Conceptual design of an innovative large PrandtlPlane® freighter

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Foreword

Air cargo represents today a marginal sector of freight transport:

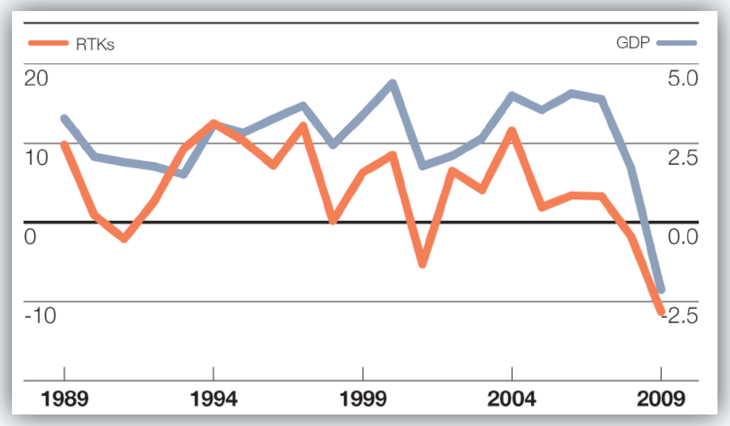
Global Tons: **0.2 %**

Economic flows: **30%**

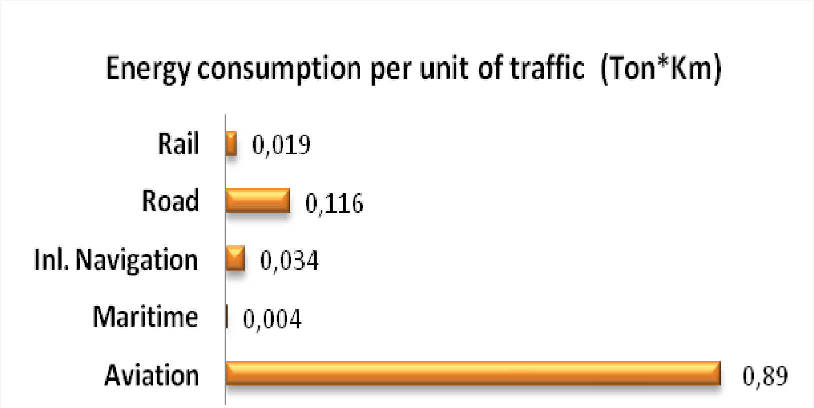
Average value of goods: about **15 $/kg**

High sensitivity to economic activity.

Source: IATA.



The difference between quantity of carried goods and economical flows depends mostly on the very high costs and in particular on the fuel consumed:

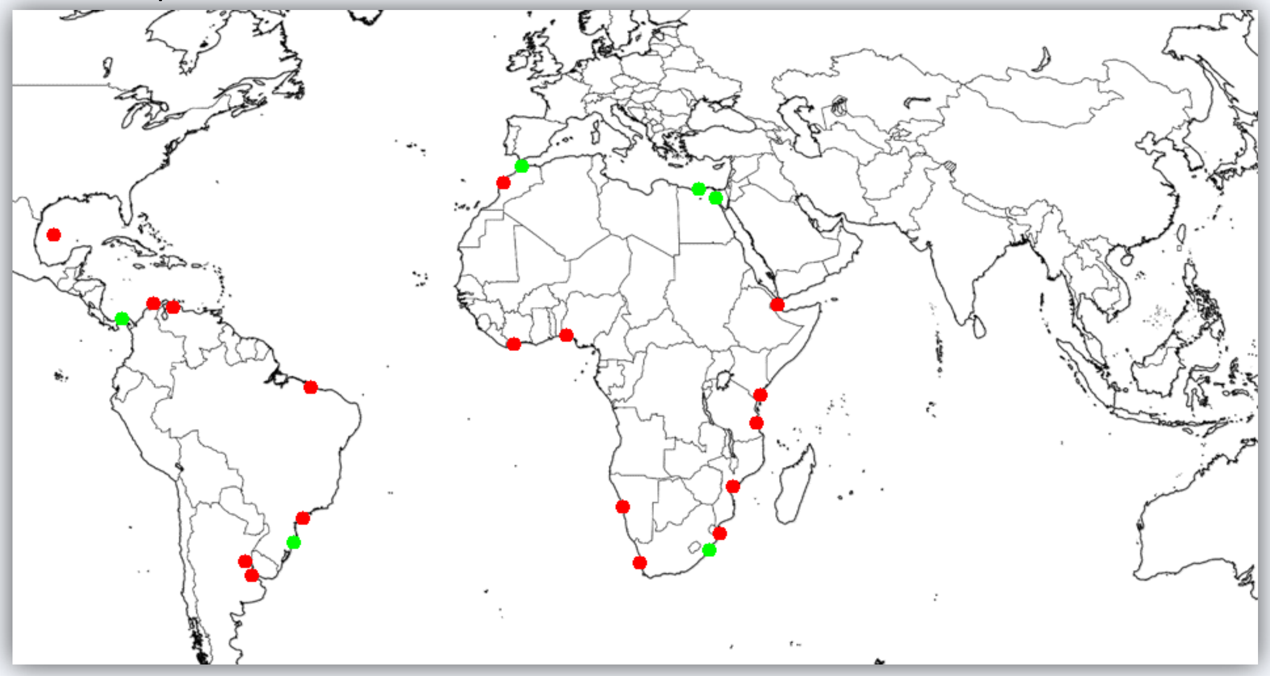


Source: European Comission , 2006

Foreword

Nevertheless, several factors could reduce the gap with the other means of transport:

- **Effective journey length:** in the case of air transport the effective journey is the minimum possible;
- **Existence of ground and maritime infrastructures;**
- **Efficiency and safety costs:** jams and accident are negligible (1/100 compared with road transport);
- **Reliability and block speed:** Air transport ensures the lowest block speed and is the only possible choice for in case of perishable value transport or emergency scenarios.
- low construction costs compared with road and rail;

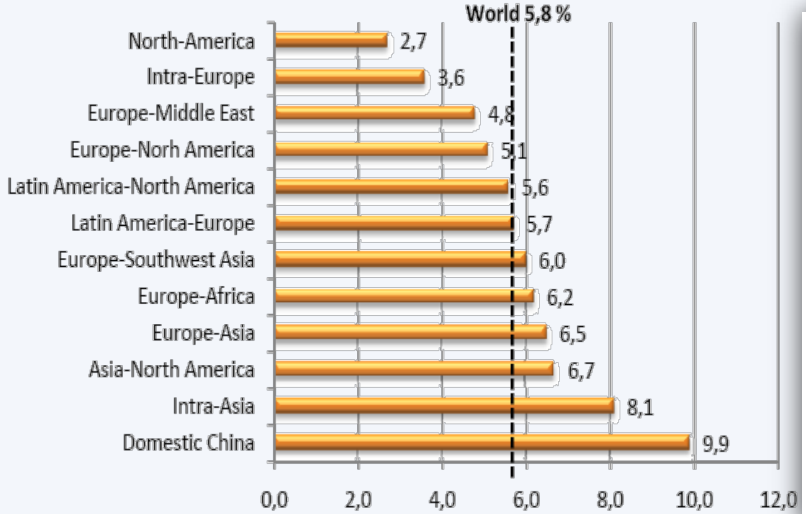


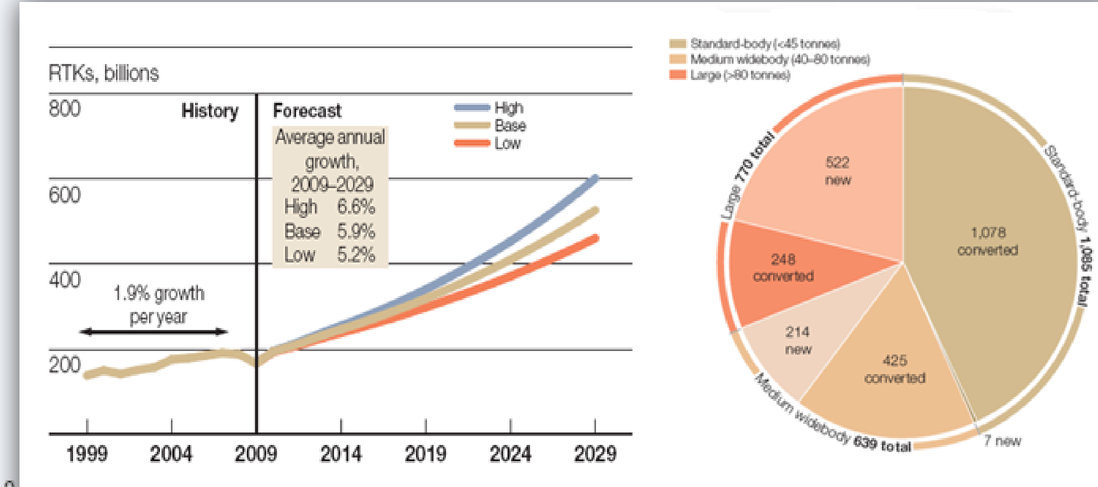
Current aspects of air freight

90% of the global air fleet derive today from the conversion of passenger aircraft in order to reduce acquisition costs; the consequences are:

- Freighter aircraft have old technology and short operative life: maintenance and flight costs are correspondingly high;
- Aircraft operational requirements have been conceived for passenger transportation; they are not optimal for freight transport, especially in terms of cruise speed, payload (low freight capacity) and range;
- The load factor hardly exceeds 65%; the operational costs per unit of freight transported are increased consequently;
- Unit Load Devices (ULD), designed to optimized the cargo volume in passenger aircraft;they cannot be used for intermodal transportation;

Airfreight long term forecast





Source: *World Air Cargo Forecast,* Boeing, 2009

- Traffic will triple over the next 20 years;
- New markets will be opened and new emerging economies will arrive(Africa, Latin America, Central Asia);
- These growth margins will be sustained by an adequate improvements in the freighter fleet (double of aircraft number):
  - shift towards large wide bodies;
  - about 700 new “conventional” freighter will be required to the aircraft manufacturers;

But…..

This forecast model remains related to the current configuration of airfreights showed.
In order to make the air commerce profitable also for the emerging countries, we need to transport a large amount of goods at a low costs also in the areas where infrastructures are missing.
The possibility to carry intermodal containers is strategic in this contest.

New freighter operating requirements: payload

Aircraft capacity must be improved in order to reduce costs per unit of freight carried, while the aircraft dimensions cannot exceed the allowable ones. Thus requirements are:

$$\text{Gross Payload} \cong 250000 \; [kg]$$

$$\text{Horizontal maximum dimensions} = 80 \text{ x } 80 \, [\text{m}]$$

The maximum dimensions constraint limit the maximum payload for a conventional monoplane to about 150 Tons: in order to overcome this limitation, a non conventional configuration is needed.

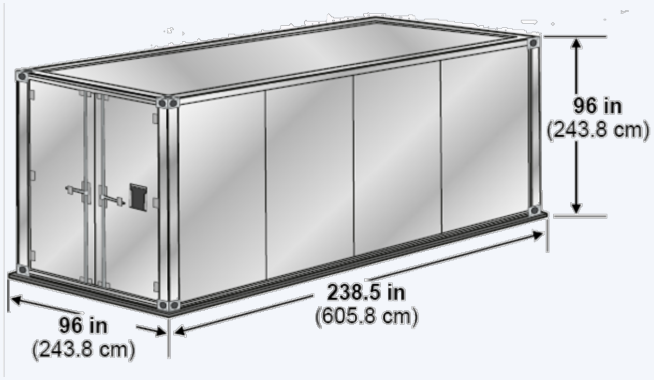
New freighter operating requirements: intermodal transport

The integration within a larger intermodal transport system is a strategic requirement to improve the efficiency of air transport.

The maritime container, realized in steel alloys have a tare weight (>3 Ton) incompatible with air transportation.

The aeronautic version of the intermodal 20 ft container already exists, made in aluminum alloy and ratified by IATA.

Feature	Value
Designation (IATA)	M-2 (AGA)
Max. Gross Weight [kg]	11340
Available Volume [m^3]	33.7
Tare [kg]	1000



Considering an average density of 220 kg/m^3 and the maximum gross payload of 250 Tons, we obtain:

$$\text{Nominal Payload} = 24\ \text{Cont.}$$

New freighter operating requirements: range

$$\text{Design Range} = 3000 \text{ N.M.}$$

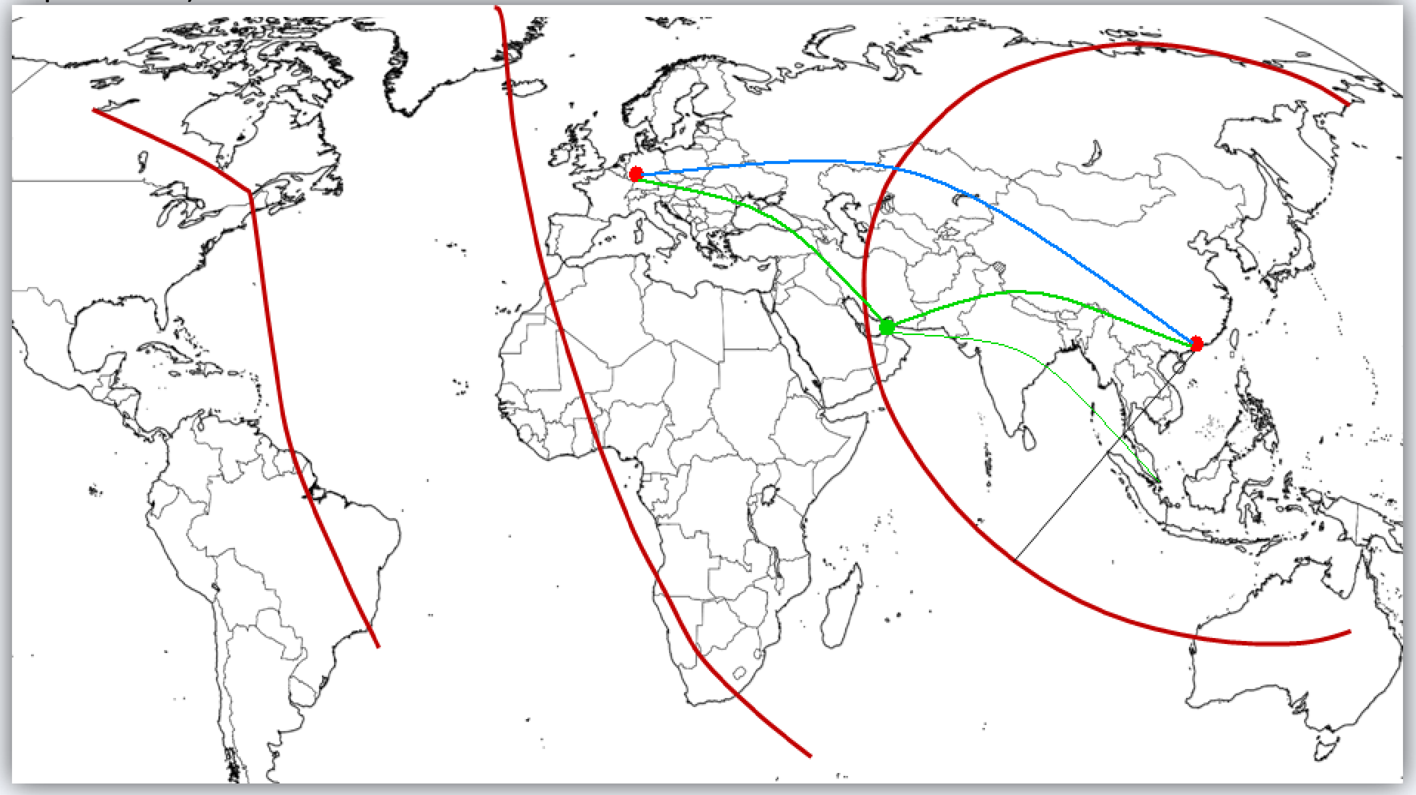
- Efficiency on a regional market (e.g. transport intra Asia).
- Benefits on fuel weight saving for the design mission.
- Long haul routes covered through intermediate landings
- Intermediate landings don't affect the competitiveness of the airfreight (goods are not sensitive to block speed increase as the passenger transportation).

Example of a typical long haul mission : Hong Kong-Frankfurt (5100 NM): estimation of the block time:

11 Hrs (direct flight)

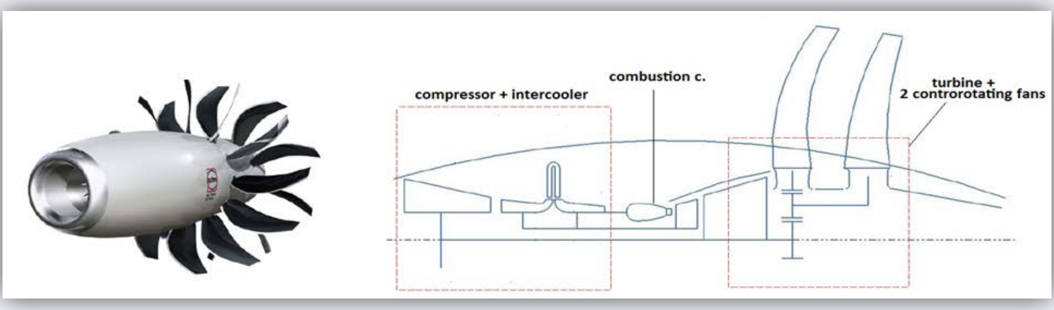
15.5 Hrs (one refueling)

The payload coming from one origin can be redistributed for multiple destinations, increasing the aircraft load factor.

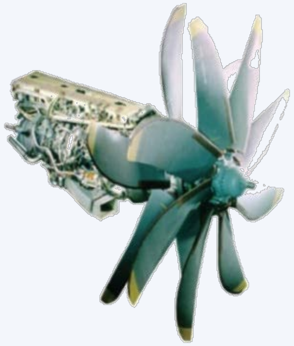


New freighter operating requirements: engines

- The specific fuel consumption of existing turbofans is not compatible with cost reductions.
- Need to find new engine architectures that are able to reduce the consumption maintaining high available power;
- Open rotor engines are a suitable solutions:



The operating performance of existing open rotor engines (e.g. Ivchenko Progress D-27) are considered as reference point for the design procedure of the proposed design.

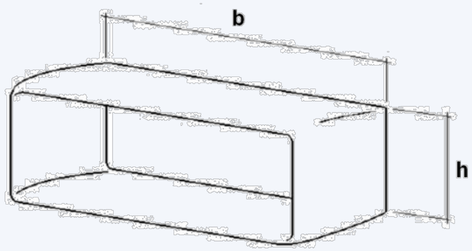


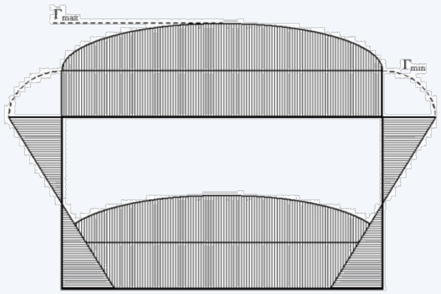
Cruise Speed	M = 0.6-0.7
Cruise alt.	20000 ft.
Max. Power	14000 ehp
Prop Efficiency	0.9
Weight	2000 kg
Prop. Diameter	4.5 m
SFC	0.13-0.17 kg/(ehp*h)

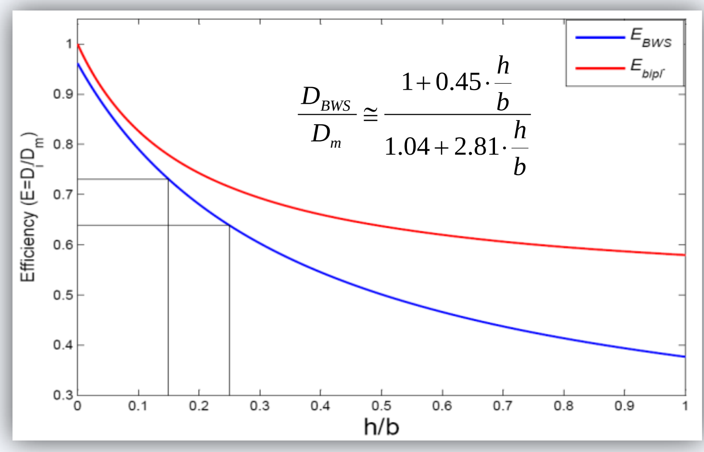
Drawbacks: noise, vibrations, integration with the aircraft.

The PrandtlPlane configuration

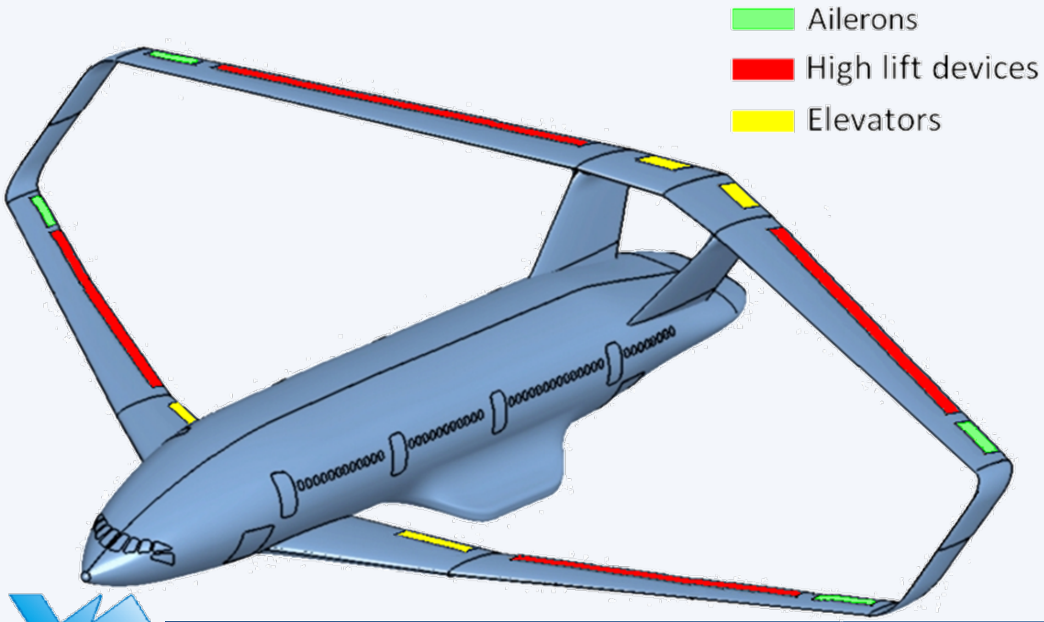
According to Prandtl studies (1924), it's possible to define a "*Best Wing System*" able to minimize the induced drag; it is made by a box wing.







The *PrandtlPlane®* is the engineering application of the BWS concept:

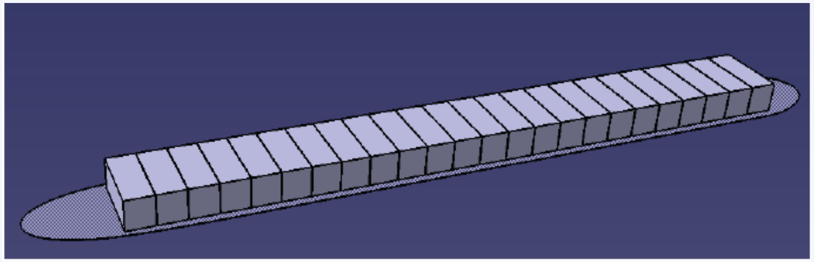


Main aspects

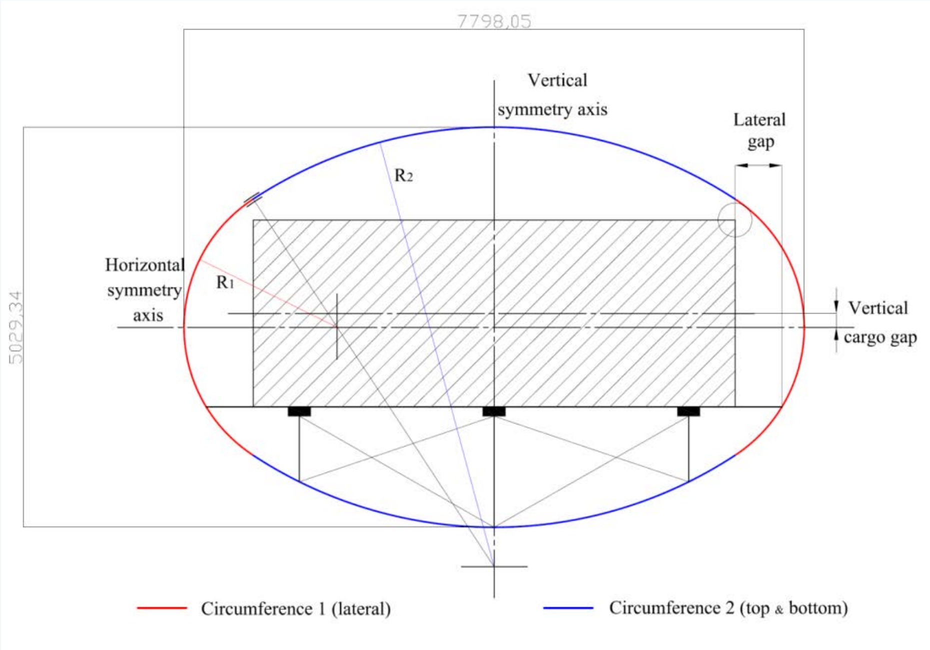
- Reduction of the total drag: 15-20% during cruise;
- Improvements of longitudinal stability and maneuverability;
- Improvements of low speed performances;
- Fuselage enlarged horizontally, not vertically;
- Weight saving in fuselage structure;
- Flexibility in engine integration.

Prandtlplane Freighter: fuselage shape

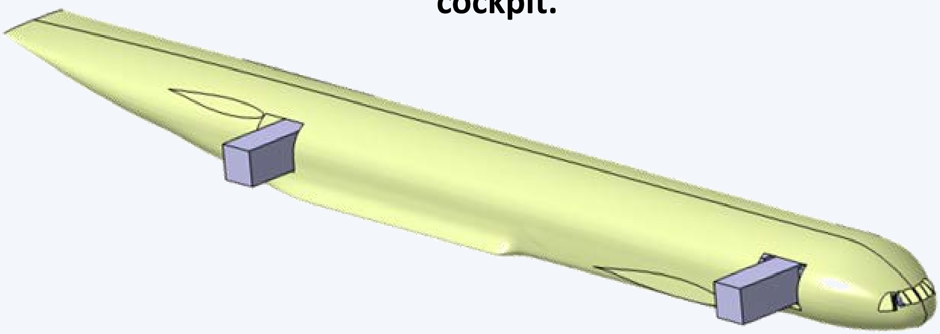
1. Payload disposal



2. Definition of the transversal shape



3. 3D model, definition of: lateral booms, doors, cockpit.

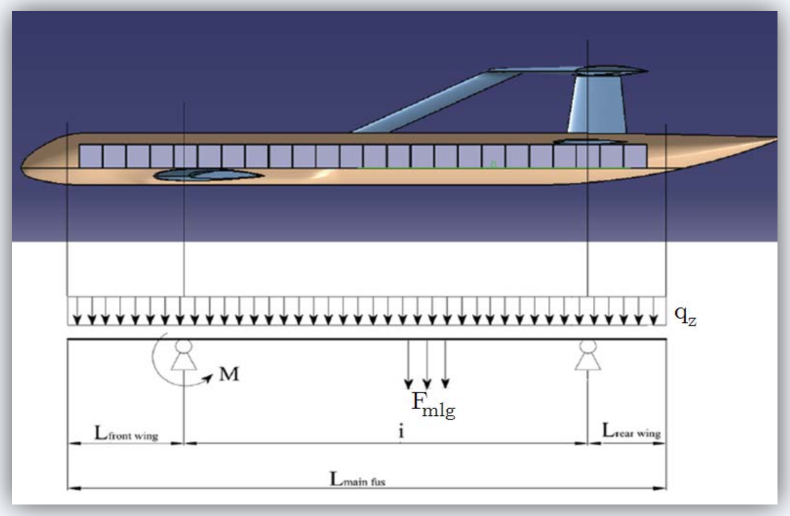


Features

- One single cargo deck;
- Pressurization limited to the cockpit area.
- Manufacturing simplicity (double symmetry);
- Adequate height to guarantee bending stiffness;
- Lateral gap for crew;
- The cargo deck ensure no interferences with wing box and space to locate the main landing gear;
- Cockpit in the front part of the fuselage compatible with the view envelope;
- Main landing gear located in the rear part of the fuselage ensures adequate tipback angles.

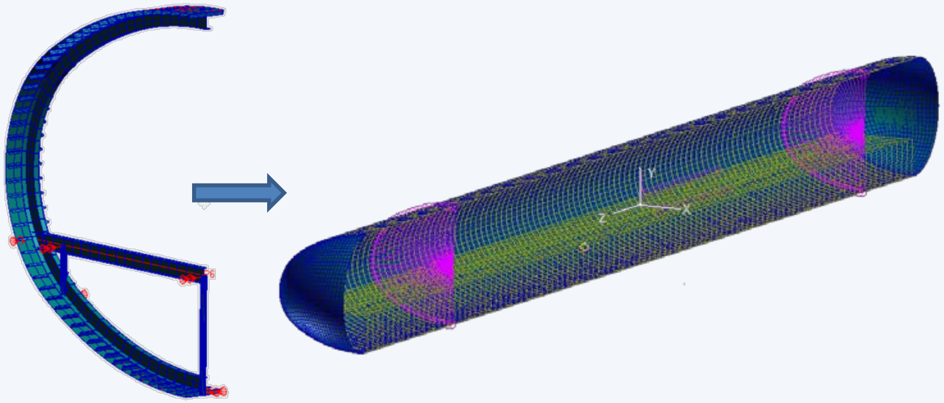
Prandtlplane Freighter: fuselage structure

During flight, the fuselage is equivalent to a doubly supported beam in correspondence of the two wings.



Loads (no pressurization):

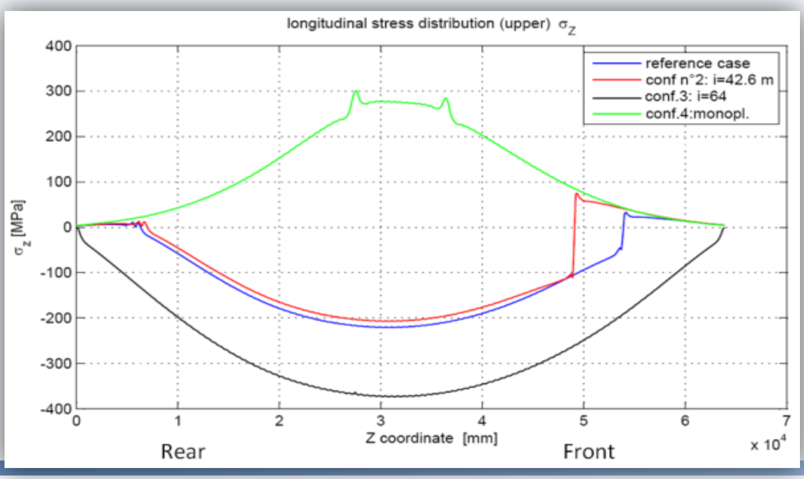
- Distributed Mass load (q_z) is one order of magnitude bigger than in the passenger aircraft (≈10.8 *kg/mm*)
- A pitch moment *M* is added to obtain the actual lift on the two wings.



F. E. analysis to evaluate the effects on stress distribution caused by wing positioning and lack of pressurization.

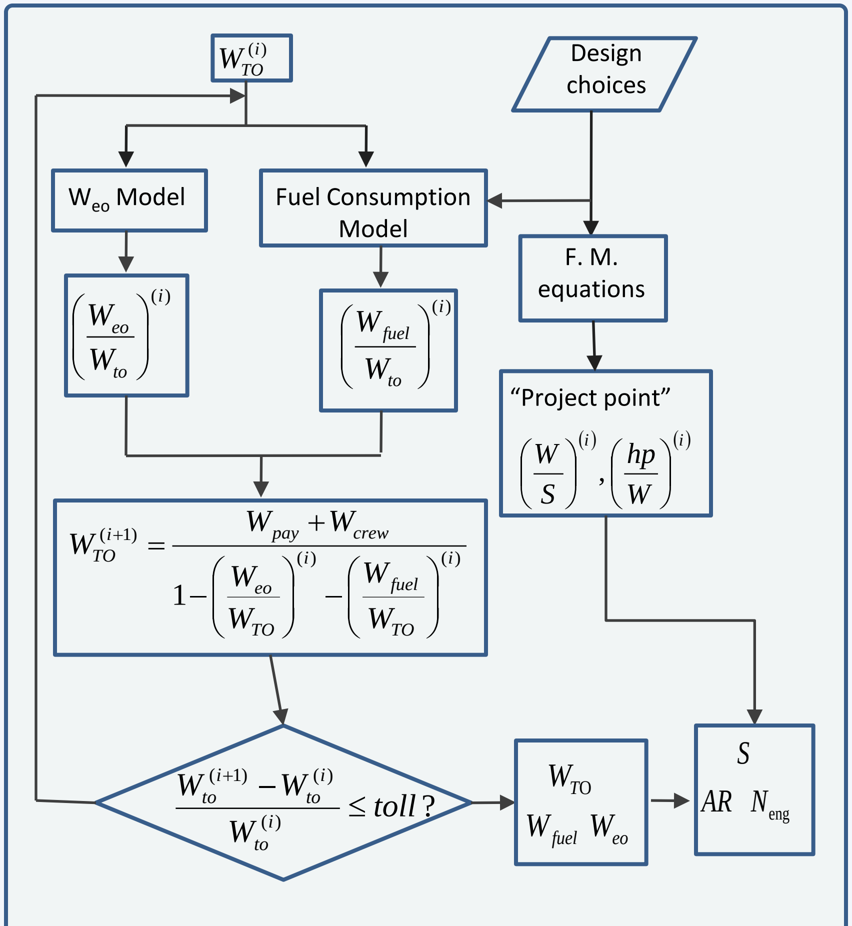
F.E. model: bar for frames and stringers, and quad for skin: their dimension is constant.

Material: AL-alloy 2024-T3 Max admissible stress: 220 MPA at n_z=2.5



Preliminary estimation of weights and performance

Calculation Procedure



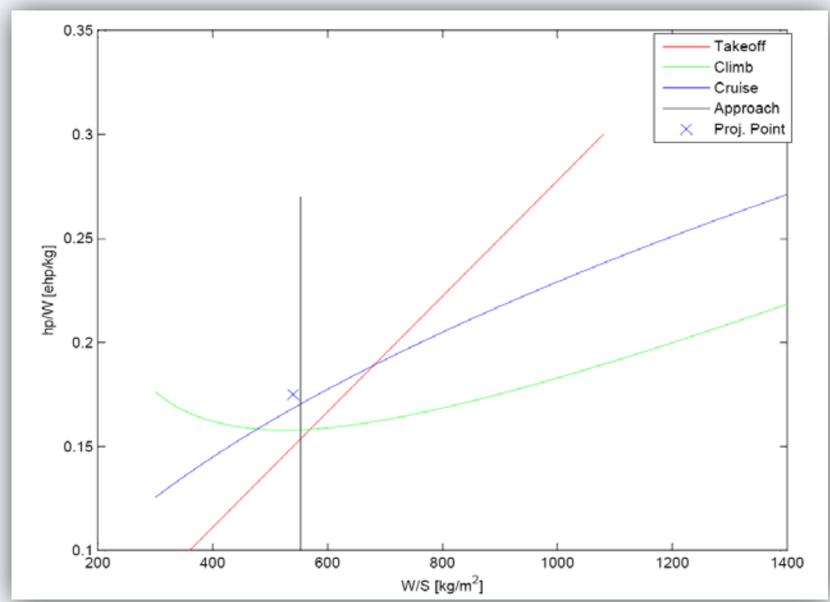
- Statistical models to determine W_{eo}/W_{TO} :

$$\frac{W_{eo}}{W_{to}} = A \cdot W_{to}^{\ B}$$

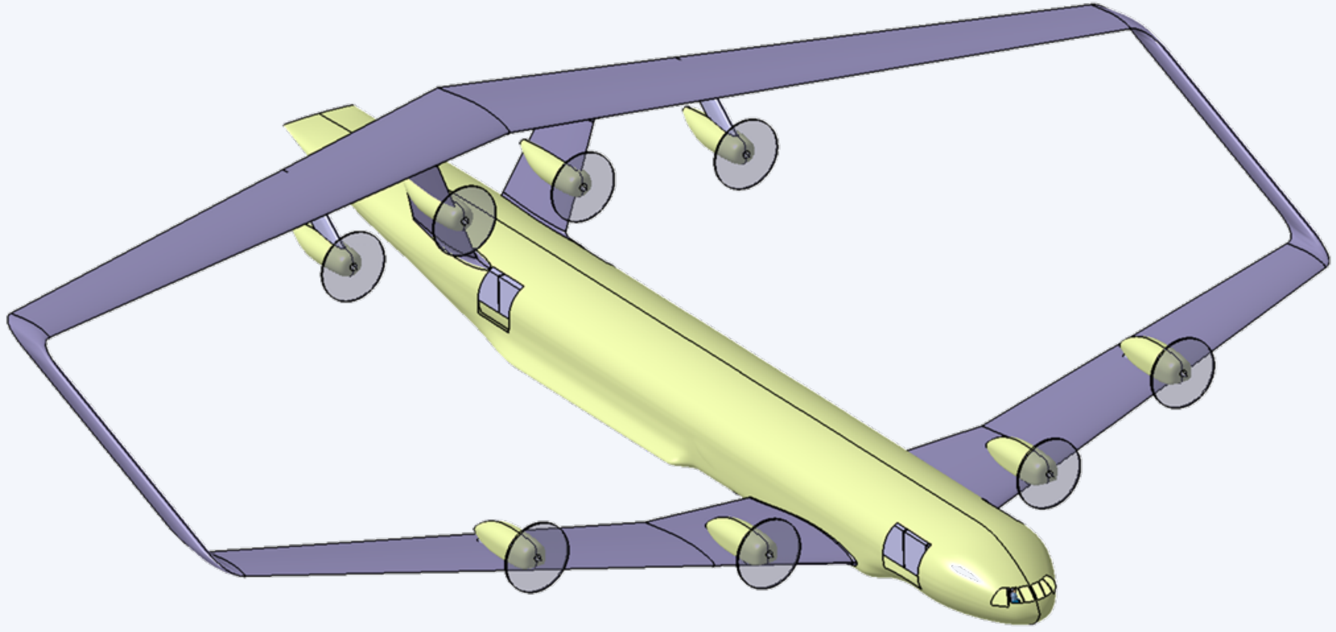
- Breguet formula to determine W_{fuel}/W_{TO} :

$$\left.\frac{W_{fin}}{W_{in}}\right|_{cr} = e^{-\frac{Range \cdot SFC_{cr}}{\eta_p \cdot E_{cr}}} \qquad \left.\frac{W_{fin}}{W_{in}}\right|_{loi} = e^{-\frac{v_{loi} \cdot Loi \cdot SFC_{loi}}{\eta_p \cdot E_{loi}}}$$

- Flight mechanics equations for each flight condition for the project point.



Result: the conceptual layout



MTOW	624	[Tons]
W_{eo}	248	[Tons]
W_{fuel}	124.4	[Tons]
W_{pay}	250	[Tons]
W/S	540	[kg/m^2]
hp/W	0.175	[ehp/kg]
S_{tot}	1150	[m^2]
Hp	109 [kehp]	
N_{eng}	8 propfan (Iv.D-27)	

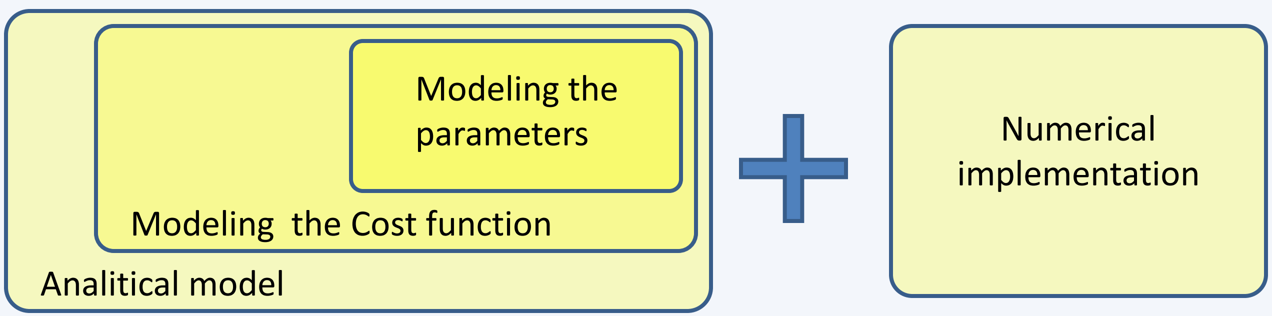
- Low cargo deck;
- Easy and quick loading/unloading procedures;
- Many possible engine integration;
- MTOW comparable with existing large freighters while the payload is increased by more than 30%;

In order to reduce the costs, the technological improvement must be integrated with a definition of a proper net of field worldwide

The freight-net model: introduction

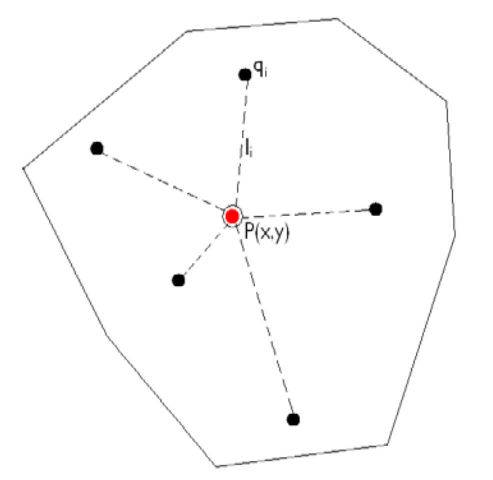
Statement of the problem:
Find the optimum location for a set of N airports (with N fixed) on a given region, in order to minimize the transport cost function.

Some remarks:
- Two methods are possible: continuous or discrete model?
- The model must include some constrains, e.g. the maximum distance between two near airports must be shorter than the design range of the freighter.
- The region on which the model must be defined, is related to the geography: some gaps have to be considered (e.g. the airports cannot be located on the sea) ;
- How the costs can be modeled? What are the parameter which the cost depends by?



Weber Problem

The Weber discrete model (single hub location problem) is useful to determine the main parameter.



Given a set of existing airport in which the transport demand q_i is defined, it's possible to determine the optimum location *P=P(X,Y)* for a single hub that connects all the other airports. The cost function is:

$$\min_{X,Y} C = \sum_{i=1}^{n} q_i^{\alpha} l_i(X,Y)^{\beta}$$

- The dependence of the cost air transport by both the distance and the airfreight is in general non-linear;
- Need to find a model for the spatial distribution of the airfreight demand q.

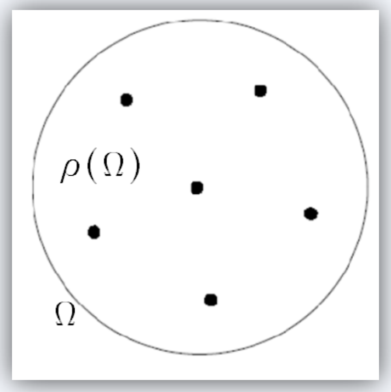
Model proposition

Extension of “optimum location problems” (continuous) developed at the department of Mathematics of the University of Pisa by Prof. Buttazzo.

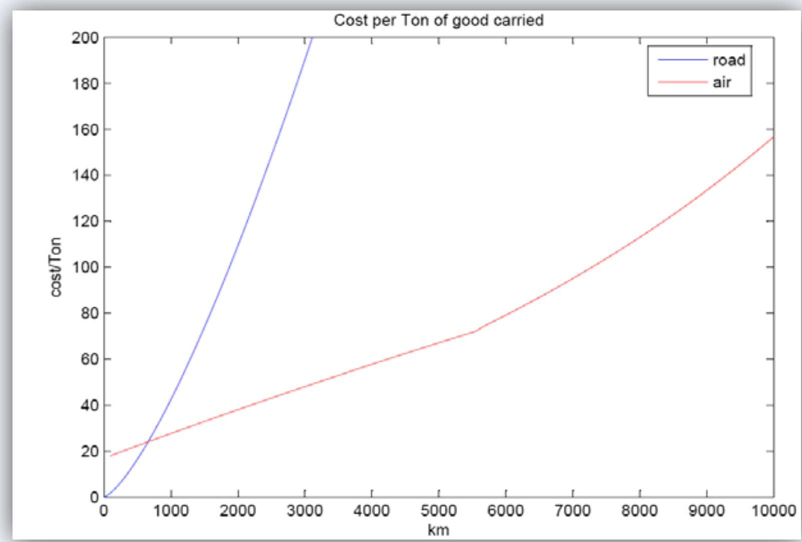
$$\min C(X_1, X_2,\ldots X_N) = \min \int_{\Omega} \rho(\Omega)\cdot d(X,x)d\Omega$$

$$\Downarrow$$

$$\min C(X_1, X_2,\ldots X_N) = \min\left(\int_{\Omega} \rho(\Omega)\cdot d^{\alpha}(X,x)d\Omega + \sum_{i,j} A\cdot d^{\beta}(X_i, X_j) \right)$$

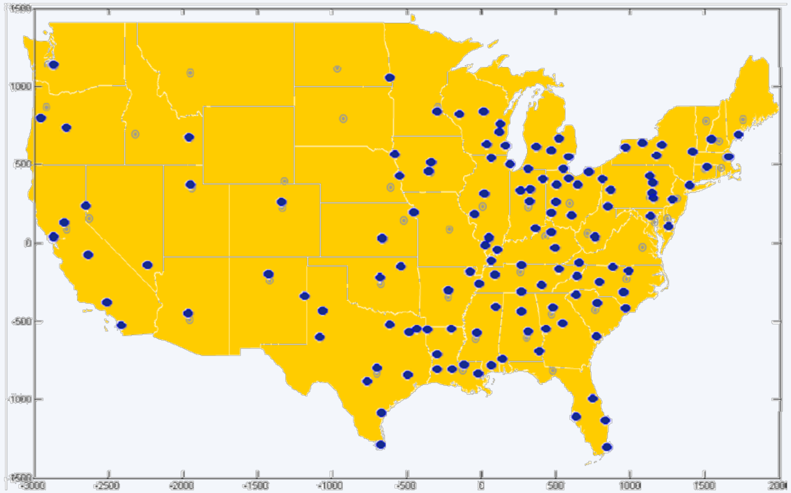


•The first term is the costs connected to the transport from any point to the airport and vice versa (kind of model for the ground transportation);
• The second term takes the cost of the connection between two airports into account;
•$\rho(\Omega)$ is the spatial distribution of the airfreight demand over the region;
• α, β remark that the dependence is not linear;
• First assumption: cost function deriving by Breguet formula.



The airfreight demand

Correlation between some socio-economic parameters and the airfreight demand (AlKaabi -University of North Carolina-2010).

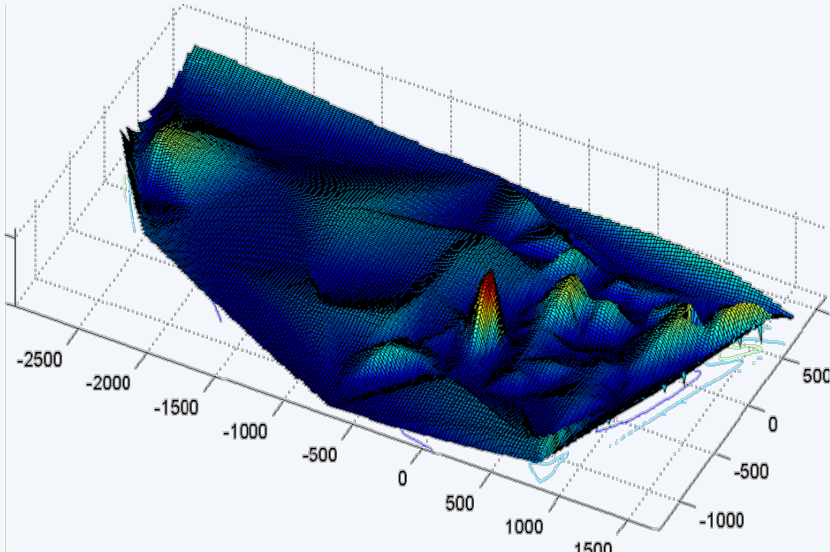


$$\ln(AF) = C_0 + C_1 \cdot PC + C_2 \cdot TSE$$

Where:

- ***AF*** is the volume of airfreight demand (lb);
- ***PC*** is the Pro capita personal income (k$);
- ***TSE*** is the transportation-shipping-logistics employment market share (%);
- C_0, C_1, C_2 coefficients depending by the economy of scale.

Moreover, from the ground side, the airfreight activity affects the economies at a small scale (regional and urban scale) so that the data have to be referred to relatively small areas: cities or districts.



Example: spatial distribution of airfreight over the USA.

- The socio-economic parameters are taken from U.S. Census database for each "CSAs" and "MSAs" (similar to Eu. Provinces);

- From a set of points and socio economic data (matrix input), a program was implemented to determine the region and the spatial distribution of AF (figure2);

Conclusions

- The airfreight needs consistent improvements in both technology and logistic system in order to achieve the high growth margins expected for the future;

- The conceptual layout of a possible new generation freighter is presented; the different operational requirements, the improvements in both aerodynamics and engine allow to reduce significantly the fuel costs:

$$\text{current fuel cost} \cong 9.33 \frac{\$cents}{Ton \cdot Km} \qquad \text{projected fuel cost} \cong 7.6 \frac{\$cents}{Ton \cdot Km} \Rightarrow -19\%$$

- The technological effort can be extended to all the air industry, also for future application on the passenger aircraft; the costs for research and development about non conventional configuration must be sustained by all the air sector, not only by the airfreight.

- In the present case, the main challenge is represented by the developments of an adequate open rotor engine and its integration with the aircraft; if improvements in available power will be possible, the number of the engine can be reduce (8 to 6).
- A new network based on freight airport can introduce new markets and improve the economies of the developing countries: Africa represents the natural bridge for the commerce between Latin America and Europe/Asia so that the position of some developing countries could become strategic from an economic point of view;

Future studies:

- Cargo deck floor: systems for the handling and the locking of the intermodal container;
- A/C Preliminary design: airfoil and wing aerodynamic optimization, structure analysis, models for weight prediction;
- Model for the determination of DOCs in the case of goods transportation;
- Development of the “optimum location routing model” and implementation.