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OPTIMIZATION OF REVENUE SPACE OF A BLENDED WING BODY

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Abstract

The revenue space of an aircraft consists of the passenger cabin and the cargo hold. In case of passenger aircraft, the most important parameter is the cabin floor area. It correlates directly with the possible number of passengers. Blended Wing Body concepts do not have a tubular fuselage. The cabin can be arranged in different layouts within the aerodynamic shape. This paper analyses different concepts for passenger cabin and cargo hold arrangements, and investigates their potential benefit. Conceptual methods are used to estimate the mass of the pressurized vessel. Three different aerodynamic shapes are being investigated. The basic conclusion is that BWBs are a useful alternative beyond the capacity of current aircraft. Further, a twin deck arrangement appears as most promising solution to maximize revenue potential of the aircraft.

1 Introduction

1.1. Blended Wing Body Concept

Since beginning of civil aircraft operation the average size of aircraft has grown considerably. While 25-35 passengers were normal capacities in the 1930ies, today's aircraft in majority seat above 100 passengers. Wide body aircraft seat several hundred passengers, and the largest aircraft in service is certified for up to 853 passengers. The growth in size has been enabled by improved technologies. Larger aircraft promise better economy in operation as their overall performance is better.

The current aircraft configuration type, consisting of a tubular fuselage and wings, has reached its maturation limit, and it is approaching the end of its growth potential. First, the limitation to 80m overall length limits the capacity of the fuselage. Second, the weight of the structural elements grows faster than the added capacity [1]. Hence, even without considering the reception of the market, the technical viability of aircraft larger than the A380 currently appears doubtful unless new technologies are used.

A possible new technology is the blended wing body. The BWB is essentially a large wing, which houses a payload area within its center section. The concept was originally introduced in the late 1980ies and analyzed in the 1990ies. The motivation of the BWB was primarily its superior aerodynamic efficiency compared to conventional configurations. The concept promises to reduce the wetted area per available seat. A considerable advantage was shown in comparison with a smaller version of the then A3XX [2].

The BWB offers a number of design challenges. Besides the optimization of the aerodynamic shape, and the design for satisfactory handling characteristics, the integration of the payload section still represents one of the challenges. Pressurization is necessary to offer a comfortable atmosphere at optimum cruising altitude. The classic tubular fuselage offers a structurally very efficient shape for a pressurized vessel. In case of the BWB, the integration of the payload section could follow two different paths:

I - Integral Concept: the entire section of the center wing containing the payload is built-up as an integral pressurized vessel, hence the shape of the pressurized section is the one of the outer aerodynamic shape. In this the integrated payload compartment offers a lower efficiency with respect to pressurization loads, when compared to the tubular shape. At the same time the aerodynamic shape should be kept unaffected by pressurization. This may lead to a substantial increase of the structural weight.

II - Segregated Concept: The pressure vessel is mostly independent on the outer shape and can be optimized for minimal structural weight, when subject to the only pressurization loads. However, additional structural components need to be provided to sustain the aerodynamic loads on the external shape.

Both concepts have been investigated using a variety of methods in [2], [3] and [4]. The configuration designed by NASA originally used the first concept. However, an aerodynamic shape optimization has shown that the optimal solution is substantially different from the initial baseline layout [5]. Thus, the second concept was also considered. The research project VELA also used the first concept [6].
Further integral concepts are currently under investigation [AIAA 2014-0259]. NASA N+3 publications used the Integral Concept. Researchers recently focused on the second concept, and looked into the detailed structural design necessary for minimum weight [7].

The pressurized compartment needs to enclose the payload section. Payload is traditionally accounted as mass, nevertheless, this does not fully represent the nature of the payload of aircraft primarily intended for passenger transport. Passengers require a certain amount of floor area per seat with a minimum cabin height above it. Further floor area needs to be made available for the location of the monuments (e.g., lavatories and galleys), and for the exit lanes. Hence, the most important parameter is the cabin floor area with sufficient height. The cargo hold is subject to similar requirements, requiring a lower minimum height. Irregularly shaped volumes are of low value for payload accommodation. While corners with reduced height may serve for some purposes, irregular floor height is not useful for any payload.

1.2. Previous Work

The blended wing body has been subject of research for over 20 years. The attention focused on different areas. The arrangement of the payload section has been shown in various studies. The first was the BWB presented by Liebeck. Liebeck presented both twin deck and single deck layouts. An overview is presented in [2]. Liebeck proposed cabins comparable to current single aisle layouts within the body being separated by structural walls. Monuments are placed in different places.

The MOB BWB configuration was the result of the European MOB project (A Computation Design Engine Incorporating **M**ulti-Disciplinary Design and **O**ptimization for **B**lended Wing Body Configuration) which was a cooperation between the European universities, research institutes and industry in a research program of three years duration [8]. The main objective of the MOB project was to demonstrate the multidisciplinary design and the optimization of innovative concepts. The primary purpose was the development of a distributed and modular design system aimed to exploit the disciplinary expertise of each partner. The first baseline for the BWB configuration was set up by Cranfield University and was initially intended to be a passenger-carrying commercial aircraft version.

The subsequent project VELA (Very Efficient Large Aircraft) [6] investigated different aspects of the blended wing body configuration. It featured two different configurations. VELA applied single deck layouts with a cargo floor below the passenger deck. The first structural concept was chosen: a fully integrated pressurized vessel within the contours of the aerodynamic shape. VELA adopted separated cabins with twin aisles. The VELA shape is also used in this paper as one of the three configurations analyzed.

The TU Delft attempted to create a smaller BWB concept that is more comparable to current twin aisle wide body aircraft in terms of capacity [5]. In this case the second concept was used, the payload area is housed in a pressure vessel independent of the external shape. The structural concept appears to be more efficient than those used on VELA and the Liebeck configurations. In this case the used aerodynamic shape did not allow a twin deck layout.

A realistic assessment of the weight of a pressurized vessel requires physics based methods, such as FEM. The TU Braunschweig used its design software PrADO for a BWB assessment [9]. The results belong to the few attempts of an integrated concept using FE methods for the estimation of the structural mass and performance. However, the validity of FEM-based methods is very difficult to ensure as no reference is available, and no calibration can be performed, as usually required for FE based methods.

NASA has conducted research into smaller BWBs in the 250-seat capacity region. This is in contradiction to the currently accepted assumption that only at large capacities a BWB-concept yields significant advantages over the conventional reference [10].

The payload integration is not only affected by the structural layout of the pressurized cabin. Certification requirements and operational requirements have a large impact on the actual internal layout. A strong driver is passenger safety. Evacuation needs to be possible, also in situations like ditching on a water surface or with collapsed landing gear. Airport compatibility requires sufficient access to the cabin and cargo hold ([11] looks at all aspects using one of the VELA concepts).

1.3. Research Question

As shown the BWB was assessed by a number of researchers, often with very capable tools. The identified shortcoming is not in methodologies, but in the basic conceptual layout of the BWB. This work focuses on optimizing the revenue space, by providing the best internal arrangement in terms of maximizing the floor area and the cargo volume, within a given overall surface of the pressurized section.

2 Methodology

2.1. Assumptions

This work assumes that an optimal aerodynamic shape has been computed for the intended cruise condition. The aerodynamic shape adheres to some boundary conditions (for example 80m span limitation) and general coupling between structural weight of a wing and the lift distribution. However, no pressurized vessel is integrated. The resulting efficiency potential for passenger transport is hence strongly influenced by the ability to accommodate as many passengers as possible within the given shape.

The main figure of merit is the floor area. In particular, floor area providing a minimum prescribed height to house passengers. Additional height does not represent an advantage. For passenger cabins rectangular floors are preferable, whereas irregularly shaped floor parts can be used for monument installation and additional passenger facilities.

There is always the possibility of trading cargo capacity for passenger capacity and vice versa. In this work the relationship between cargo capacity and passenger seats is reduced compared to current wide body airliners. A B777-300ER offers approximately 370 seats in a cabin with approximately 340 m^2 floor area [12]. The cargo volume is 214 m^3. The A380-800 features a cabin with approximately 580 m^2 of cabin floor area. Airbus uses a reference seat number of 525, which is achieved by some operators. The cargo volume is 175 m^3 [13]. Hence, the A380 has 0.91 passengers per square meter and a relationship of floor area to cargo volume of 3.3 to 1. The B777-300ER seats 1.09 passengers per square meter and the floor to cargo volume ratio is 1.59 to 1. These data are summarized together with B747-400 and a narrow body A320-200 airliner in Table 1.

Parameter	B777-300ER	A380-800	B747-400	A320-200
	wide body			narrow body
Seats typical / high	370 / 550	525 / 853	416 / 624	150 / 180
Cabin floor area [m^2]	340	580	380	102
Cargo volume [m^3]	214	175	181	37
Floor to volume ratio	1.59	3.3	2.1	1.47
PAX per m^2 ratio typical / high	1.09 / 1.62	0.91 / 1.47	1. 09 / 1.64	1.47 / 1.76

Table 1: Cabin and Cargo parameters of wide and narrow body airliners

As the BWB is intended for a future scenario, less cargo is assumed. This is due to the assumption that rising energy prices will make air cargo less attractive and the transport of passengers will be the dominating mission. This will also result is denser seating layouts. Many airlines operate the B777-300ER on long range routes with up to 430 seats (1.26 passengers per square meter). For the current study, the assumed passenger density is 1.1, and the maximum floor-to-cargo ratio is set at 3.5.

2.2. Principles of Pressurized Cabin Design

The ideal shape for pressurization is a sphere or a tube with rounded end caps [14]. The ideal shape for passenger accommodation is a rectangular area, preferably with the length being several times longer than the width. This sort of shape is found in current conventional aircraft. In conventional aircraft design the cabin is enclosed by a circular cross section. This allows the integration of a passenger deck roughly in the center of the circular section, thus offering the highest amount of floor area. Below the passenger deck a cargo hold can be integrated. Figure 1 shows the basic principles all current aircraft adhere to. The volume above the passenger deck remains unused except for crew rest facilities.

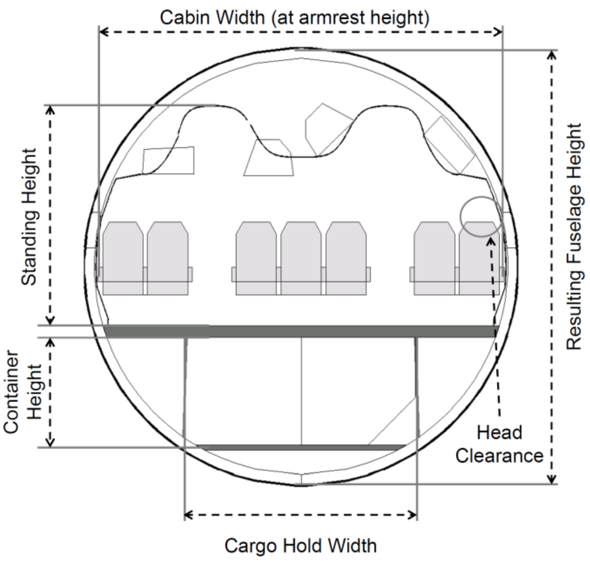
Figure 1 also shows the room required for seating and standing. The height of overhead bins is usually 1.6m. Many wide bodies use more clearance. Standing height needs to be at least 1.9m, while 2.1m is preferable. The A380 has approximately 2.7m distance between its two decks. This distance is reasoned by the necessary standing height and the presence of structural and system installations between both decks. The height of the floor grid carrying the actual cabin can be assumed with at least 20cm. The circular cross section becomes inefficient above a certain size as the cross section area cannot be used very efficiently any more. This is shown in Figure 2 (a) and (b), which depicts a fictional 8-abreast wide body and a fictional 11-abreast wide body. The 8-abreast uses a large proportion of the frontal area whereas the 11-abreast has huge unused areas above the cabin and below the cargo hold. An obvious solution is the introduction of a second passenger deck. The challenges offered by this are a non-ideal cross section and issues with arrangement of exits and systems. In Figure 2 (c) such a cross section is shown. A twin deck layout offers the advantage of less surface area for a given floor area. In Figure 2 a simple example is provided. Both single and twin deck offers a floor area of 512 m². The single deck solution result 1274 m² of surface of the pressurized volume. The twin deck solution has 928 m² pressurized surface, a reduction of 27%.

2.3. Analyzed BWB Configurations

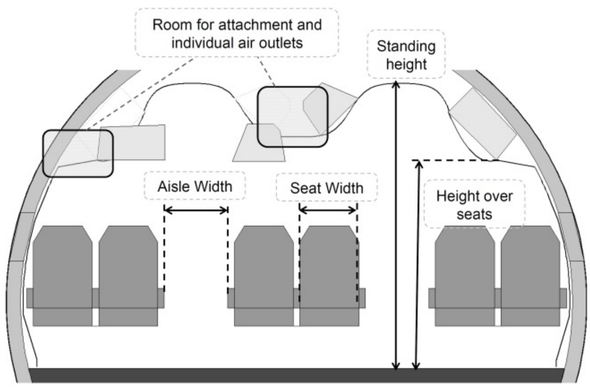
For the current study, the aerodynamic shapes of the different configurations for the intended analysis are already available. It is necessary to point out that the designs of these configurations have been mainly driven by aerodynamic performance optimization, and they only included a limited set of constraints regarding the payload integration.

Hence, the concept used here assumed external shape optimized for best cruise performance being completed, and then fit the most efficient

cabin inside. Minor modifications may be possible later.
An overall integrated concept, including in the optimization task the payload integration metrics previously discussed, would be desirable.

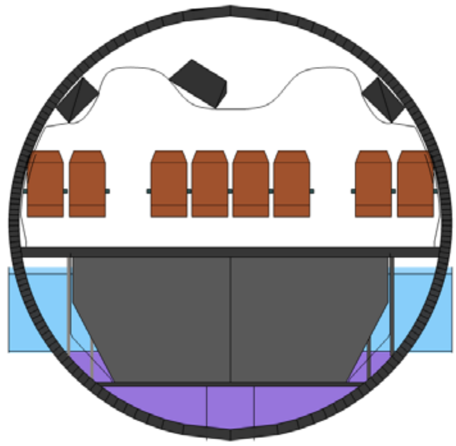


(a) Cross Section Layout

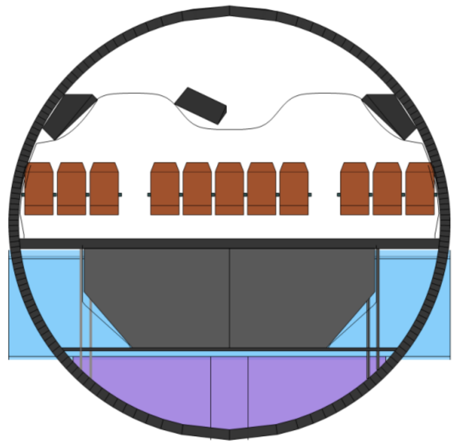


(b) Cabin Parameters

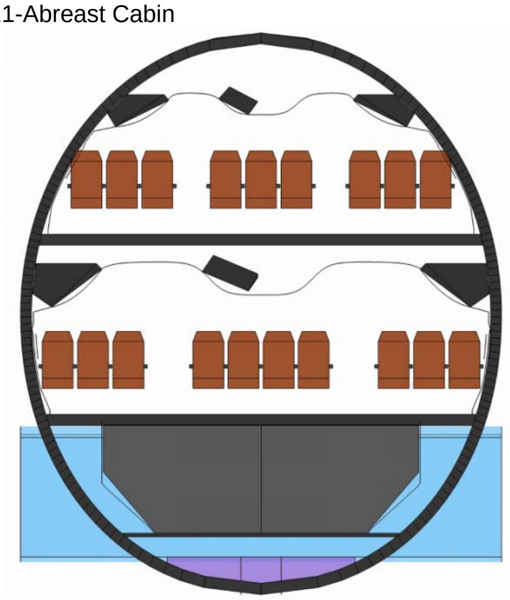
Figure 1: Characteristics of a typical cross section. Note that the floor is usually arranged in a way that the maximum width of the cabin is at armrest level.



(a) 8-Abreast Cabin



(b) 11-Abreast Cabin



(c) Twin Deck

Figure 2: (a), (b) Characteristics of a typical cross section. Note that the floor is usually arranged in a way that the maximum width of the cabin is at armrest level. (c) Twin deck cross section. The cross section geometry is comparable to the A380, but not exactly the same

Presenting of the three Reference Concepts

The three concepts which are used here are the MOB, VELA and the DLR-LY-BWB concepts which are presented above. All three configurations are shown in the Figure 3 and the basic parameters in Table 2.

Differently from the others, the MOB configuration was planned as a freighter configuration with a non-pressurizes center body. This freighter was designed for a range of 5100 nm and for a payload capacity of 115 tons.

For the realization of the VELA configuration there were designed and analyzed two extreme configurations the VELA 1 and VELA 2. Based on the knowledge acquired a third configuration was derived, the VELA 3. The design requirements for all the three configurations were a range of 7650 nm and 750 seat capacity.

The DLR-LY-BWB configuration is a configuration designed by DLR and results from the study are presented in [15] and [16]. The mission requirements of this configuration were a range of 7560 nm and 500 seat capacities.

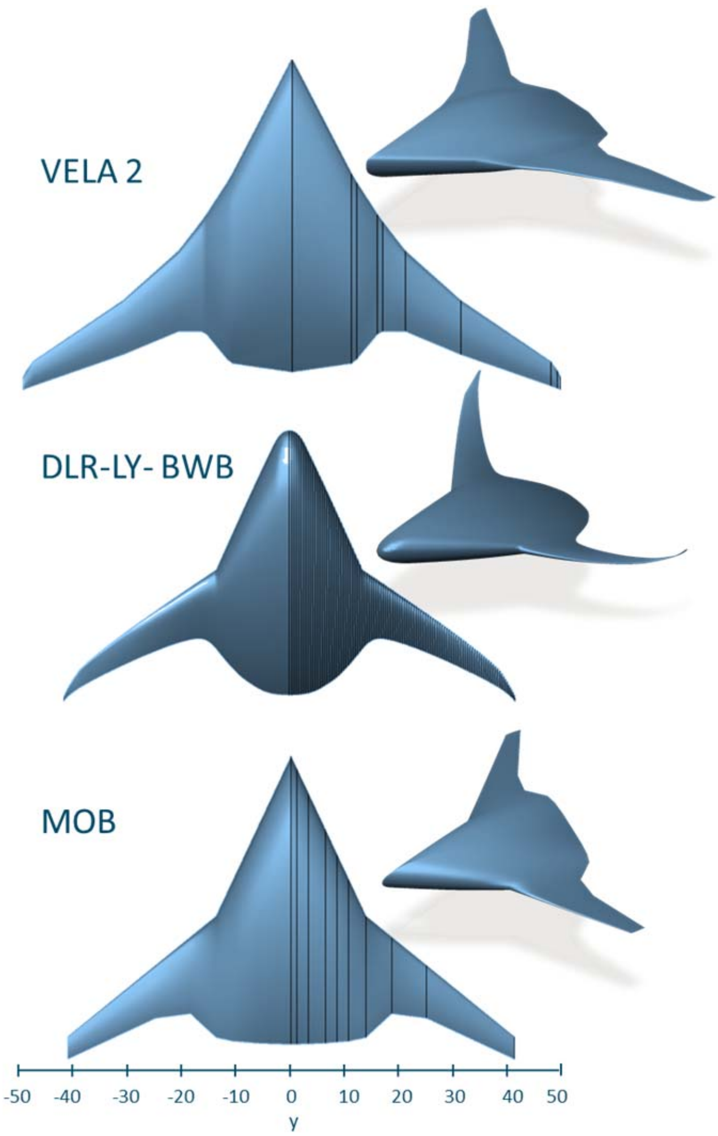


Figure 3: Three analyzed configurations

	VELA2	MOB	DLR-LY-BWB
Span	100	80	88
Length	60	48	50
Area [m²]	1923	1362	1339
Wetted Surface [m²]	3962	2802	2749
Payload[num. of PAX/ cargo in tons]	750/10	-/110	650/10

Table 2: Baseline parameters of the three configurations

3 Analysis and Results

Deck Concepts

The integration of the cabin and cargo compartment is based on different concepts on how both deck types fill the usable volume. The study investigates four different concepts of cabin and cargo compartment integration, whose principles are shown in Figure 4. The first concept is a single passenger deck above a single cargo deck and is comparable to conventional fuselages arrangements. The second concept is a double deck cabin for passengers above a single cargo deck, comparable to the A380 cross section layout. The third concept also comprises two decks for passengers, but also a lateral unpressurised cargo compartment is added on both sides. The idea of an unpressurized cargo deck originates from the fact that many cargo items do not require pressurization (though temperature control is required). The fourth concept is similar to the third concept with an additional rear pressurized cargo deck.

Based on the described metrics, the following minimum constraints for the cabin optimization have been set in this study. The passenger decks have as requirement a minimum height of 1.9m for standing areas and 1.55 for seating areas which need to have a minimum distance to standing areas. The required minimum cargo deck dimension is 1.65 m to hold a LD3 container inside.

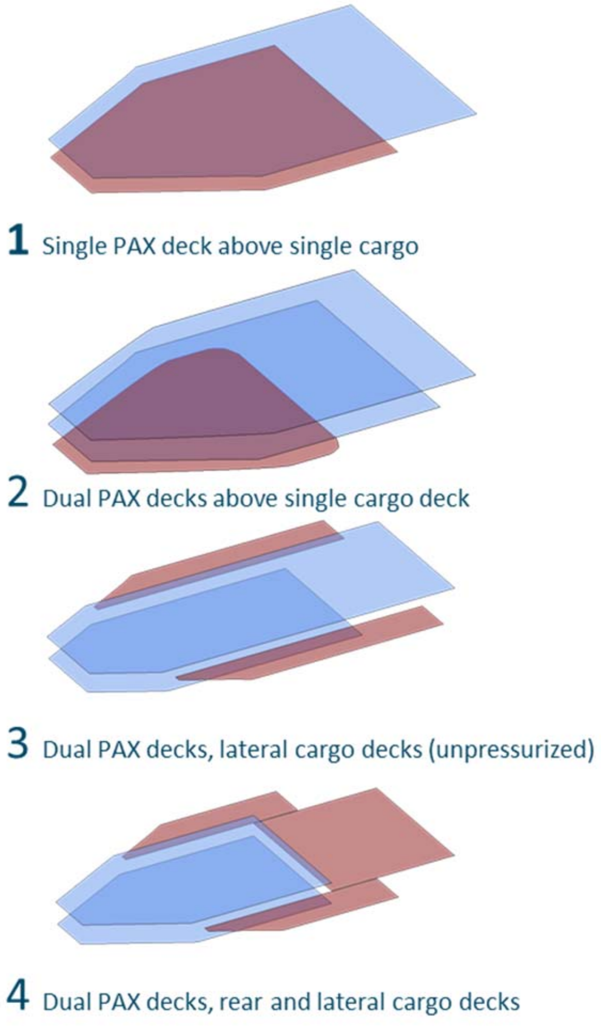


Figure 4: Concepts of payload deck integration

Details of Cabin Integration

The integration of the cabin includes the placement of doors, emergency exits, aisles and stairs, galleys and lavatories. Further seats and a potential crew rest compartment need to be accommodated. One exemplary design of the fourth concept is shown in the Figure 5. There are two large doors for boarding and de-boarding on each deck. Emergency exits are provided by six additional doors with stairways to the upper and lower side. The cabin area is subdivided in areas for the seats, aisles and monuments. There are seat areas in the nose section with a four abreast seating and in center section for six abreast seating. This detailed view of integrating is the plausibility check, if the optimized result makes sense and fulfills the overall requirements (e.g. if there are enough doors for emergency evacuation).

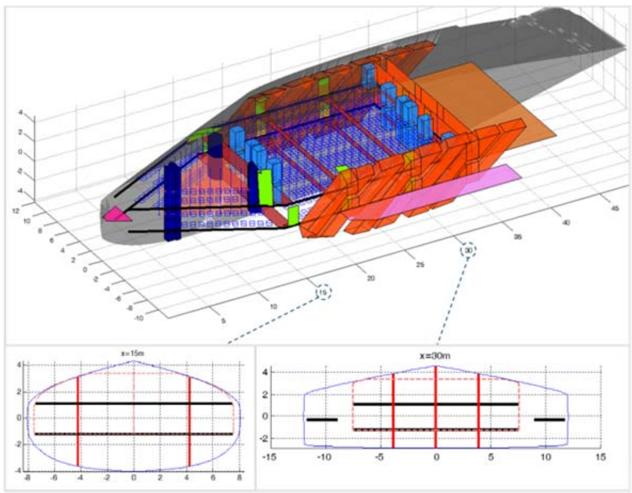


Figure 5: Example integrated Cabin and Cargo compartment

Optimum Deck Position

To find the best position of the floors in the usable volume, the floors of either concept are positioned at different vertical locations. For each the total area that fulfils the requirements is calculated. Figure 6 shows the result of the second concept applied to the DLR-LY-BWB concept. The maximum seat area is 1017 m². However, when using this position the cargo hold completely disappears. This shows that the optimum design is not necessarily at maximum cabin area and depends on the required specified capacity and desired cargo capacity.

The assumed minimum size of the cargo hold is oriented on the current A380 and uses a cargo-to-floor ratio (the inverse of floor-to-cargo ratio) of 1/3.5 (= 29%). For the concept one and two it is possible to find a solution which fulfills this requirement cargo and passenger revenue space is depending on each other. The other two concepts have in this analysis a cargo floor independent of the passenger (see Figure 7).

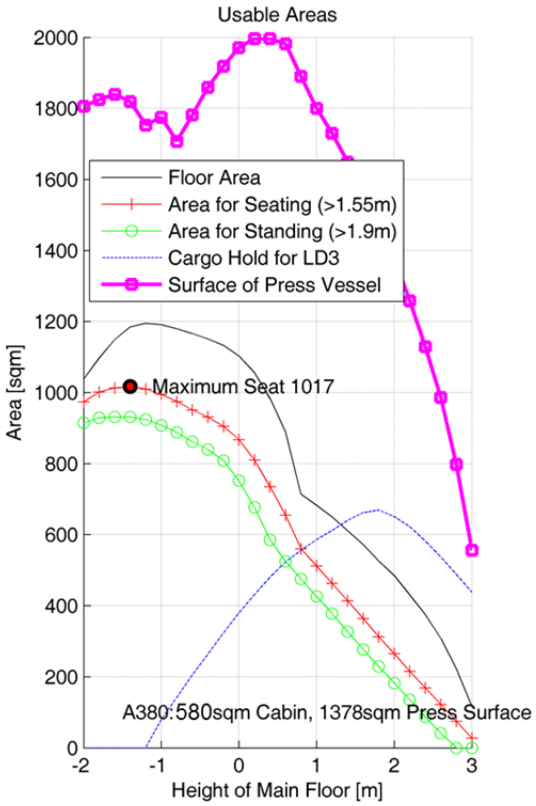


Figure 6: LY BWB dual PAX decks above single cargo deck

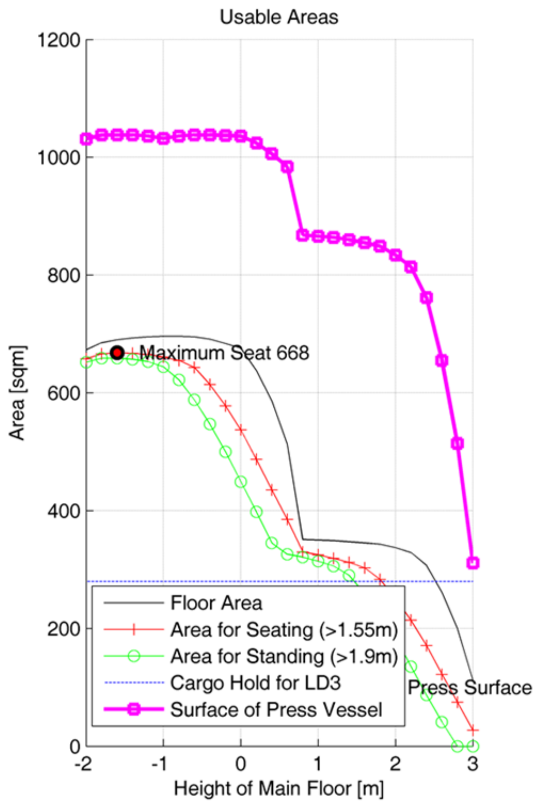


Figure 7: LY BWB dual PAX decks, rear and lateral cargo decks (unpressurized)

The optimum values of all four deck concepts of the three configurations are shown in the Table 3. It can be seen that the second concept (twin passenger deck) has the most potential in terms of maximum number of seats for all three configurations and fulfills the required cargo area. On the VELA 2 configuration, the improvement respect to the single deck configuration is 72% for the passenger deck, but with a reduction of 62% for the cargo deck. The reason for the reduction of the cargo is driven by the minimum required cargo-to-floor ratio of 29%. The disadvantage of this concept is that the optimum is more sensitive to the variations of the wing thickness at the central section.

Concept	VELA Cabin	VELA Cargo	MOB Cabin	MOB Cargo	DLR-BWB Cabin	DLR-BWB Cargo	
	Area [m²]						
1 Single PAX deck above single cargo	870	687 134	689	493 122	751	494 117	Variable Cargo Area
2 Dual PAX decks above single cargo deck	1493 72	259 -62 29	1050 52	175 -62 31	1169 63	198 -59 30	
3 Dual PAX decks, lateral cargo decks (unpressurized)	1066 23	191 -72 36	842 22	116 -76 31	884 24	147 -70 35	Fix Cargo Area
4 Dual PAX decks, rear and lateral cargo decks	660 -24	325 -53 109	630 -9	259 -47 92	696 -3	280 -43 87	

Relative differences to concept 1 [%]
Cargo volume to seat area ratio [%]

Table 3: Results of optimal placing of each concept in each configuration

Also the third concept shows an improvement compared to the single deck layout. For these configurations the cargo-to-floor ratio exceeds the required ratio because of the fixed cargo compartment (and parts of the cargo space are unpressurized). The concepts tree and four can be considered as opposite cases, the first has a large rear cargo deck, whereas for the latter the rear cargo deck area is zero. Between both concepts exists many combinations of cargo-to-floor ratios. Nevertheless, the concept three achieves the highest cargo-to-floor ratio.

In comparison to the current existing conventional configuration A380, the cabin floor increases by using the concept 2, compared to VELA2 around 157%, to MOB around 81% and to the DLR-LY-BWB around 101%. The cargo volume is equal or higher for all three configurations.[1]

Concept	VELA		MOB		DLR-BWB		
	Cabin	Cargo	Cabin	Cargo	Cabin	Cargo	
	Improvement [%]						
1 Single PAX deck above single cargo	50	293	18	182	23	182	Variable Cargo Area
2 Dual PAX decks above single cargo deck	157	48	81	0	101	8	
3 Dual PAX decks, lateral cargo decks (unpressurized)	84	9	45	-33	52	-16	Fix Cargo Area
4 Dual PAX decks, rear and lateral cargo decks	14	86	9	48	20	60	

Relative differences to concept 1 [%]
Cargo volume to seat area ratio [%]

Table 4: Concepts and configurations compared with A380

4 Summary and Conclusion

This paper presents the principles of cabin design, adopting a flexible method to integrate the payload compartment into pre-existing BWB external geometries. The method is based on the optimization of the “revenue space”, by placement of different floor concepts within an arbitrary BWB shape, including the placing of monuments in the cabin.

It shows the potential benefit of integrating multiple deck concepts compared to a single deck solution as often used in BWB concepts. The multideck-concept yields advantages for all BWB shapes analyzed.

A future step will be the usage of the presented cabin concepts within the overall aircraft design process. This allows to create multidisciplinary optimization problem. Hence, overall optimum will be compared in terms performance, payload capacity, and fuel burn and operation costs.
The final usable floor area is of high importance for the assessment of the BWB. Only with a optimum number of seats the BWB will have sufficient performance advantage over conventional aircraft.

[1] These comparisons ignore the span of VELA 2 and DLR-LY-BWB configures, which exceeds the 80 meter box. But it shows the potential of MOB configuration which is inside the 80 meter box is also high.

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