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# DESIGN TRADES FOR A LARGE BLENDED-WING-BODY FREIGHTER

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## Abstract

An advanced design study examined the capabilities of a large Blended-Wing-Body (BWB) freighter. Reductions in the cost of transporting freight were sought from cutting the time to transfer between air and ground transport modes through use of intermodal containers, capturing efficiencies of scale by configuring an aircraft to carry a maximum number of containers, and capitalizing on natural efficiencies of BWB configurations. The large size of intermodal containers, set by efficiency considerations for the truck transport mode, presented some challenges in determining the most efficient way to carry large numbers of containers in the BWB. Several BWB freighter configurations with different arrangements for carrying containers were analyzed and optimized with the Wing Multidisciplinary Optimization Design (WingMOD) code. Airport pavement loading and 80-meter box constraints ultimately limited the size of the BWB freighter. Measuring efficiency as the weight of freight carried divided by aircraft takeoff weight, a large, dedicated BWB freighter was shown to offer significant improvements in efficiency that could be used to develop new opportunities for the air cargo business.

## Introduction

The Blended-Wing-Body (BWB) concept has been studied for its potential to provide improved efficiency for commercial passenger and military operations (Refs. 1-2). Weight and fuel burn reductions provided by the BWB lead to lower operating cost. The same efficiency improvements could be used for reducing the cost of airborne freight delivery. Since approximately 1% of transoceanic freight is currently carried by air, significant reductions in airborne freight costs could allow aircraft to compete against ships for a portion of the remaining 99% of the shipping market, opening a very large market for freighter aircraft (Ref. 3).

Since airborne transport is only part of the system for shipping freight, maximizing cost reductions requires consideration of the other pieces, particularly the cost of ground transport and the cost of transferring freight between air and ground modes. To become competitive with ship-borne freight, it is necessary to emulate the capability provided by International Organization for Standardization (ISO) standard containers, which are carried on both ships and trucks and can be transferred as a unit between modes. Current containers for air cargo are not suited for efficient truck transport, meaning the airborne freight is typically unloaded from air cargo containers and repacked into ground transport containers. While the size and weight of ISO containers are too large to be efficient for use on aircraft, a lighter and somewhat smaller container could be efficient for truck transport and still be accommodated on aircraft. By designing the aircraft to carry these intermodal containers, significant cost savings can be achieved from avoiding the transfer between air and ground containers.

Since larger aircraft tend to be more efficient, the greatest cost reduction should come from a very large freighter. This size-driven efficiency should reduce the fuel burned per pound of cargo delivered. It should also reduce aircraft takeoff weight per pound of cargo. In addition, costs that are fixed per trip get distributed over a larger payload. Costs that are fixed per trip or driven by weight, such as crew pay and landing fees, get better per pound of cargo as an aircraft gets bigger to accommodate increased payload.

By using intermodal containers, carrying many containers on a very large aircraft, and exploiting the efficiency of the BWB, large reductions in cost for airborne freight should be possible. To explore this potential, a study was conducted by Boeing Phantom Works to configure and evaluate the performance of a large BWB freighter capable of carrying intermodal containers.

This study first looked at different arrangements for carrying large numbers of intermodal containers on the

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BWB. The Wing Multidisciplinary Optimization Design (WingMOD) code was used to optimize several BWB configurations, each designed around the dimensions needed to enclose and carry a different cargo arrangement. By determining the best performance possible with each cargo arrangement, WingMOD would provide very useful information for selecting the best cargo arrangement for reducing cost.

During the study, efficiency was used to indicate differences in cost between configurations. Here, productivity is defined as the payload weight times the design range times the aircraft Mach number. Efficiency is defined as the productivity divided by the aircraft takeoff weight. An aircraft is more productive if it can carry more payload farther and faster. It is more efficient if it can be as productive with a lower takeoff weight. Since cost correlates strongly with takeoff weight, efficiency approximates how much payload can be sent a given distance for a given cost.

Using efficiency as the metric for comparison, a freighter configuration was selected from the WingMOD study and was examined in greater detail to verify its airport compatibility and its ability to load intermodal containers. The resulting BWB freighter appears to be viable while providing significant improvements in efficiency over existing freighters.

## Approach

### Requirements

To perform the study, notional requirements were developed for intermodal container carriage, airport compatibility, and performance. These requirements would guide the aircraft configuration to a fairly realistic and practical freighter design.

The freighter was designed to carry a maximum number of intermodal containers. These containers were dimensioned to be practical and efficient for truck transport so that the entire container could be transferred from aircraft to truck, avoiding the ground handling cost of unpacking and re-packing the cargo. The containers were 96 in wide, 156 in long, and 108 in tall. These dimensions were roughly optimized for ground transport with some consideration for airplane carriage. The width is the same as existing ISO containers. The length is shorter than ISO containers, a feature that allows the intermodal container to fit through aircraft cargo doors. The height is greater than ISO containers, which recovers some of the volume lost by the reduced length while still allowing the container to fit under highway overpasses during truck transport.

While the freighter was designed to carry as many containers as possible to reduce cost through economies of scale, it was required to operate out of existing airports. The possibility of operating the freighter from a few airfields dedicated to the low-cost freight operation was considered. To achieve reduced-cost freight service, it made sense to operate out of low-utilization remote airfields instead of high-utilization airports serving urban areas, especially when trucks would be used to move the freight over moderately long distances to its final destination. These remote airfields could be designed specifically to handle the freighter, allowing the aircraft to be sized to carry more containers. One consideration that drove the requirement to fit existing airports was the potential to sell additional aircraft for freight and commercial service, which could lower the cost of producing the freighters. Another consideration was that retaining compatibility with existing airports also provides options for alternate landing sites for emergency situations and weather. For compatibility with Group VI airports, a wing span less than 80 meters was required. The freighter weight was also constrained under 1.3 million pounds, a weight similar to an A-380 freighter, to satisfy pavement loading requirements.

To fit typical air cargo operations, it was desired that this new freighter be able to complete a 4,200 nm round trip in 24 hours. This capability enables an operator to provide daily service in both directions with a single airplane, reducing the required fleet size. It allows the airplane to be based in a single location, reducing basing cost. It also simplifies crew scheduling and reduces flying time to reduce crew cost. To achieve the 24 hour, 4,200 nm round trip, study requirements were set for a 0.85 Mach aircraft with sufficient doors to minimize the turn time from loading and unloading containers.

### Blended-Wing-Body Efficiency

Based on efficiency shown in previous studies (Refs. 1-2), a BWB configuration was studied as a way to meet the low cost freighter requirements. Aerodynamically, the BWB has less wetted area than a conventional configuration, resulting in reduced drag (Fig. 1). Structurally, the BWB benefits from being more span-loaded than conventional configurations, with weight distributed along the wing where it cancels lift to reduce the bending loads that increase structural weight (Fig. 1). The BWB takes a structural penalty for carrying pressure loads with a flat-sided pressure vessel, but it benefits from having the fuselage pressure vessel integrated with the wing box such that it carries wing bending in addition to pressure loads. The depth provided by the fuselage makes it efficient for carrying wing-bending loads and the fuselage weight increase for the flat-sided pressure vessel is offset by a reduction in wing weight. The result of these aerodynamic and structural benefits is a BWB configuration that is

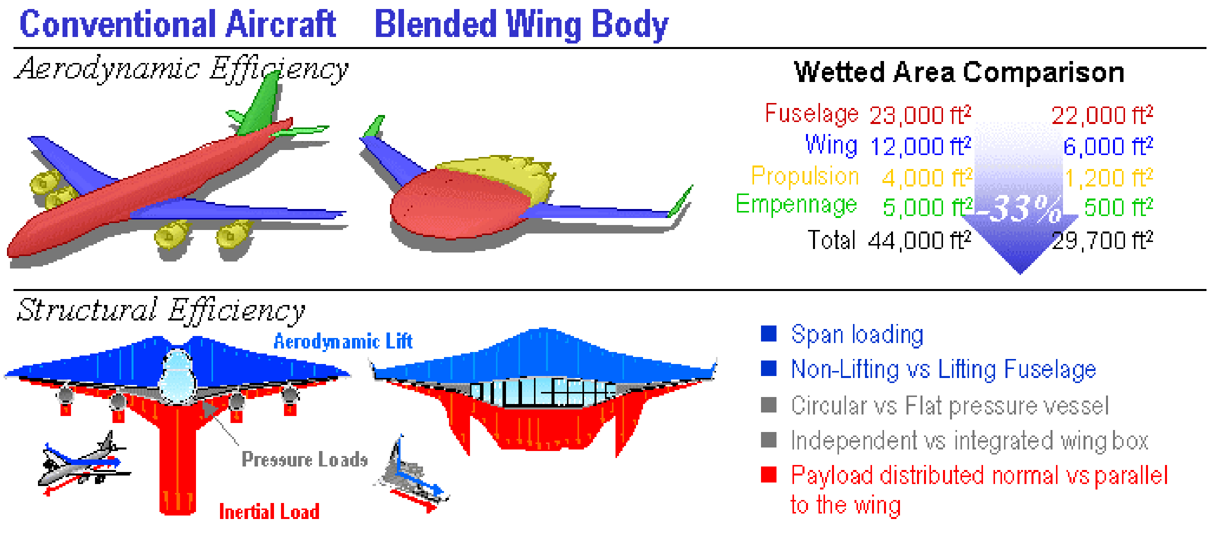



**Fig. 1 BWB aerodynamic and structural efficiency.**

lighter and more fuel-efficient than a conventional configuration with equivalent payload-range capability.

While the BWB efficiency advantage is attractive, the technology for the flying-wing control system and low-cost composites that enable the concept require additional development. This study explored what capabilities the BWB could provide once those technologies are developed.

## Optimization Method

To rapidly explore the design space for these large BWB freighters, the WingMOD configuration optimization tool was used. WingMOD is a tool for optimizing transport aircraft wings and tails that has been extended to optimize aspects covering most of a BWB configuration (Refs. 4-7). WingMOD typically minimizes takeoff weight through optimizing wing planform shape and other characteristics while observing hundreds of constraints evaluated from analysis of dozens of design conditions. During an optimization, wing chord and thickness are sized to wrap around the payload. Chord lengths along the span are set by trades between reducing area for reduced drag and increasing area for low-speed lift requirements. Trades between drag and structural weight set outer wing twist and thickness. The configuration is trimmed by adjusting control surface deflections through all flight conditions. Balance is assessed and the distribution of wing fuel is optimized to manage the center of gravity. Conditions where control power is critical are evaluated to determine the stability limits. The result of the optimization is an aircraft configuration that meets many real constraints that are not usually captured in conceptual design. Thus, the resulting configuration can be considered a closed design. The ability of the WingMOD optimizer to handle many design variables allows it to push the configuration up against many constraints to achieve the lowest weight solution.

## Results

### Cargo Arrangement

Since packaging the largest number of containers in the freighter would lead to the highest efficiency, initial studies focused on finding the best arrangement of intermodal containers. Options for laying out the cross section of the cargo bay were studied first. These options are depicted in. The cross section used for a passenger-carrying BWB is too short to carry intermodal containers. Carrying containers with the long side running fore and aft creates the tightest-fitting cross section. This arrangement results in 106 inches between rib centers, with 2 inches of space on the sides of the container and 6-inch thick ribs, including structure and coverings. Placing the intermodal container with the long side going across the cargo bay results in a 116-inch wide bay with 2 inches of clearance around the container.

The diagonal Y-bracings at the upper corners of the cargo bay shorten the distance that the upper skin panel must carry pressurization loads, reducing bending moments on the panel. On the passenger version, the nominal unsupported span between Y-braces is 77 inches. This span was maintained in the container-carrying variants by adjusting the skin panel position relative to the braces while moving the braces upward to clear the containers. With the long side of the container running fore and aft, the cargo bay is narrower than the passenger version, allowing short braces to produce the required unsupported span. With

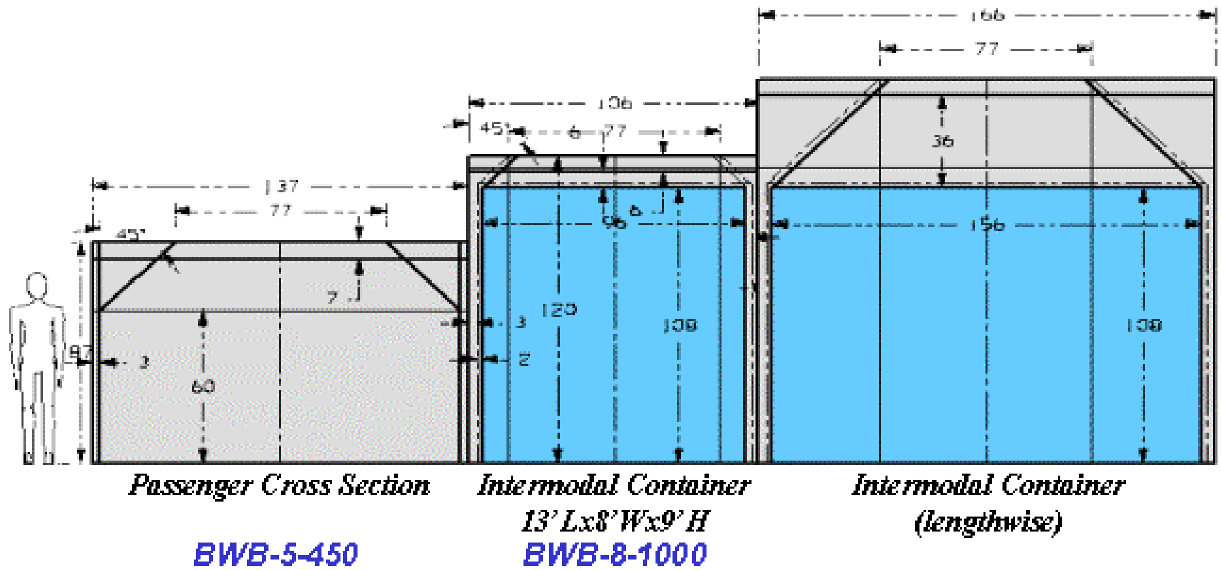



**Fig. 2 BWB freighter cross-sections.**

the long side of the container running sideways across the bay, long braces are needed to produce the required unsupported span. The longer braces create a significant amount of unused space above the container. The increase in body thickness due to the unused space was expected to have adverse effects on aerodynamic performance. Orienting the containers with the long side running longitudinally resulted in very little empty space, so that orientation was selected.

After selecting the cargo bay cross-section, trade studies were performed on the arrangement of cargo containers. Since the BWB external geometry results from wrapping the cargo, varying cargo arrangement was expected to result in significant performance differences. Several BWB configurations were optimized for different cargo arrangements using WingMOD. The productivity and efficiency of these configurations were compared.

Fig. 3 shows the results of the cargo arrangement study. Different cargo arrangements are sketched with the number of intermodal containers carried by each arrangement indicated next to each sketch. A large BWB designed for passenger use and modified to accommodate intermodal containers carries 18 intermodal containers plus 28 special containers packed into the rear and the very front. These special containers are 96 in wide, 125 in long, and 80 in tall. They have the same footprint as AMJ containers used on MD-11 freighters but are shorter. While such an airplane would benefit from commonality with the passenger variant, the number of intermodal containers it carries is relatively low. Two configurations designed for 44 and 50 intermodal containers on a single deck are more productive and efficient than the passenger derivative freighter. Putting intermodal containers on two decks can produce more efficient and productive configurations, with the lower deck containers located around the middle of the cargo bay. The configurations with 46, 58, and 68 containers trended toward increasing efficiency with increasing payload. The configurations with 64 and 70 containers looked at variations in planform geometry. The 64-container configuration looked at increased leading edge sweep in the cargo bay; the 70-container configuration looked at lengthening the cargo bay. Both of these variations did worse than the trend set by the other double-deck configurations. The double-deck 58- and 68-container arrangements had the best efficiency and were selected for additional study. While the 68-container freighter had the highest efficiency at this point, it was slightly over the 1.3 million pound limit chosen to ensure airport pavement loading compatibility, so the 58-container freighter was carried along as a risk-reducing alternative.

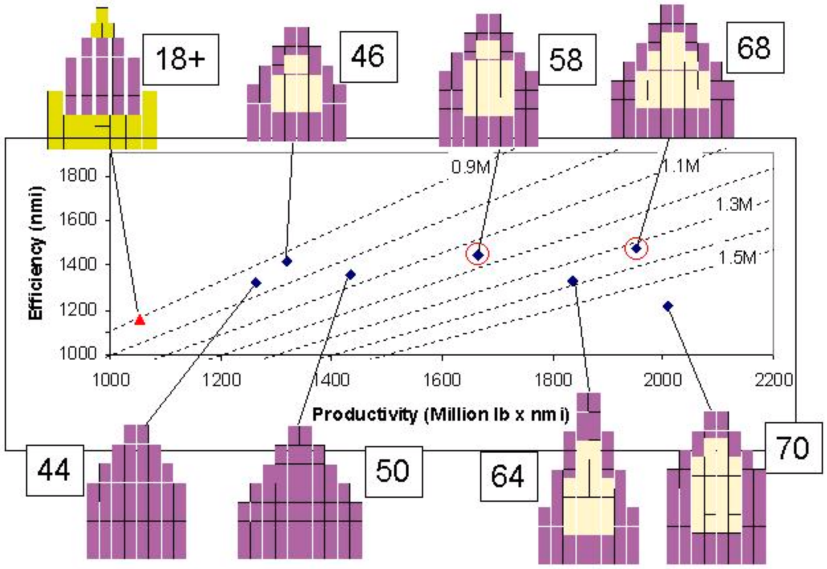



**Fig. 3 Cargo arrangement trade study.**

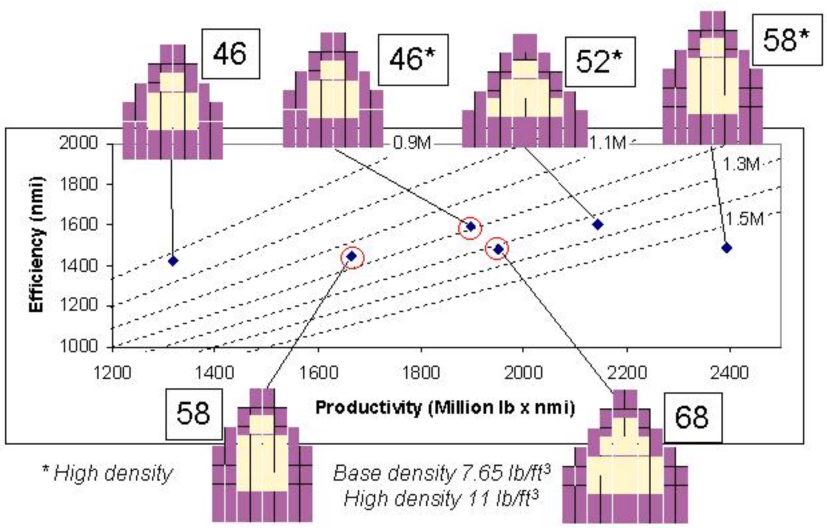



**Fig. 4 Cargo density trade study.**

**Cargo Density**

It was observed that the containers were adding a lot of volume and wetted area to the aircraft and that packing containers more densely would reduce the volume needed and restore some aerodynamic efficiency. It was further noted that pursuing ship-borne freight was likely to result in higher-density payloads than typically carried by air. To examine this effect, higher-density payloads were studied, with densities of 11 lb/ft$^3$ instead of the 7.65 lb/ft$^3$ baselined in the study. These configurations are shown in Fig. 4 compared with the best configurations with 7.65-lb/ft$^3$ density. While the high-density configurations with 52 and 58 containers exceeded the 1.3 million pound limit, the high-density 46-container configuration was under the limit and had the best efficiency. The 58-container high-density configuration actually had worse efficiency than the high-density 46-container configuration, probably because limitations on parameters such as span were hurting performance at these high weights. These results suggest some attention should be paid to getting the correct cargo density: underestimating the density would result in an aircraft that is penalized by being unable to fully use its volume. The high-density 46-container configuration was carried along with the basic 58- and 68-container configurations for additional study.

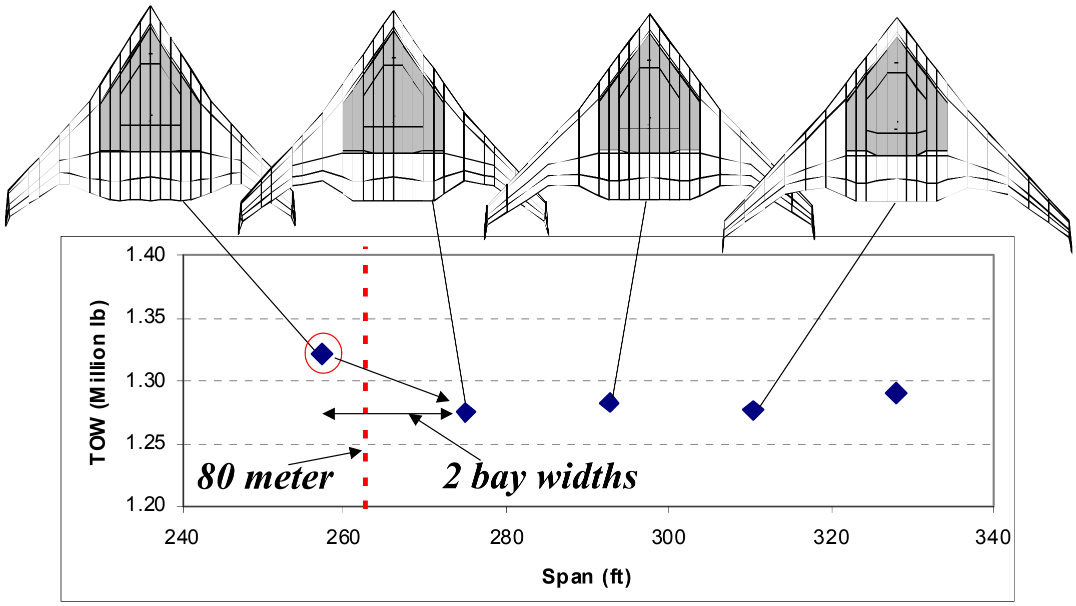



**Fig. 5 Span trade study.**

## Span

Although the 68-container freighter was essentially at the 80-meter span limit, a study was conducted to see what improvement could be gained by exceeding the limit. Fig. 5 shows the result of optimizing configurations for increasing span. An improvement is seen for just exceeding the span limit. Further increases in span do not yield additional improvement. This result suggests the aircraft is nearly at its optimal span and that the small penalty for staying within the 80-meter limit is probably worth the benefits of greater operational flexibility.

## Refined Configurations

From the initial studies, three container arrangements were selected based on their high efficiency and ability to meet the airport compatibility weight limit. The initial studies also led to a decision to keep span within the 80-meter box, based on the small weight penalty being worth the operational flexibility.

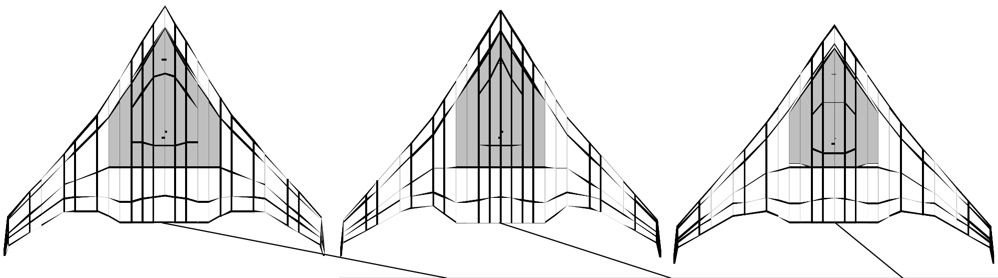
During the initial studies, it was observed that allowing the gear to move further aft relative to the aft limit could improve the designs. This degree of freedom was added to the optimization procedure and the three selected configurations were re-optimized. The refined configurations appear in Fig. 6.

Each configuration was optimized to a range of 5,000 nm at its design payload. While 4,200-nm range is more typically flown for air cargo, 5,000 nm provides flexibility to fly further or to make 4,200 nm with increased cargo density. Each aircraft was constrained to an approach speed no greater than 150 kn at its maximum payload. Basic payload densities for the 68- and 58-container configurations were 7.65 lb/ft$^3$ for the design mission and 9 lb/ft$^3$ for the maximum payload mission. The payload densities for the high-density 46-container configuration were 11 lb/ft$^3$ for the design mission and 12 lb/ft$^3$ for the maximum payload mission. While the 10-bay, 68-container configuration exceeded the 1.3 million pound limit in the initial study, it ended up within the limit after refinement.

Fig. 7 compares the efficiency of the three configurations as a function of payload density. For configurations compared at the same range and Mach number, productivity is proportional to the payload weight carried and efficiency is proportional to payload weight divided by takeoff weight.

Design points at 5,000 nm are shown in open symbols. The high-density 46-container configuration has the highest efficiency of the design points.

The variation in efficiency with payload density at 4,200 nm is shown with the solid symbols and lines. The 58- and 68-container configurations do not make 4,200 nm with maximum payload density. The 58-container configuration can carry 8.70 lb/ft$^3$ at 4,200 nm; the 68-container configuration can carry 8.66 lb/ft$^3$. The aircraft are more efficient at the higher densities. The 46-container high-density configuration can fly 4,200 nm at its maximum payload density of 12 lb/ft$^3$. The 46-container configuration has better efficiency at high density than the 58- and 68-container configurations; however, it has worse efficiency at the basic 7.65 lb/ft$^3$ density.



| | 10 Bay | 8 Bay | 8 Bay High Density |
|---|---|---|---|
| TOW (lb) | 1,253,000 | 1,106,000 | 1,120,000 |
| OEW (lb) | 492,000 | 449,000 | 418,000 |
| Design Payload (lb) | 390,000 | 333,000 | 379,500 |
| Max Payload (lb) | 459,000 | 391,500 | 414,000 |
| Des./Max Density (lb/ft$^3$) | 7.65 / 9.00 | 7.65 / 9.00 | 11.00 / 12.00 |
| Containers | 68 | 58 | 46 |

**Fig. 6 Refined cargo and density trade configurations.**

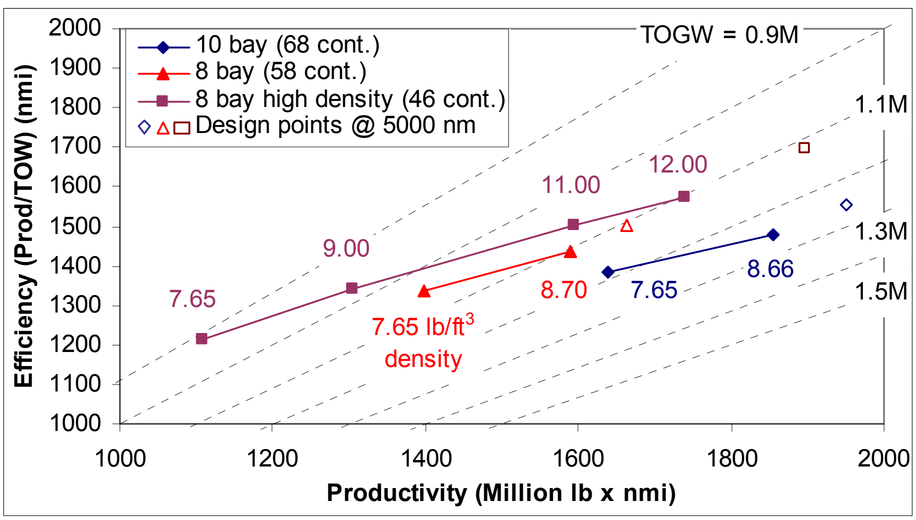



**Fig. 7 Fixed-planform cargo density trades at 4,200 nm range.**

While the 46-container configuration offers the flexibility of carrying denser payloads and the potential for more efficiency at high density, it was decided that getting the best efficiency at the basic density was more important. The 68-container configuration was selected for further study based on having the highest efficiency at the 7.65-lb/ft$^3$ density.

**Final Configuration**

Following its development in WingMOD, the 10-bay, 68-container configuration was modeled in the Unigraphics computer aided design (CAD) program. This step would help verify the container capacity and the ability to load the containers in the aircraft.

The resulting aircraft is shown in Fig. 8. This freighter, named the BWB-8-1000, has a main deck that spans 10 cargo bays. The six center-bays are deep enough for a lower deck capable of carrying intermodal containers. The freighter accommodates 50 intermodal containers on the main deck and 18 on the lower deck.

An interior arrangement of the freighter is shown in Fig. 9. Cargo door openings are shown and a method for loading containers on the upper deck is indicated. Containers would pass through openings in the structural ribs to move between bays.

The concept for loading containers is illustrated in Fig. 10. The interface with cargo loaders is shown. The flow of containers into the main deck bays is indicated with the arrows.

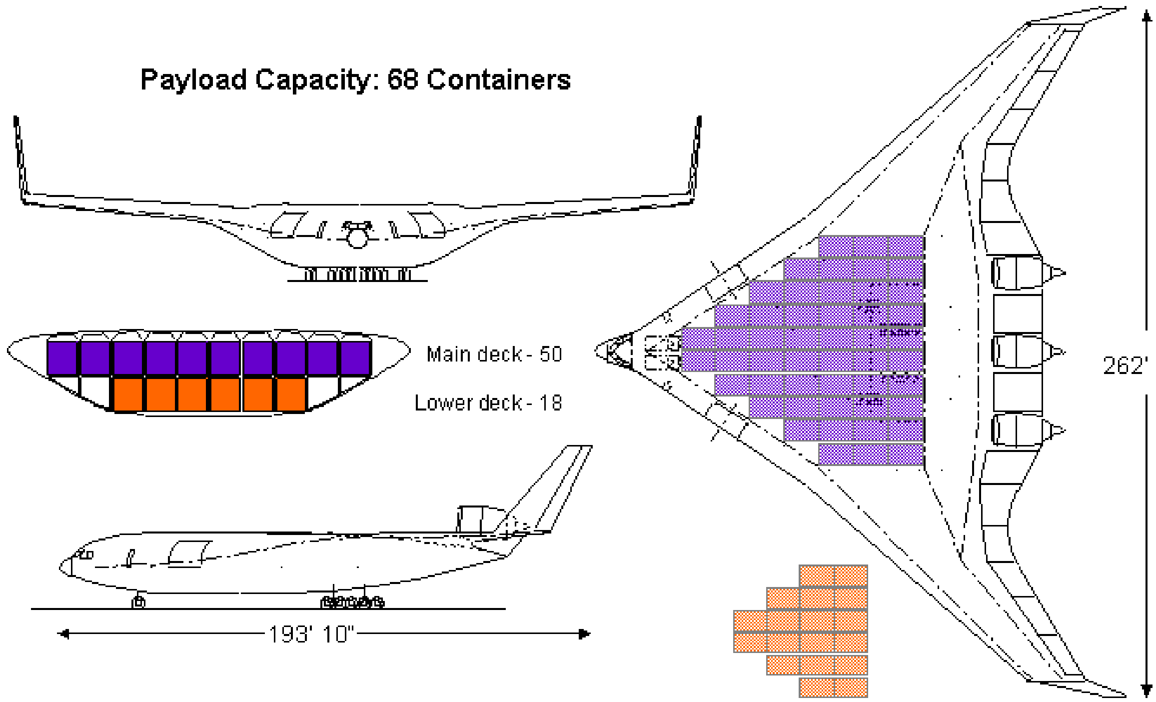



**Fig. 8 BWB-8-1000 large freighter concept.**

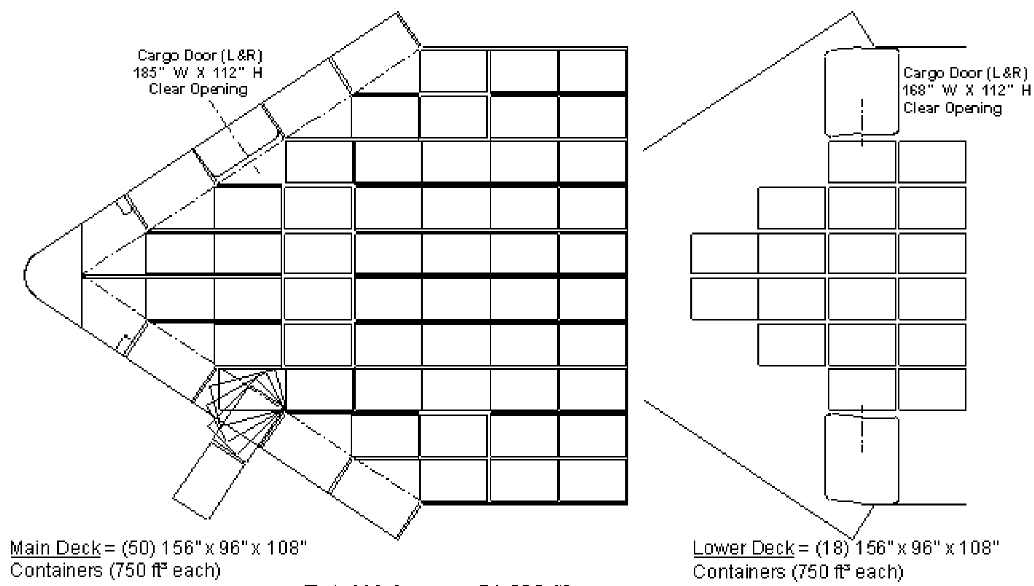



**Fig. 9 BWB-8-1000 freighter interior arrangement.**

The BWB-8-1000 performance was analyzed with the Computer Aided Sizing and Evaluation System (CASES). The payload-range capability of the BWB-8-1000 is shown in Fig. 11. The more-detailed CASES evaluation resulted in a higher takeoff weight than predicted in WingMOD. Although this weight was slightly over the 1.3 million pound limit set for this study, it was considered close enough that a solution

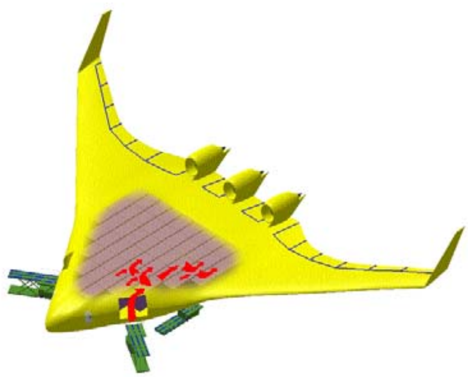


**Fig. 10 Payload loading.**

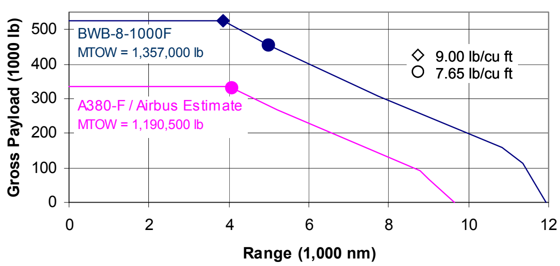


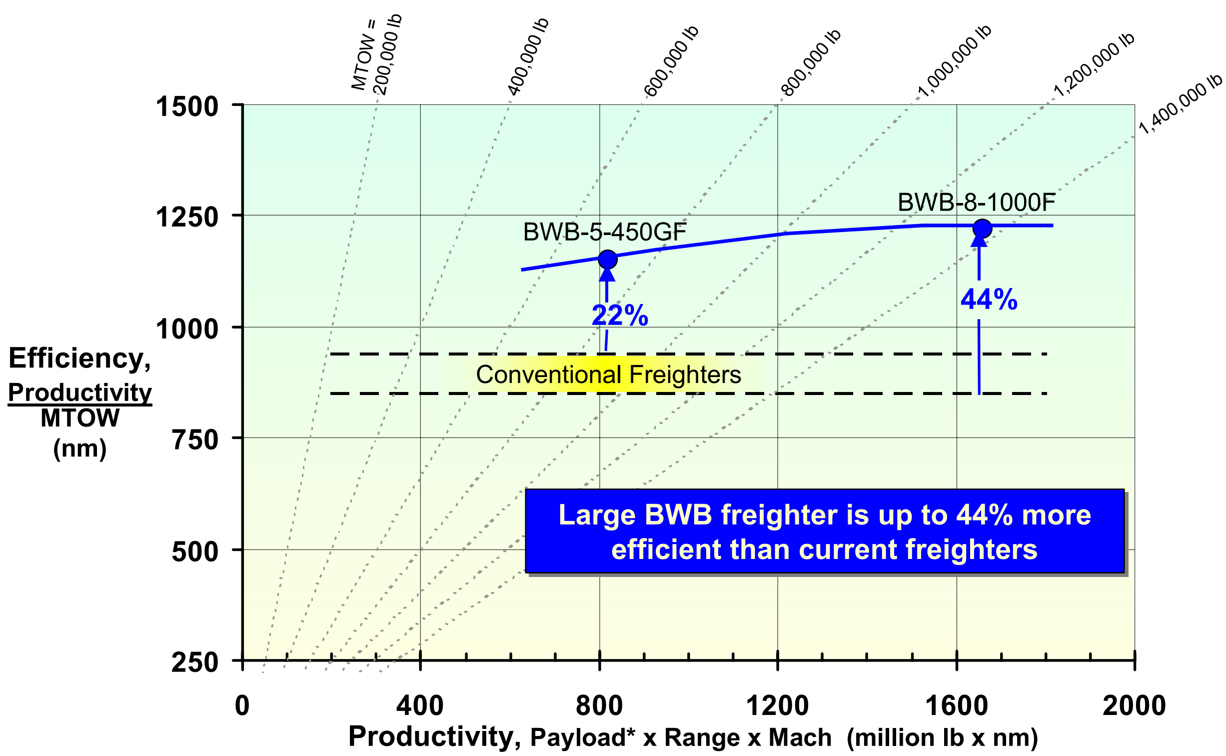

**Fig. 11 Payload-range capability.**

for pavement loading would be worked out. The payload-range for an A-380 freighter is shown for comparison. The increase in payload and range offered by the BWB is apparent in the figure. The A-380 cannot actually carry the intermodal containers accommodated by this BWB, and its payload-range shown in the figure is based on more conventional air cargo containers. The BWB also offers the capability to load up with denser cargo than the A-380.

The efficiency and productivity of the BWB-8-1000 is plotted in Fig. 12. Compared against existing large freighters, the BWB-8-1000 is up to 44% more efficient. This efficiency gain can help reduce cost, but achieving maximum cost reductions is dependent on combining this efficiency with productivity gains from increased payload capacity and ground handling reductions from carrying intermodal containers. These improvements are captured in the large BWB freighter and open the potential for expanding the market for airborne freight.

## Conclusion

A study was conducted to design a BWB freighter to achieve significant efficiency improvements aimed at reducing the cost of delivering airborne freight. A BWB freighter design was developed to carry a large number of intermodal containers. This design was ultimately limited by airport compatibility considerations, with a span near the 80-meter limit and a maximum takeoff weight around 1.3 million pounds to allow acceptable pavement loading. The efficiency




*All payload density = 7.65 lb/cu ft

**Fig. 12 Freighter efficiency versus productivity.**

of large freighters was shown to increase with the number of containers carried as well as with the density of payload. The large BWB freighter has more payload capacity than current freighters and is up to 44% more efficient than existing large freighters. The improvements shown in productivity and efficiency, coupled with the time-savings from carrying intermodal containers creates potential for significant reductions in the cost of delivering airborne freight. These cost reductions could open new markets for airborne freight, but additional study is required to quantify these potential gains. This study explored the potential gains from a large BWB freighter. Additional development of the BWB concept and technology will be needed to turn this potential into a reality.


## Acknowledgement

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