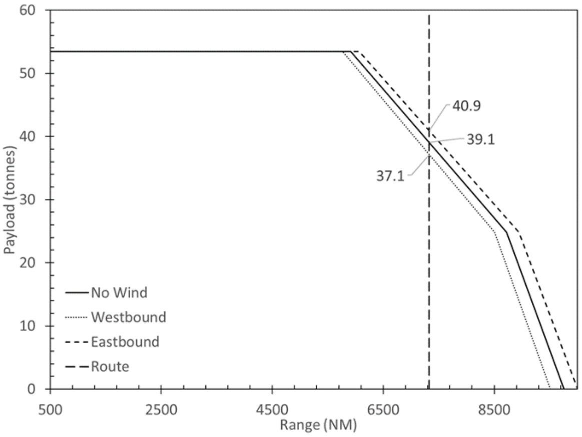

Figure 3. Payload range diagram of the Airbus A350-900XWB, with 3 curves for the no wind condition, westbound, and eastbound. The mission range between Singapore (SIN) and San Francisco (SFO), and the corresponding mission payloads are marked

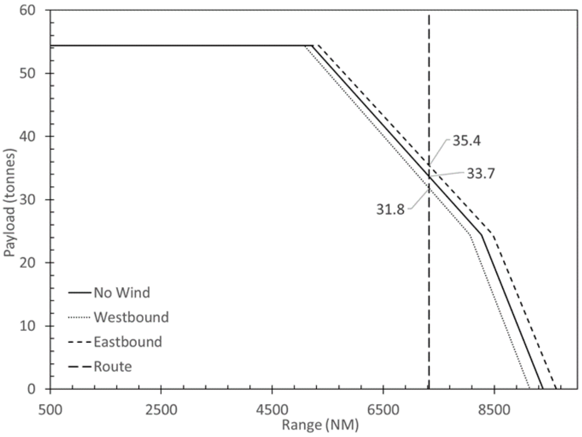

Figure 4. Payload range diagram of the Boeing 787-9, with 3 curves for the no wind condition, westbound, and eastbound. The mission range between Singapore (SIN) and San Francisco (SFO, and the corresponding mission payloads are marked

Table 7. Air cargo payload potential for the two-case aircraft and the resultant difference (Δ), for the six initial conditions

Condition	Airbus A350-900XWB cargo payload (tonnes)	Boeing 787-9 cargo payload (tonnes)	Δ (tonnes)	
No wind, maximum PAX	15.0	9.7	5.3	
Eastbound, maximum PAX	16.9	11.5	5.4	
Westbound, maximum PAX	13.1	7.9	5.2	
No wind average load factor	20.1	14.5	5.6	
Eastbound average load-factor	21.9	16.2	5.7	
Westbound average load-factor	18.2	12.6	5.6	

5. Conclusions

The air cargo mode plays a critical role in the global economy and in many firm’s supply chains. Air cargo also plays a significant role in both the full-service network airlines' revenue streams and air cargo revenue can often make the difference between profit and loss on a route. The full-service network airlines carry air cargo in the lower lobe belly-holds of their passenger aircraft.

The introduction of the Airbus A350-900XWB and the Boeing 787-9 aircraft have enabled airlines to operate ultra-long-haul (ULR) services. This study has examined the air cargo carrying potential of the Airbus A350-900XWB and the Boeing 787-9 aircraft deployed by Singapore Airlines and United Airlines, respectively. The study focused on the San Francisco (SFO) to Singapore (SIN) and Singapore (SIN) to San Francisco (SFO) air routes. Despite the very long flight stage length of 13,596.09 kilometres both aircraft types offer a meaningful air cargo payload. If the flights are not impacted by any prevailing winds, then Singapore Airlines Airbus A350-900XWB potentially offers an air cargo payload of 14.7 tonnes and United Airlines Boeing 787-9 a payload of 12.8 tonnes.

If we consider the available air cargo capacity when there is the maximum passenger compliment on board, the difference between the A350-900XWB in Singapore Airlines cabin configuration and the United Airlines Boeing 787-9 is 5.3 tonnes (in favour of the Airbus A350-900XWB), which increases slightly to 5.4 tonnes in the east bound direction and reduced slightly to 5.2 tonnes in the west bound direct. However, if we utilise the typical load factors of each airline, the difference becomes 5.6 tonnes in favour of the Airbus A350-900XWB aircraft, which increases to 5.7 tonnes in the east bound direction (and remains at 5.6 tonnes in the west bound direction).

A limitation of the current study was that it was not possible to calculate the incremental fuel burn costs to accommodate the air cargo loads on the Singapore to San Francisco and San Francisco to Singapore sectors operated by Singapore Airlines and United Airlines as the airline and sector specific fuel costs were not available in the public domain. Should such data become available then a future study could quantify the incremental fuel burn cost to carry air cargo vis-à-vis the potential revenue that could be earned from the carriage of this air cargo traffic.

Appendix 1

Definitions of the Key Aircraft Operational Weights

1. Maximum landing weight (MLW): is the structural capability of the aircraft upon landing. The aircraft's main landing gear is structurally designed to absorb the forces encountered by the aircraft during landing; the larger the forces, the heavier the requirement on the aircraft's landing gear (Mair and Birdsall, 1998, p. 63). The MLW is the total of the aircraft OEW, cargo payload and reserve fuel load (passenger and baggage weight for passenger services) that an airline is required, by law, to carry on a flight (Khurana, 2009).
2. Maximum take-off weight (MTOW): the MTOW is the maximum aircraft weight at lift-off from the runway, that is, when the front landing gear detach from the ground (Curtis and Filippone, 2009, p. 30). The MTOW includes the aircraft's OEW, payload (cargo and passengers and baggage weight for passenger services) and fuel load less taxi fuel (Khurana, 2009, p. 263).
3. Maximum zero fuel weight (MZFW): the MZFW is the maximum weight permitted before fuel is loaded, as limited by aircraft strength and aircraft airworthiness requirements (Khurana, 2009, p. 263).
4. Operating empty weight: the OEW is the aircraft's weight from the manufacturer, plus some other additional removable items which are required due to operational requirements. These include the aircraft engine(s) oil, the unusable fuel, the flight catering and in-flight entertainment equipment (IFE), flight and navigational manuals, life vests and emergency equipment (Horonjeff *et al*., 2010).

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