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CONFIGURATIONS OF LARGE TRANSPORT AIRCRAFT: PROSPECT AND PROBLEMS

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Abstract– This paper discusses about problems of possible development of dedicated, high capacity, large civilian freighter aircraft. The main disadvantages of currently operating air transport are discussed. The flight performance of proposed dedicated cargo aircraft with 120 tonnes payload capacity is compared with existing converted freighter aircrafts Boeing 747-200F and Antonov 124 (Ruslan). A wide range of values of payload and flight range are studied to get the better results from parametric research. An assessment of flight performance and economical features are evaluated by three criteria: weight efficiency, fuel efficiency and transportation cost.

Key words– aircraft, freighter, cargo transportation, fuel efficiency.

I INTRODUCTION

The share of cargo transport using aircraft is growing steadily over the last decade of years throughout the world. Currently, the total amount of air transportation exceeds 250 billion tonnes per year (fig. 1). The rate of growth of cargo transportation over the past ten years increased on average by 4.3% annually [1].

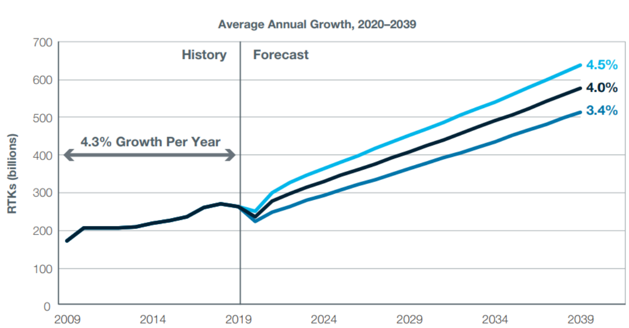


Fig. 1: World Air Cargo Traffic 2009-2039 [1]

In addition to the long-term trend of dedicated freighters carrying more than 50% of global air cargo traffic de-

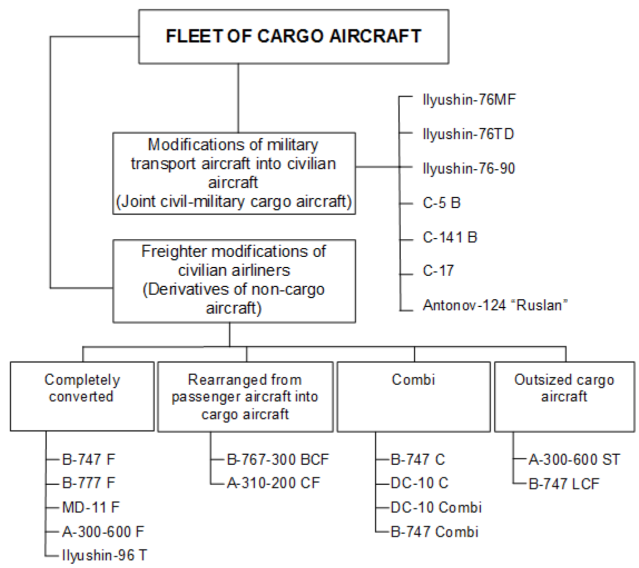


Fig. 2: Fleet of cargo aircraft

spite growing wide-body passenger fleets, the COVID-19 pandemic has highlighted the importance of main-deck freighters in our global air transportation system [1]. While increasingly capable passenger widebody airplanes have helped the air cargo industry grow during the past decade, dedicated freighters are anticipated to continue to comprise at least 50% of the world air cargo traffic carried.

There are several key reasons for freighter preference in air cargo flows: 1) most passenger belly capacity does not serve key cargo trade routes; 2) twin-aisle passenger schedules often do not meet shipper timing needs; 3) freight forwarders prefer palletized capacity, which is not available on single aisle aircraft; 4) passenger bellies cannot serve hazardous materials and project cargo, a key sector in air cargo flows; and 5) payload-range considerations on passenger airplanes may limit cargo carriage, which decreases the likelihood that cargo will arrive at its destination on time.

According to the forecasts from the leading airplane manufacturers Boeing and Airbus Industry the annual growth rate of cargo air transport will be not less than 4.1% in the next 20 years. Picture 1 shows that world air cargo traffic may increase more than two times during the next 20 years [1].

Currently more than half of the air transportation work is carried out with almost 2000 freighter modifications of long-haul passenger aircrafts. The second half performs in the cargo compartments of conventional passenger jets. Most aircrafts are not initially designed as a freighter and converted from passenger airliner jets into freighter aircraft by rearrangement and uninstallation of equipment in the passenger compartment (fig. 2, 3). More than 1000 aircrafts are completely converted for cargo transportation such wide-body airplanes as: B-747F, A-300F, MD-11F, A-330F, Ilyushin-96T.

Basically, cargo modifications of airplanes have the same take-off weight and geometrical shape to keep same flight performance equally to conventional passenger airplane. However, in this case the cargo compartment of cargo airplanes become extremely oversized comparing to its payload capacity. For instance, the maximum payload of a B-747-400F equals 122 t, the volume of the cargo compartment is 1002 m^3. In other words, available volume to carry 1 t of freight is 9 m^3. However, analysis of statistical data shows that the maximum capacity for transportation of 1 t of freight needed less than 6 m^3. This means that the relation of ‘cargo compartment capacity and necessary volume for carrying given payload is 30% larger than needed. In addition, if we consider the volume of the external contour of the fuselage (which is equal to 1996 m^3) it is twice as big as the cargo compartment. Therefore the actual necessary capacity for carrying 112 t of freight on the B-747F is only 672 m^3. It is less than 34% volume of the external contour of the fuselage [4, 5]. Inside the cargo compartment of the airliner Ilyushin-96T more than 34 cargo pallets R6 and R2 can be arranged which can total more than 230 t of weight. However the maximum payload carrying ability of this airplane is only 92 t. These examples show us the existence of significant reserves to improve the air cargo transportation efficiency by developing Dedicated Freighter Aircraft (DFA) [6].

In contrast, passenger networks are much broader and often include destinations where cargo demand is minimal. This difference in passenger and cargo traffic distribution explains the considerable load factor difference in belly space and freighters, which average approximately 30% and 75%, respectively over the last decade. In addition, range restrictions on fully loaded passenger aircraft and limited passenger service to major cargo airports make freighter operations essential. For these structural reasons, freighters are forecast to carry more than half of the world’s air cargo for the next 20 years [1].

The main purpose of design of any transport including the airplane is increasing the fraction of the payload in the total weight balance. It is obvious that any kind of machine must do as much useful work as possible while it is as small as possible. The main principle of transport vehicle design is a minimization of its structural mass.

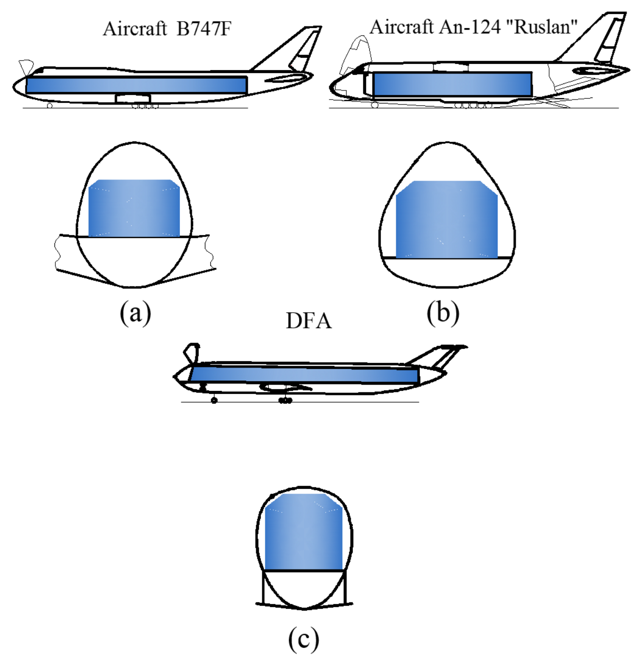


Fig. 3: The cargo compartments of various transport aircrafts: (a) converted, (b) modification of military into civilian (c) DFA

Much research has been done relatively to the flying-wing (FW) configuration [2, 3] but most have disadvantages in stability and implementation into real life comparing to conventional configurations. This paper presents an assessment of the flight performance and the economical features estimation for proposed dedicated freighter aircraft. A wide range of values of payload and flight range are studied to get the better results from parametrical research.

The remaining sections in this paper are organized as follows. In section 2 a comparison of flight and economic performances of existing cargo aircrafts with dedicated freighters are studied. Section 3 introduces about the parametric research of cargo aircrafts. Section 4 shows novel design concepts of aircraft structure. Finally, a conclusion with discussion is given in section 5.

II Dedicated Freighter Aircrafts

The proposed configurations of the dedicated (universal and specialized) freighter is an aircraft which has been designed from the beginning as a freighter, with no restrictions caused by either passenger or military requirements and belongs to the absolutely new class of air vehicle with new design (fig. 3-c).

Let's look at the example of DFA. The airplane designed for a maximum payload of 120 *t*, an estimated flight range is 6000 *km*. In this design an original decision is applied to the airplane's fuselage. An originality of the fuselage is the location of the flight deck. It is in the lower part of the nose.

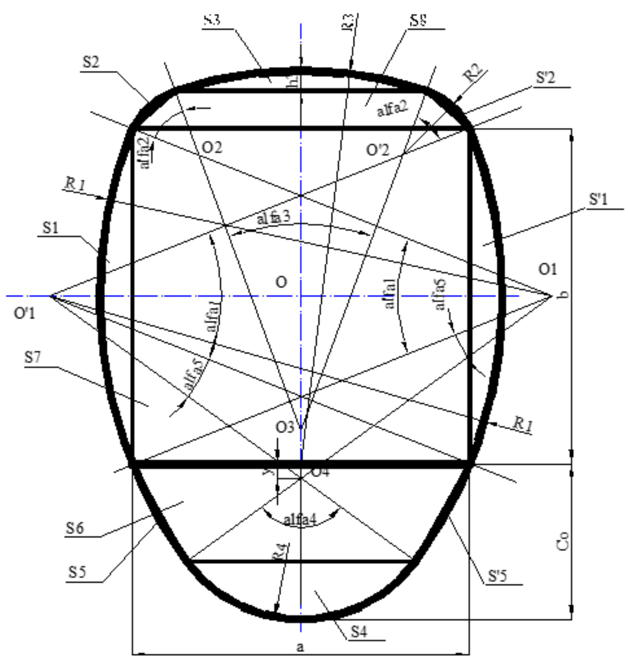
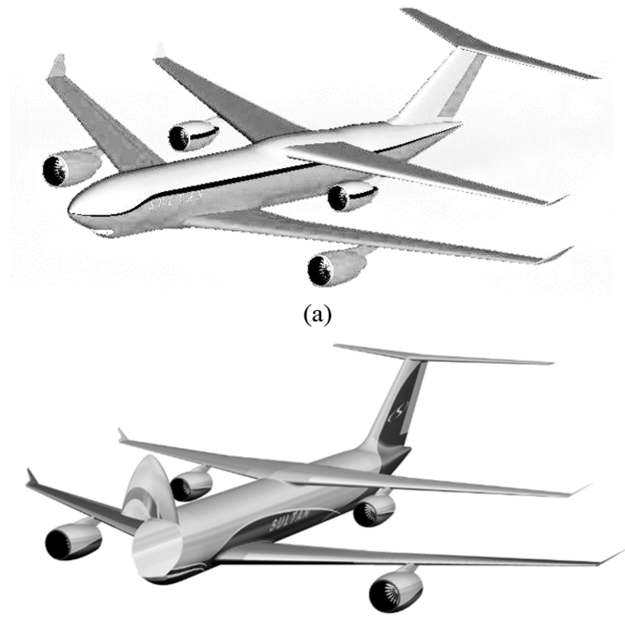


Fig. 4: DFA fuselage cross section

The volume of the cargo compartment (720 m^3) defined as with consideration of relation coefficient of freight density $\mu_{freight}$ equally to 6 m^3/t [7, 8]. The fuselage cross section (fig. 4) is generated with the multiple arc curves and designed as much possible to reduce the empty volume around the containers.

The location of main door for cargo compartment is in the nose part and it opens to upper side (fig 5). Cargo compartment is structurally designed as a regular construction without cutouts on lateral direction of the fuselage. The floor of cargo compartment has a double function. It receives loads from the payload and at the same time carries longitudinal stress from the bending moment which is distributed along the fuselage. The landing gear consist from multiple axle bogies (fig. 6).



(a)

(b)

Fig. 5: DFA with two wing scheme: (a) flight mode (b) cargo compartment door is open

Fig. 6: Multiple axle bogies in landing gear

The upper panel of the wing center section connects to the structural scheme of the cargo compartment's floor in the joint area of wing and fuselage. Thus the upper panel of the center wing section works under longitudinal as well as lateral stress due to the bending moments of wing and fuselage [7, 8].

TABLE 1: COMPARATIVE PERFORMANCE CHARACTERISTICS OF CARGO AIRPLANES

Parameter description	Symbol	Units	B-747-400F	An-124-100	DFA
Maximum Take of Weight	W_{TOW}	t	396.9	405	375
Maximum Payload	$W_{payload}$	t	112	120	120
Volume of Fuselage by external shape (theoretical contour)	V_{fus}^{ext}	m^3	1996	2597	1072
Cargo compartment Capacity (volume)	V_{cargoc}	m^3	1002	1027	720
Usefulness coefficient of fuselage's volume	k_u^V	%	50	39	67
Weight of fuselage (design estimation)	W_{fus}	t	36.1	50.8	24.2
Fuselage Drag in Cruising mode	D_{fus}	t	10	12	6.2
Fuel consumption for Range R=6000 km	W_{fuel}	t	81	108	68
Fuel efficiency (fuel consumption of 1 $t \times km$)	q_{fuel}	$g/(t \times km)$	120	150	95
Weight efficiency (useful takeoff load ratio)	$W_{payload}/W_{TOW}$	%	28	26	32

On the basis of these technical characteristics we have performed some design calculations to define the airplane performance characteristics. Table 1 presents a comparison of some performance characteristics of the proposed airplane with Boeing-747-400F and Antonov-124-100 'Ruslan'. First of all, we may notice the high percentage of the cargo compartment's capacity compared to the external shape of the fuselage (67%). Therefore estimated mass of the DFA fuselage is twice lighter than the Antonov-124-100 Ruslan's fuselage and 1.5 times lighter than the fuselage of the B-747-400F because of the smaller fuselage size.

An estimation of the fuselage aerodynamic drag in cruising regime is equal for DFA =6.2 t, for B-747-400F is equal 10 t and for Antonov-124-100 'Ruslan' is 12 t. Thus, DFA's fuselage drag is 1.5 2 times less than other prototypes. The notably high weight efficiency at 32% (useful takeoff load ratio) and the high aerodynamic quality makes the DFA considerably advantageous in terms of fuel efficiency.

Generally the definition of the necessary volume of the fuselage's cargo compartment results from volumetric density of the cargo.

For example, the design of a dedicated 'container carrier aircraft' may assume $\mu_{freight}$ = 4.2 m^3/t, an aircraft designed for carrying granular cargo $\mu_{freight}$ =2.0 m^3/t, and the tanker for liquid cargo may assume $\mu_{freight}$ =1.2 m^3/t. Thus the fuselage of the most dedicated freighters will have a smaller geometric size, which permits the enhancement of weight and fuel efficiency.

There are two parameters are widely used in assessment of the transport aircraft performance characteristics:

- Freight tonne-kilometer (FTK): One tonne of cargo carried one kilometer.
- Revenue tonne-kilometer (RTK): One tonne of revenue freight carried one kilometer. Usually used interchangeably with freight tonne-kilometer but can include passenger weight for total revenue

To estimate technical and economic factors of DFA we have performed parametric studies. The scope of the parametrical research covered a payload from 100 t to 250 t and estimated flight ranges (R) from 6000 km to 12000 km.

Two main technical criteria have been considered:

- weight efficiency ($W_{payload}/W_{TOW}$) and
- fuel efficiency $q_{fuel} = (W_{fuel}/FTK)$, $[gram/(tonne \times km)]$ which means fuel consumption of carrying 1 t cargo to 1 km range.

One economic criterion is considered: transportation cost (a), which includes 'cost of flight hour', payload and speed:

$$a = \frac{cost\,of\,flight\,hour}{\varepsilon \times W_{payload} \times V_{average\,speed}} \quad \left[\frac{\$USD}{tonne \times km}\right]$$

where ε is the payload factor, taking into account the average annual partial load of the aircraft average loading factor $\varepsilon \approx 0.6 \div 0.8$.

III Parametric Research

In the parametric research we have considered three types of DFA:

1. **Universal Cargo Aircraft (UCA).** The cargo compartment of this aircraft has payload capacity per unit of $\mu_{freight}$ = 6 m^3/t.
2. **Aircraft for Granular Cargo (AGC).** The cargo compartment of this aircraft has storage with payload capacity per unit of $\mu_{freight}$ = 2 m^3/t.

3. **Tanker for Liquid Cargo (TLC).** The cargo compartment of this airplane has tanks for transportation of liquids with payload capacity per unit of $\mu_{freight} = 1.2$ m^3/t.

The result of the parameter study of UCA is given below.

Fig.7 presents dependency of weight efficiency ($W_{payload}/W_{TOW}$) on payload of the UCA designed for maximum payload ranges of 6000 *km*, 9000 *km* and 12000 *km*. It is noticeable that these relations have maximum in their weight efficiency. For instance, for the aircraft designed for a range of 6000 *km* the maximum weight efficiency is 0.42 when it carries 180 *t* of payload. In other words, by criteria of weight efficiency an optimum performance of UCA estimated with payload 180 *t*. In this case the maximum take-off weight of the aircraft is estimated at 427.8 *t*. For an UCA designed especially for a range of 9000 *km* the maximum weight efficiency of 0.37 corresponds to the aircraft with a maximum payload of 170 *t*, take-off weight of 465 *t*. An UCA designed especially for a range of 12000 *km* obtains its optimum performance with a payload of 160 *t*, weight efficiency of 0.32 and take-off weight of 507.7 *t*. The results for UCA show that for increasing estimated range the optimum shifts to the left side, and payloads of optimum aircraft decrease. The weight efficiency for an increase of range from 6000 *km* to 12000 *km* payload decreases by about 10%.

In general, we may conclude that the optimum UCA for maximum weight efficiency should be specially be designed for a payload between 160 and 180 *tonnes*. Fig. 8 shows dependence of the fuel efficiency (q_{fuel}) on payload $W_{payload}$ for UCAs designed for ranges of 6000 *km*, 9000 *km* and 12000 *km*.

For the airplane designed for a range of 12000 *km* the optimum payload is 200 *t*, for range of 9000 *km* optimum payload is 220 *t* and for range of 6000 *km* optimum payload corresponds to 250 *t*.

Thus, maximum payload value exerts negative influence on fuel efficiency. How estimated distance is larger, the airplane have to be designed for less payload for good performance. Analysis of dependencies reveals following features. Primarily, it seems that to shorter estimated range corresponds higher fuel efficiency of the airplane. However, in reality, the fuel efficiency of UCA designed for flight range of 9000 *km* shows better results than UCA's designed for flight range of 6000 *km*.

Fig. 9 shows the dependency of economic criteria: the transportation cost (a) on payload ($W_{payload}$) for UCA designed for various flight ranges.

According to this result main characteristics of optimal aircraft are:

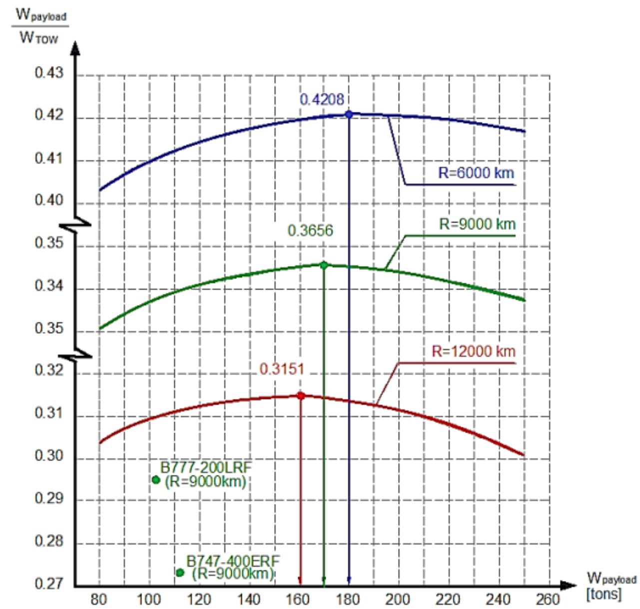


Fig. 7: Dependency of weight efficiency W_E = f ($W_{payload}$, R) on payload for UCA

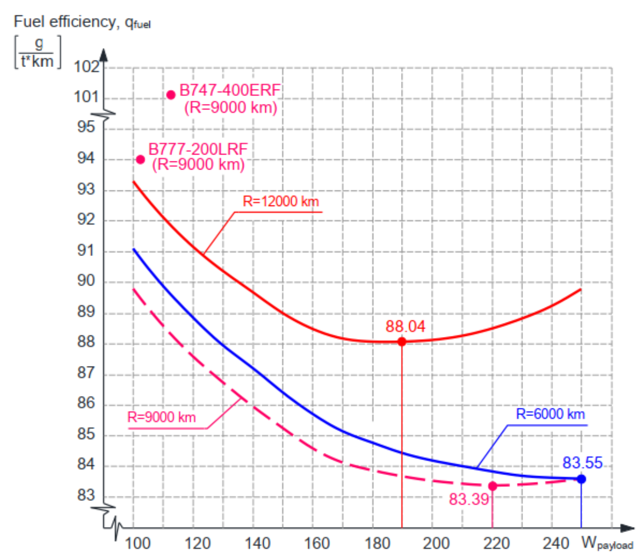


Fig. 8: Dependency of fuel efficiency on payload q_{fuel} = f ($W_{payload}, R$) for UCA

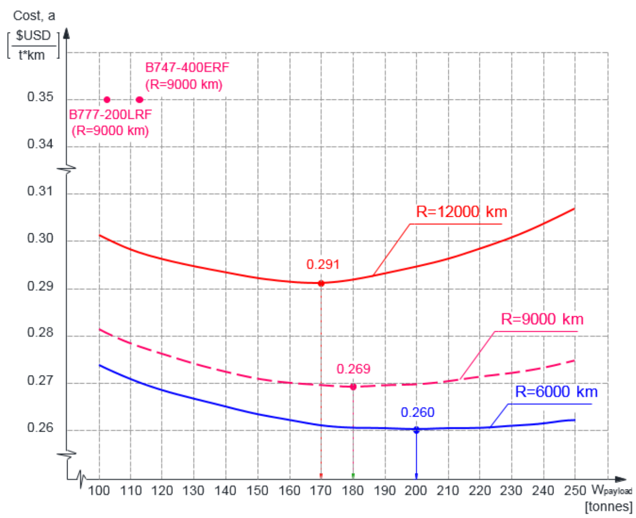


Fig. 9: Dependency of transportation cost on payload a = f (Wpayload, R) for UCA

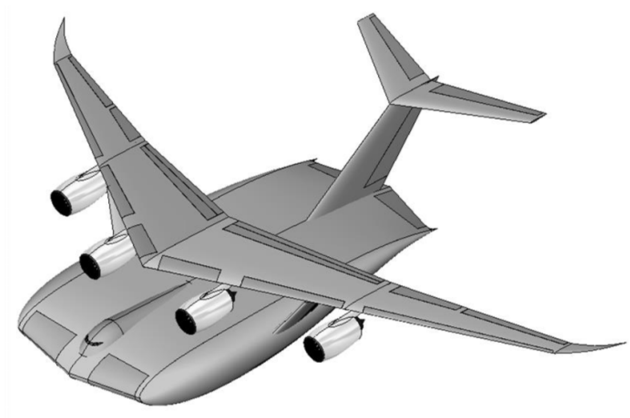


Fig. 10: The hybrid configuration of large cargo aircraft

- with a maximum payload of 200 *t*, takeoff weight 475.8 *t* in estimated flight range of 6000 *km*;
- with a maximum payload of 180 *t*, takeoff weight 492.84 *t*, in estimated flight range of 9000 *km*;
- with a maximum payload of 170 *t*, takeoff weight 540.14 *t*, in estimated flight range of 12000 *km*.

Analysis of these results shows that with the increase of the estimated flight range, the optimal values of the payloads decrease. Additionally, if increase of estimated range from 6000 *km* to 12000 *km* cost of transportation rises from $USD 0.26 to $USD 0.291, i.e. it increases about 12 %.

Similar results were obtained from parametric studies of AGC and TLC projects.

IV Future aircraft schemes

The future aircraft are predicted to set new standards in civil aviation for the next couple of decades. Aviation community is trying to make future aircraft more environmentally friendly, making fewer harmful emissions, being quieter and cheaper. Here are some latest prototypes of future aircraft are shown in fig. 10-12. The hybrid configuration ('Lifting-body configuration') of large cargo aircraft is shown in fig. 10-11. Based on preliminary estimations it is assumed that the aircraft's main specifications defined as Maximum payload of 300 *t*, takeoff weight of 800 *t* in estimated flight range of 12 000 *km*. An originality of this scheme is its fuselage also can generate lift.

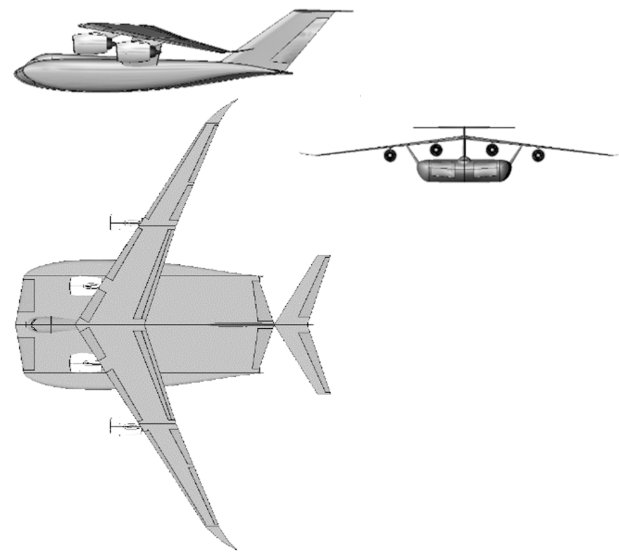


Fig. 11: Three view of the hybrid configuration of large cargo aircraft

The results of studies show [2], that the flying wing can have better results in operating cost than conventional aircraft, especially for large long range transport aircraft. However, the design of a large flying wing transport aircraft can only be successful if one succeeds to find an integrated optimum solution for the key disciplines aerodynamics, flight mechanics and structures. While the problems in the area of aerodynamics and flight mechanics can be solved using existing methods and tools, there still is major work required in the area of structures. Despite the development of several finite element models, mass estimates for this type of aircraft configuration are still hampered by a high degree of uncertainty and more work is required in the future [2].

The Airbus Company engineers are developing a concept which can surely compete with the bravest fantasies of science fiction. The futuristic Airbus concept is following a

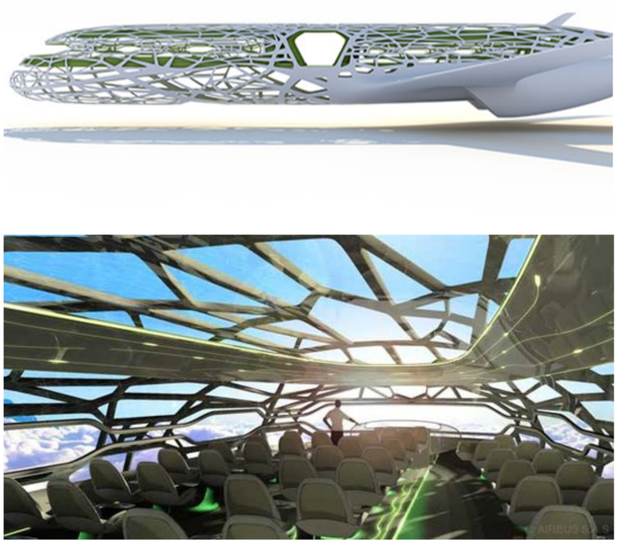


Fig. 12: The fuselage of bionic structure aircraft [9]

“bionic” plane structure (fig. 12). This structure will be based on the properties of a skeleton of the bird [9] and can be 3D printed.

V Conclusions

Advantages and disadvantages of currently operating air transport are discussed. The need for dedicated cargo aircrafts analyzed and studied. The estimation results of the flight performance and the economical features of proposed configuration of DFA are highlighted. The results of parametric study shows that reasonability of further study and development of DFA. The comparative analysis of DFA by three criteria indicates that DFA can have 7-10% better weight efficiency $W_{payload}/W_{TOW}$, 7-13% better fuel efficiency and 20% lower transportation cost than existing cargo modifications of passenger aircrafts Boeing-747-400ERF and Boeing-777-200LRF.

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