VYOM PIONEERS, IIT Kanpur

Reconfigurable Aircraft Concept

Modular Aircraft Concept for enhancing load factor and fuel efficiency, decreasing carbon footprint, increasing capability to land at different airports and decreasing capital investment.

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1. Executive Summary

The time for 'Intelligent transportation system' has arrived. Over the next 50 years the non-renewable sources would become expensive and thus there will be a premium on product design which utilizes capital and material resources optimally. The aviation industry currently accounts for 2% of the global man made carbon emissions, and this figure is expected to grow at a rate of 5% every year. In 2000, passenger air travel stood at 3,300 billion passenger kilometre. This number is expected to grow by 5.5 times to 18,400 billion passenger kilometre by 2050. [1]

As the demand for air travel will increase, so will the supply. However such a growth in number of aircrafts will cause significant congestion and this will only grow worse in future. A modular approach enables a large aircraft quickly morph into a smaller one by removal of a section of the aircraft or vice-versa. The state of the art in this field is negligible and it opens up an entire new field in the area of intelligent transportation system.

Through this report we propose a greener, modular and reconfigurable aircraft concept design which will improve the current passenger load factor, ensure less fuel consumption, will be deployable on large as well as smaller runways, and its acquisition in an aircraft fleet will need lesser capital and maintenance costs vis-à-vis conventional aircraft designs.

Our design is expected to decrease the global CO_2 emissions by a massive 6.5 million tons per year. Further, the fuel saved by our design in a year can serve the energy needs of India for more than 15 days.

2. Objectives

2.1 Aim

Through this proposal, we propose a modular and reconfigurable design offering following benefits:

- Improved passenger load factor thereby increasing the net fuel efficiency.
- Reduced capital and maintenance costs.
- Enhanced ability of airlines to serve airports with shorter and longer runways without necessarily increasing the overall fleet size.

2.2 Design Considerations

We have evaluated our idea by addressing the following questions:

- What is the technical feasibility of such an idea?
- What would be the benefits from such a system in terms of fuel consumption, operating cost, capital expenses and carbon footprint?
- How would such a concept be integrated into the existing system of air transport?

For designing such a concept we adopted a "systems engineering" approach with the following broad categories:

1) Aircraft Design
    - Aerodynamic Design
    - Design of Interconnects
        - ✓ Structural
        - ✓ Hydraulic and pneumatic
        - ✓ Electrical
2) Deployment System at airport
3) Economics Assessment & Environmental benefits.

We started off by selecting an existing family of aircraft for our analysis which may benefit from the re-configurable aircraft design *(Section3.1)*. For this, we selected the A320 family as the reference system for all the analysis. Once this family was decided, a preliminary estimation of the economic and environmental benefits of the proposed concept was carried out (*Section3.2*).The design concepts for a modular aircraft which may be compatible with this family were ideated and their analysis in terms of technological feasibility was done. A few concepts were then finalized and a detailed analysis was carried out on each design from standpoints of fuel efficiency, stability, inter-modular connectivity (structural, electrical, hydraulic, pneumatic) and deployment at the airports (*Section3.4*). One design concept was then finalized and detail designing of the same was carried out (*Section-4*). A comprehensive economic analysis of the final design was also conducted to evaluate the benefits of the design in terms of eco-efficiency and economics (*Section-5*).

3. Initial Concept Development

3.1 Selecting an appropriate Aircraft family

We accounted for both technical and economic reasons while selecting the right family as a candidate for reconfigurable design and finally selected the A320 family for the following reasons:

3.1.1 Technical reasons:

- All of them have the same wing span, fuselage width and only fuselage length is varying.
- The engines used in this family have about the same weight although their thrust ratings are different. *(In case of same engine-family)*
- The undercarriage being used is same throughout the family (except A321).

Hence, transforming our aircraft within this family will require very little modifications.

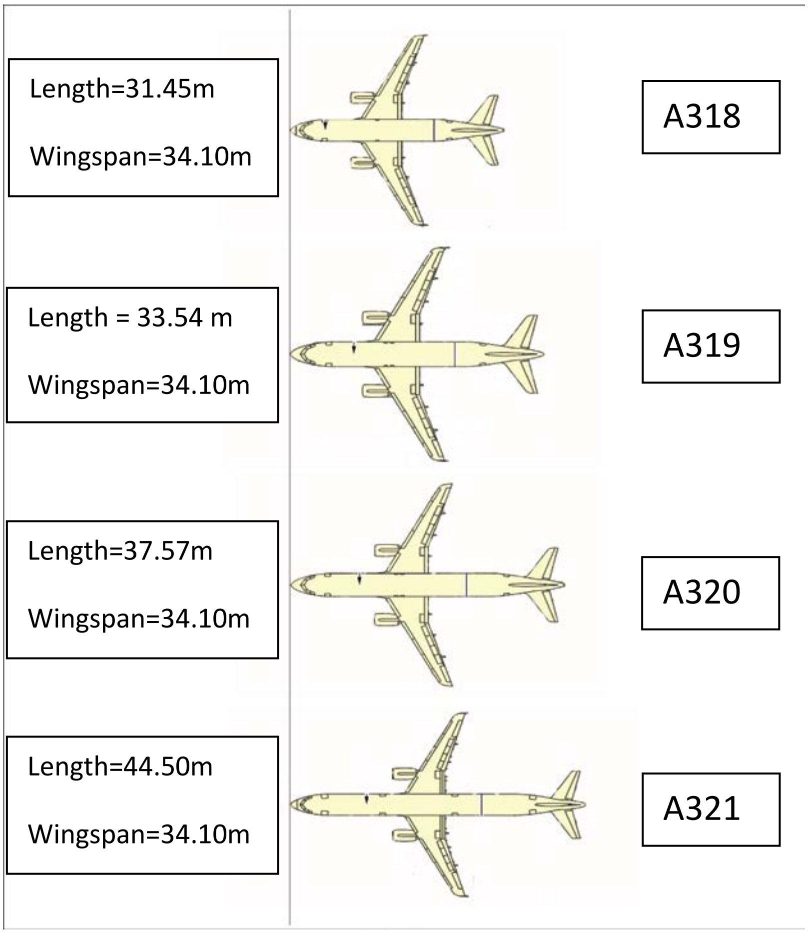


Figure 3.1

3.1.2 Economic reasons:

- This is one of the most popular aircraft families ever produced by Airbus as evident from the sales records. So, if we could somehow design an aircraft which is compatible with this particular family, then that would be the most appropriate design for the current market.

Aircraft Family	Total Orders	Total Deliveries	In Operation
A320	6925	4619	4532
A330	1126	772	767
A340	379	375	369
A350	571	0	0
A380	244	45	45

Table 3.1 **Aircraft Sales Records** (Reference: Airbus.com [2])

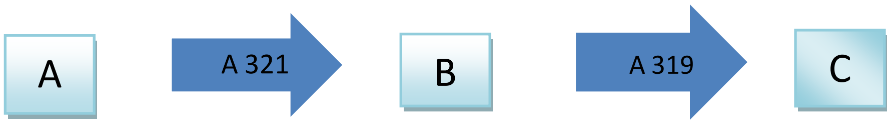
- We have used the Indian airline market for preliminary analysis. In India, there are many airports where A318 or A319 can land whereas the higher versions of the same family can't (See Appendix-B for details). A reconfigurable aircraft would enable airline to serve a larger number of airports without necessarily increasing the fleet size.

3.2 Preliminary Qualitative Estimation of Economic Benefits

A preliminary estimate of economic benefits accruing from the modular design motivated us to develop the design in detail. The estimation was done on the basis of current operational practice in airlines. Current aircraft are not flexible from standpoints of capacity. However, the modular aircraft design helps airlines achieve flexibility in the capacity thereby improving their load factors, fuel efficiency, operational flexibility, and reducing their capital and maintenance expenses. Here, we provide some very basic qualitative estimates on all these advantages.

Consider a scenario when an airline has to serve a flight route: A → B → C where:

- Airports A and B can accommodate large as well as small planes.
- Airport C can accommodate only small planes.
- Air-traffic between airports A & B is heavy while a significantly lesser no. of passengers travel between B & C. Then to serve A → B route, the airline has to acquire say A321 while it needs a smaller aircraft A319 to serve the B → C flight segment.

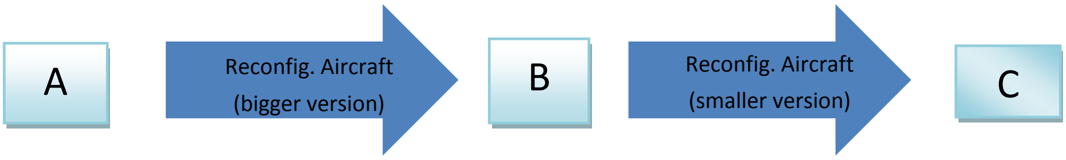


In this case, its associated expenses will be:

- Financial costs for acquiring A319 and A321
- Depreciation cost for acquiring A319 and A321
- Maintenance costs for acquiring A319 and A321
- Fuel Costs for running A319 and A321.

Alternatively, if a reconfigurable aircraft design is available, then the airline will:

- Serve route A → B using a plane similar to A321 but will achieve its capacity through an add-on module.
- Serve route B → C using a plane similar to A319 and will not use the extra capacity available through the add-on module.



If we assume that the cost of reconfigurable aircraft is approximately same as that of A321, then we can conclude that:

- Financing costs for acquiring A319 and A321 will be significantly higher than that for acquiring a reconfigurable aircraft.
- Same inference as stated above can be drawn with regards to depreciation and maintenance costs.
- Fuel costs for either scenario will be comparable.
- The reconfigurable option is still far more preferable from an environmental standpoint as such an option requires fewer resources for production vis-à-vis producing two aircraft: A319 and A321.

In another scenario, the fuel savings may be even higher. Consider a case where a flight route has heavy air traffic at some time of the year while at other times, passenger demand may not be that high. In such a case, the airline will have two options;

- Use conventional A321 aircraft to support passenger needs during high demand seasons.
- Use a modular aircraft design which enables it to run at higher passenger load factor all through the year, while simultaneously saving the fuel costs.

It is clear that in such a scenario, the airline will have significant fuel savings if it opted for a reconfigurable aircraft.

3.3 Initial Design concepts

The initial brainstorming yielded ideas for the concept of modularity. Some promising ideas which emerged were detachable tail, extra modules, symmetric dual modules, double-decker, and baby plane as shown below.

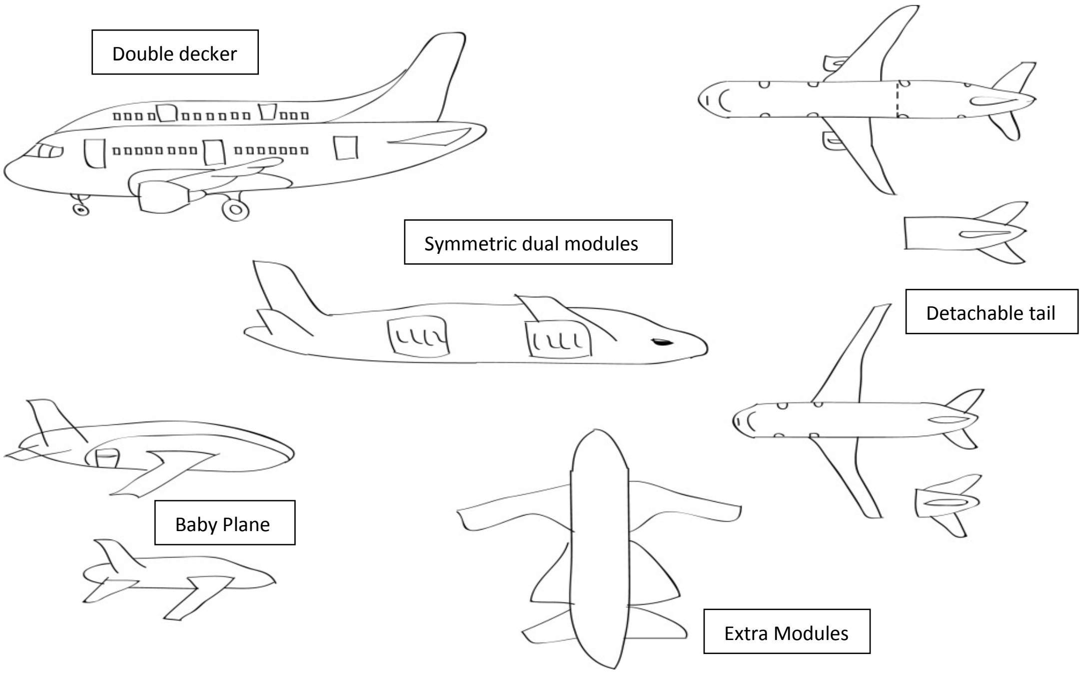


Figure 3.2: Initial Design Concepts

3.4 Initial concept evaluation

At this stage, every design concept was evaluated on the basis of stability considerations due to positional shift of CG w.r.t. centre of lift, ease of inter-modular connectivity, deployability at airport and cost. The four primary designs we focused upon were: Symmetric Dual Modular, Double Decker, Detachable Tail and its derivative Detachable Aft Fuselage.

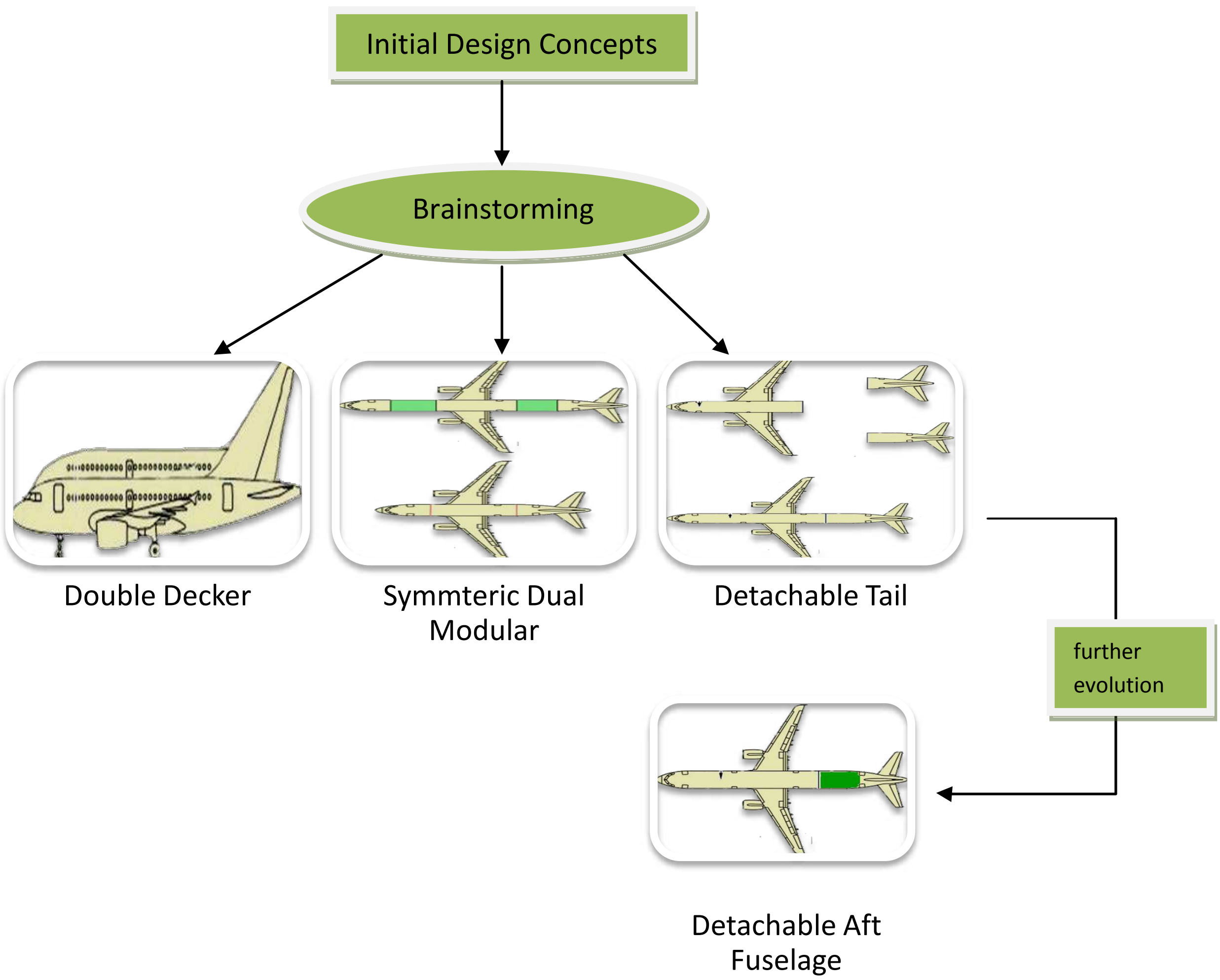


Figure 3.3

3.4.1 Major Design Considerations

Provided below are some of the major considerations that were used to evaluate the technical viability of our concepts.

- Positional shift of CG relative to center of Lift.
    - Aerodynamic stability of aircraft is to be maintained.
    - Position of wheels may require modification.
- Joint Design
    - Should sustain stress due to bending loads and due to pressure difference during flight. Further, it should not fail due to fatigue under these recurring loads.

- Hydraulic lines, pneumatic line, electrical connections should remain intact and fail proof.
- The module should be easily and quickly deployable at the airport.

3.4.2 Assessment of different Initial Design Concepts

3.4.2.1 The Detachable Aft Family: Detachable Tail and Detachable Aft Fuselage

As shown in the figure, the module is the aft fuselage portion that comprises of the tail. A particular size module can be used depending upon passenger load requirement. Due to different weights (corresponding to different modules) being added aft of the wings, the CG range of aircraft may vary significantly thereby making it unstable. Mechanical joint for joining the two parts is another issue. Also, this requires provision for reliable hydraulic, pneumatic and electrical interconnects.

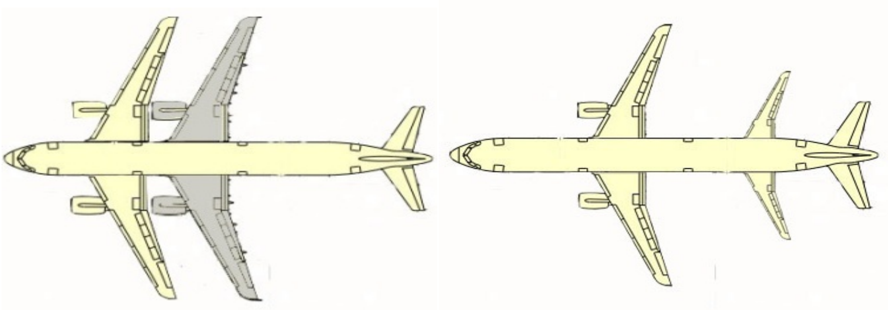
For addressing CG shift, we considered two solutions: 1) Sliding wings and 2) Tandem wings.

Sliding wings

Here, we planned to join wings to the main body through a sliding mechanism. Hence the wings would slide and change position of center of lift by appropriate amount so that aircraft stability is maintained during flight.

Tandem wings

In this approach, the module will have a set of secondary wings attached. Hence, although the CG will shift, center of lift will also get shifted due to additional lift provided by the secondary wings.



(a) Sliding wings 1 **(b) Tandem wings**

Figure 3.4

A comparison between the sliding wings and tandem wings design is shown in the following table:

SLIDING WINGS	TANDEM WINGS
Solves the problem of instability straightforwardly.	The aft wings render the aircraft less aerodynamically efficient. Hence problem is solved at the cost of efficiency.
More work will need to be done at the airport. Hence energy and time intensive.	Less work in comparison to sliding wings. Just plug n' fly.
Might add extra weight to the aircraft depending upon the mechanism we use.	Will boost the overall stability.
Various connections going through the wing will have to be maintained reliably. This is the biggest drawback.	Will help reduce the net span of the wings. Hence a less wide aircraft can land in more places.

Table 3.2

For hydraulic connections, there exist no such detachable and quickly deployable interconnects which can sustain pressures as high as 3000 psi. A significant R&D effort will be needed in developing such interconnects. Hence, we explored the possibility of using local hydraulic system controlled by electro-hydraulic actuators (EHAs) in the module itself.

Further, we explored the possibility of shifting APU, lavatory etc. to the main fuselage to make module cheaper, lighter and more manageable. Such a new modular configuration is shown in Figure-3.5. (*Inspiration: D.P. Raymer*)

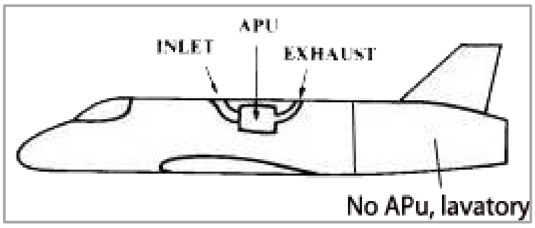


Figure 3.5

This design further evolved into the "detachable aft fuselage" to achieve cheaper and lighter modules. In such a design, the removable module will not have any aircraft control elements, thereby making the design less expensive.

3.4.2.2 Symmetric Dual Modular Design

This concept requires two modules: one front and one aft. Though a very impractical concept, it provides us with a design of relatively high efficiency since it maintains the overall aerodynamic shape of the aircraft.

The modules are attached forward and aft of the wings such that there is no CG shift. The biggest challenge this design poses is regarding the interconnects and joints. This design requires joints at four places, which would make the aircraft more sensitive to joint failure.

The hydraulic connections are the major problem since the landing gears, primary flight controls etc. would have to be provided with hydraulic connections. The only plausible solution for this is using EHAs in different sections of the aircraft. Such a design approach may be very expensive and impractical.

3.4.2.3 Double Decker

This concept involves using a removable deck on top of the fuselage. This is the easiest and the most practical design to implement as it causes manageable CG shift and also there will not be bigger issues of connections. Since the upper deck will have no actuators, there is no need for hydraulic interconnects for the removable module and only electrical and pneumatic interconnects have to be developed. The only limitation with this design is added drag due to the deck and thus such a design will be less fuel-efficient unless highly optimized.

3.4.3 Comparison and Final Design Chosen

While dual-symmetric modular is the most efficient, it is an extremely impractical design to achieve.

Detachable Aft Family is a bit more practical. For achieving this design, tandem wings design was considered. However, tandem wings are able to provide stability only at the cost of efficiency. Further, this design also would require considerable amount of research for interconnects.

Double-decker was one design that seemed practical. Though the most fuel inefficient, it appeared to be the one that the market would accept. Further, this design will also consume the least amount of research as compared to the other two since.

After this preliminary comparison, we finally selected Double Decker.

The following table summarizes the pros and cons of all the designs considered:

	Detachable Aft Family		**Dual-symmetric**	**Double-decker**
	Detachable Tail	**Detachable Aft Fuselage**		
Fuel Efficiency	***	***	*****	**
Structural Joint	***	***	**	*****
Hydraulic and other interconnects	***	***	**	****
Cost of module	**	****	****	****
Research Required for the concept	**	**	**	****
Probable Acceptability in market	**	**	*	***

Table 3.3

 # In above table, the more the stars, the better is the concept in that area. Colours denote the rankings.

4. Detailed Concept Development and Analysis for Double Decker Concept

The double-decker design is implemented by attaching a removable deck over an A319 aircraft. Through such a design, the aircraft will be able to carry 156 passengers without the module and 200 passengers with the module. Why this particular seating configuration was chosen will become clear in the economic analysis section (Section-5).

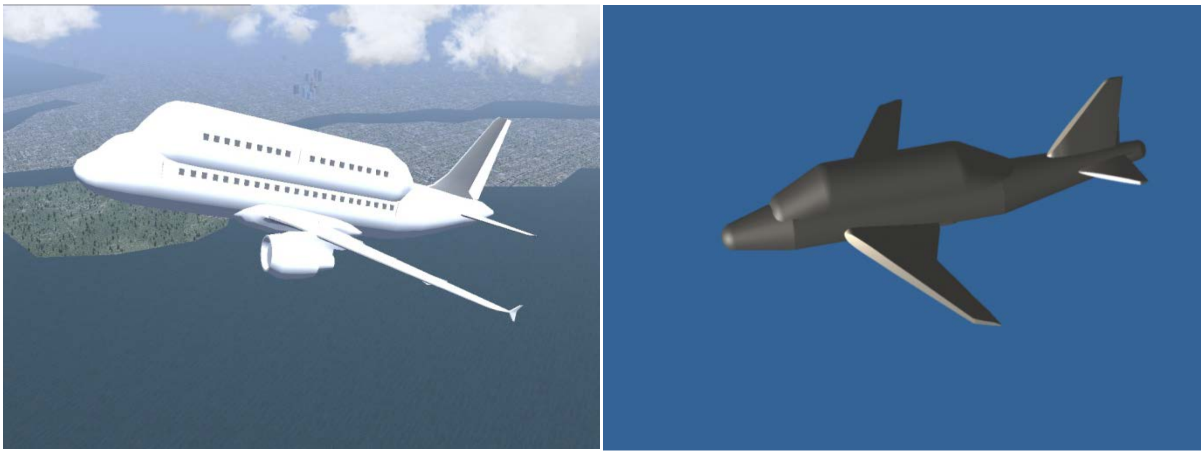


Figure 4.1 (a) 3dsMax® model [3] rendered in Flightgear® (b) Inventor® Model used for simulations

We shall call this model as A319DD. Also, we assume a non-modular aircraft with a seat capacity of 200 seats to already exist and call it A320.5 (as the seat capacity is halfway between A320 and A321). This is assumed for purpose of comparison. Further, we shall call A319DD(+) as the one with the module and A319DD(-) as the one without the module.

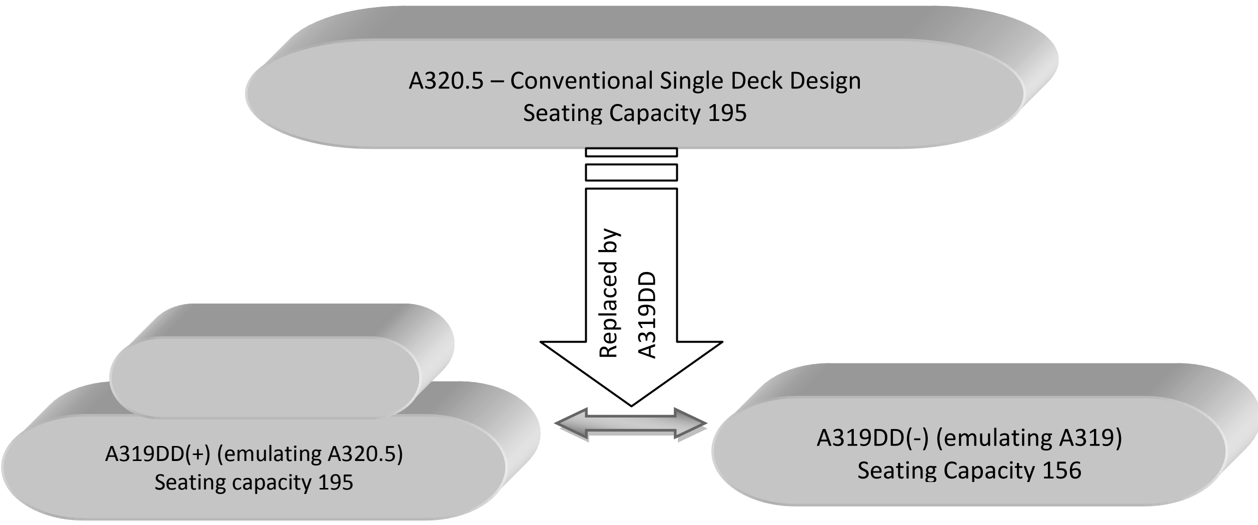


Figure 4.2

We have analysed such design from four standpoints as shown in the following table:

	Considerations in Design of A319DD
Product Design	• Design of modular deck, its attachment mechanism with base aircraft, design of interconnects (pneumatic, electrical) etc. • Deployment at airports.
Aerodynamics and Flight Mechanics	• Drag Calculation and its influence on fuel consumption. • Stability considerations.
Economic Analysis	• Fuel Savings • Energy Savings
Environment Benefits	• Carbon footprint reduction, noise reduction etc.

Table 4.1

4.1 Design Phase

4.1.1 Joint Mechanism

The joint mechanism used is a sliding type mechanism. *Figure-4.1* shows evolution of this mechanism. Part-(4) of *Figure-4.1* shows the final mechanism being used.

Explanation of Mechanism

- The main fuselage contains two 'female' sliders. Module contains the corresponding 'male' sliders.
- Surface of 'female' has a depression at the end. Corresponding protrusion is provided on 'male'.
    - These protrusions and depressions are provided so that while sliding, there is no contact between module and fuselage except at these points(protrusion and depression).
- For deployment, protrusion of 'male' is brought in contact with the front of 'female'. This protrusion is provided with roller bearings so that it slides over the 'female' with ease. The 'male' is pushed over 'female' and it finally reaches the depression and settles there.
- There are 'holes' provided on the 'male' and corresponding 'rods' on the 'female'. After protrusion settles into the depression, these holes and rods become concentric. Hence, these rods can now be driven into the holes through a control mechanism (provided in the main fuselage) for locking.

Further Remarks

- Rods are the key elements that will hold the two parts together. They will bear all the tangential loads that will be subjected to them during the flight, take-off, landing, or manoeuvring.

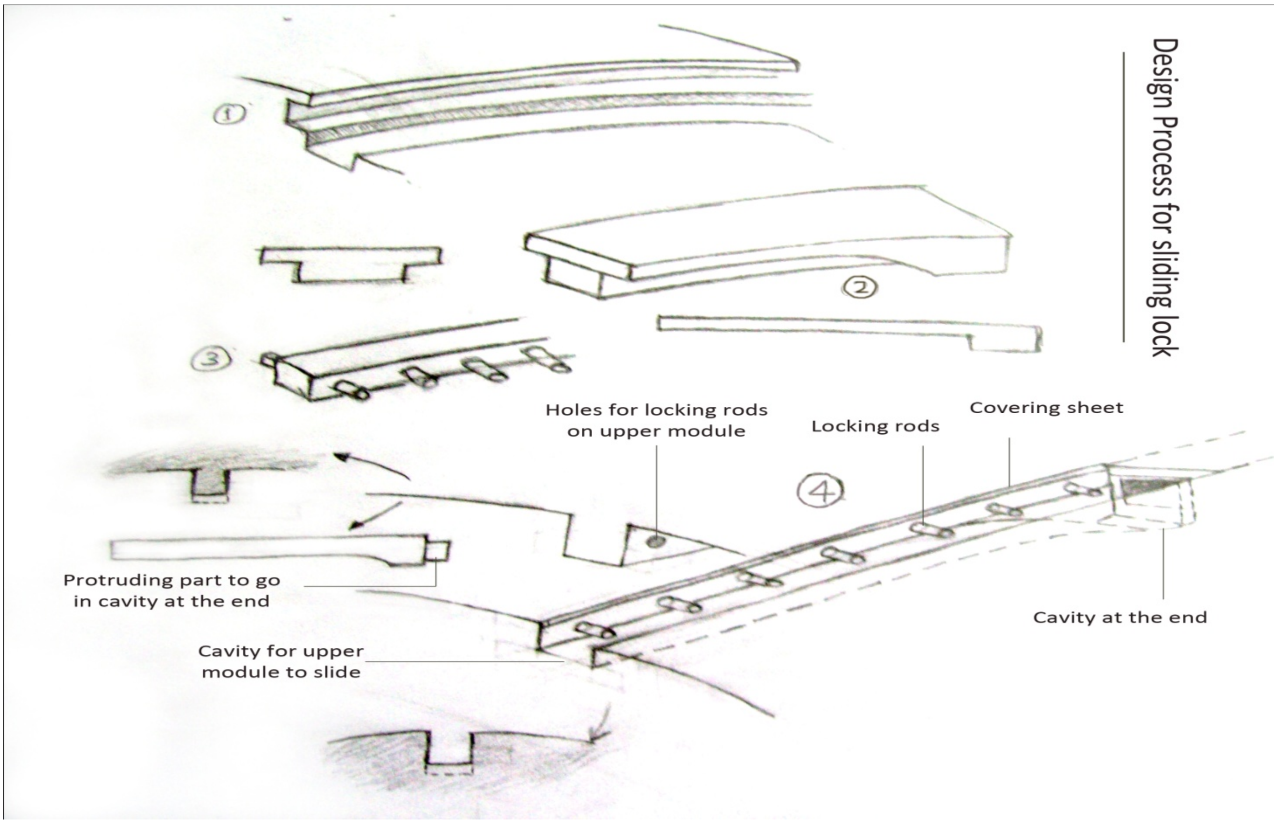
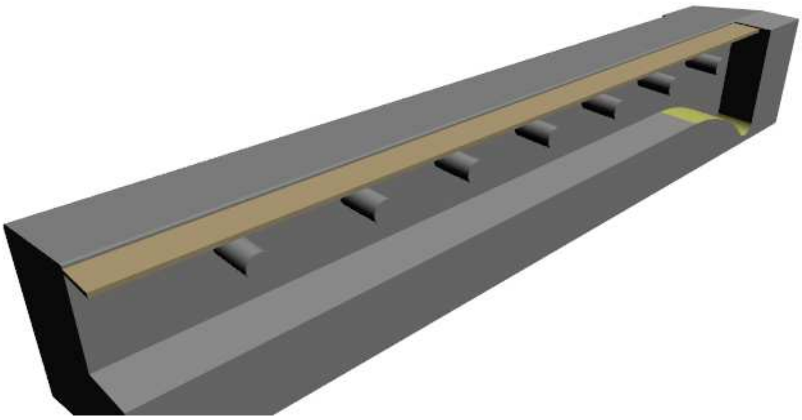
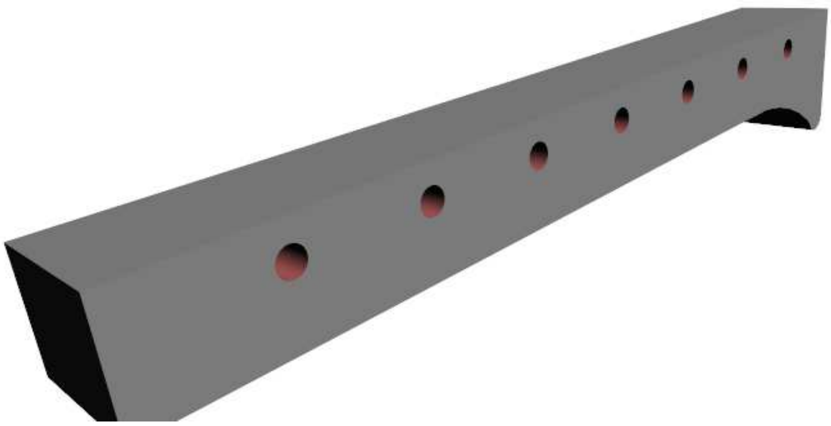


Figure 4.2



Use Adobe pdf to view this 3d model

Figure 4.3: Female (*cross-section view*)



Use Adobe pdf to view this 3d model

Figure 4.4: Male

4.1.2 Electrical Connections

Since there are no control surfaces, actuators etc. associated with the module, only a few electrical connections need to be maintained (mainly power).

Figure 4.2 gives an insight into how this would be achieved. Junction boxes will be installed on the mating surfaces of the main fuselage and the module. One junction box will contain the sockets (receptacles) and the other plugs. These junction boxes will have covers that would keep them covered. A control system provided on the main fuselage will monitor the whole process of joining. After the module is mechanically locked into the fuselage, this control system will open covers and lift the junction box of the fuselage so that the plugs get inserted into sockets thus completing the connection.

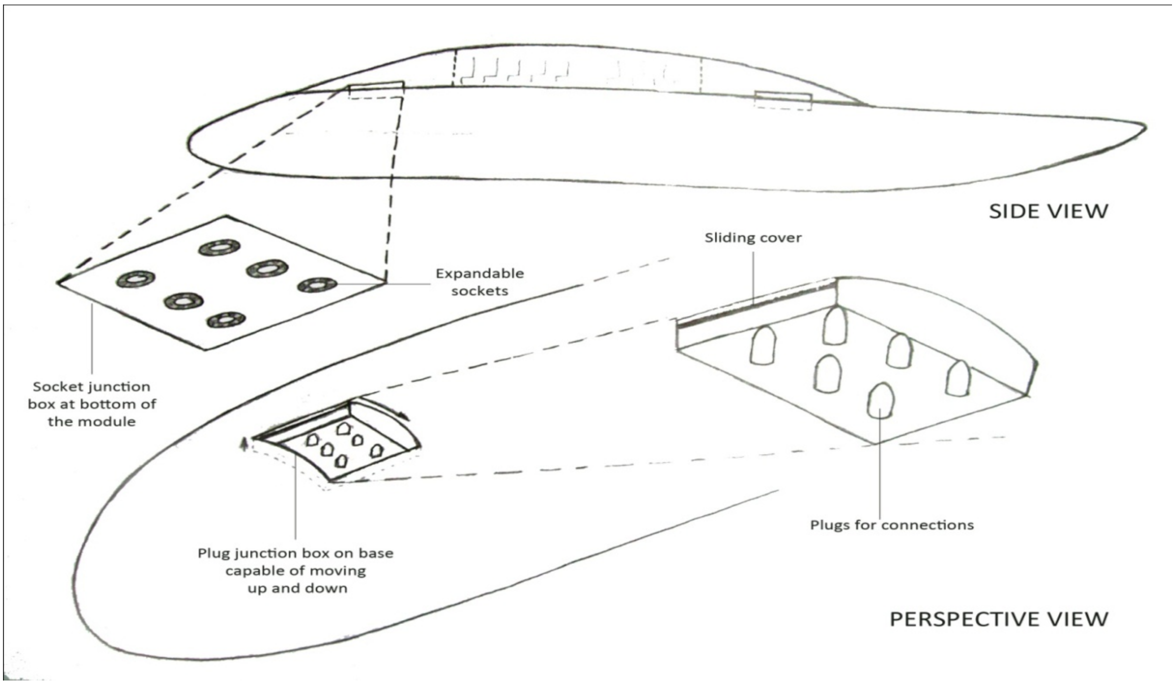


Figure 4.6

4.1.3 Pneumatic Connections

A secondary pneumatic system is required for cabin-pressurization and air-conditioning inside the module. The primary pneumatic system is still required to provide air for this purpose. Hence, we need to provide pneumatic connections between the main fuselage and the module.

The pneumatic connections involved should facilitate easy and quick assembly of the parts. Further, the connections should be able to sustain a pressure of around 30 bars. For this purpose we used **quick-connect** couplings. Such couplings are already available in the market that can sustain this much pressures.

Figure 4.2 gives further insight into the exact joining mechanism. The mechanism is same as the electrical connections. The junction box is common for the electrical and the pneumatic connections and so is the whole mechanism.

4.1.5 Other Technical Challenges

- Hydraulic Connections
  There are no issues of providing hydraulic connections since there are no actuators on the module except the doors. For doors, we can either use electro-hydrostatic actuators (EHA) or electromechanical actuators.

- Engines
  The engines with the highest thrust capacity are used that can propel both A319DD(+) and A319DD(-). Further, since the existing family uses engines that have the same weight, we can use the engine with the highest thrust ratings without necessarily increasing aircraft weight.

4.1.4 Deployment at the airport

Figure-4.2 illustrates the deployment scheme. A platform will be setup at the airport where the modules are stored and deployed. The aircraft will be positioned at a correctly aligned position according to the markings. The module will then be pushed by a pushing mechanism on the platform.

For taking out the module, slots are provided on the front of the module that are otherwise kept covered. The same pushing (pulling) mechanism can then drive it out.

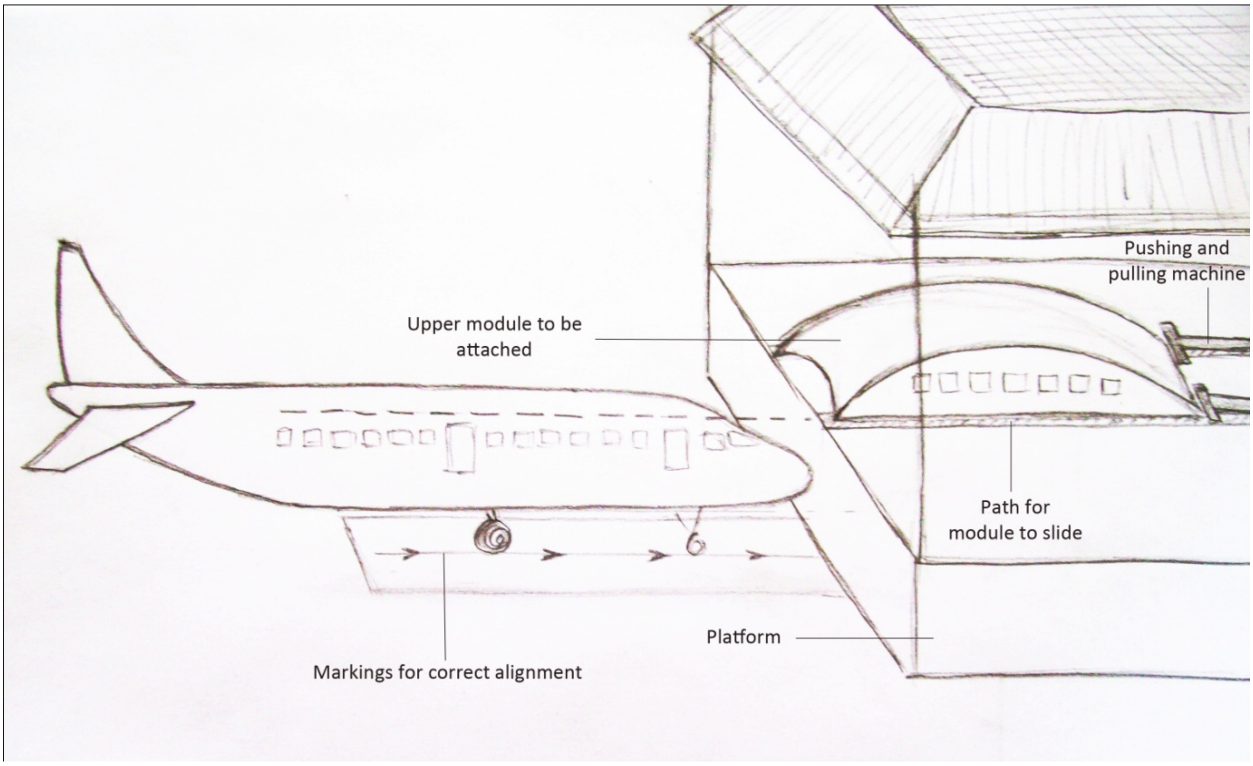


Figure 4.7

Figures 4.8(a) & (b) further show two alternative airport layouts that can be implemented according to the size of the airport terminals. If the terminal is large enough, then the deployment can be done at the terminals itself otherwise it can be done at the hangar or other suitable place.

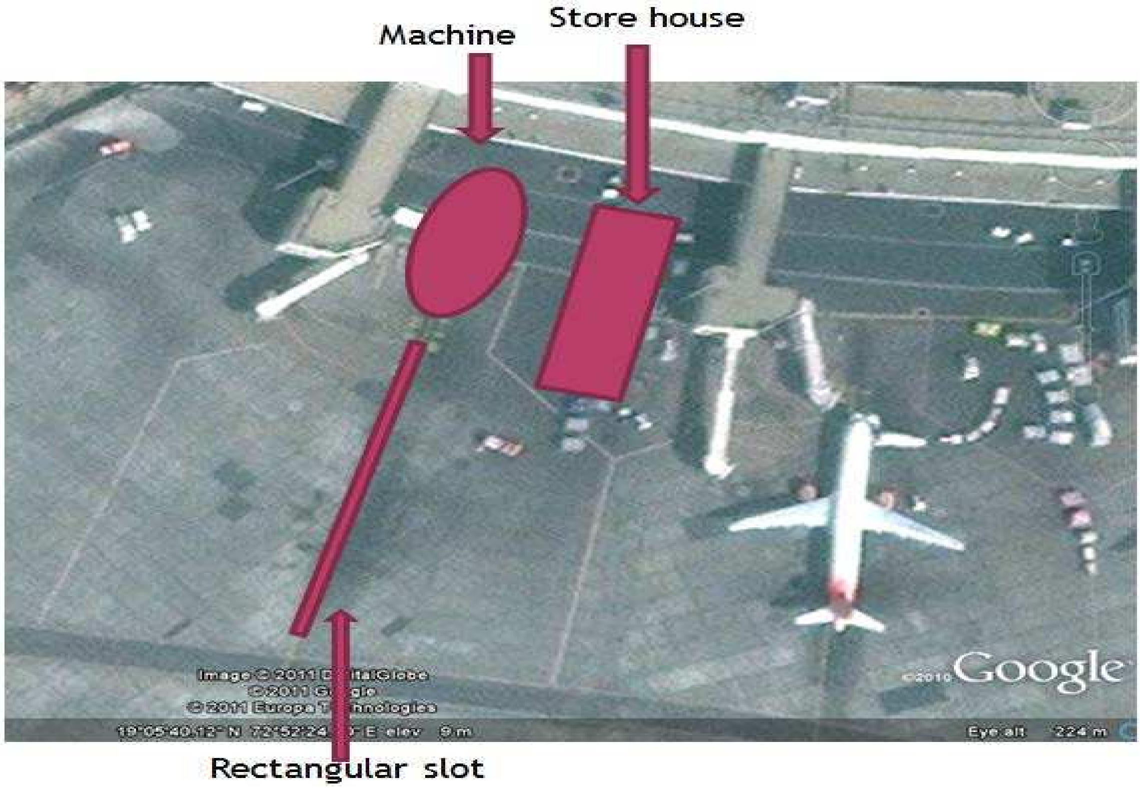


Figure 4.8(a)*: Reconfiguration Platform at Terminal: Mumbai Airport

Figure 4.8(b)*: Reconfiguration Platform at Hangar: New Delhi Airport

*Above images have been obtained using Google Maps®.

4.2 Aerodynamic and Stability Analysis

4.2.1 Drag Estimation

Refer Appendix-C for details.

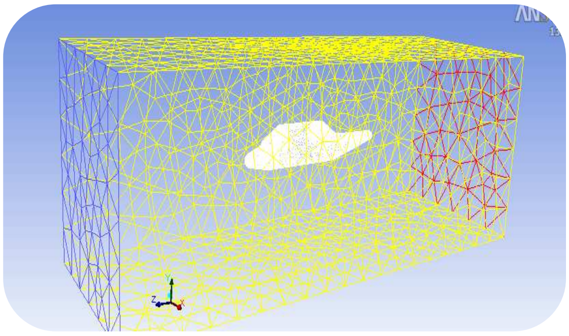
CFD simulations were performed on the double-decker model while making certain assumptions. The total drag forces were calculated on A319DD(+) and A320.5 under following conditions:

- Free air stream velocity: 241 m/s
- Cruise altitude: 31000 ft. (9.45 km)

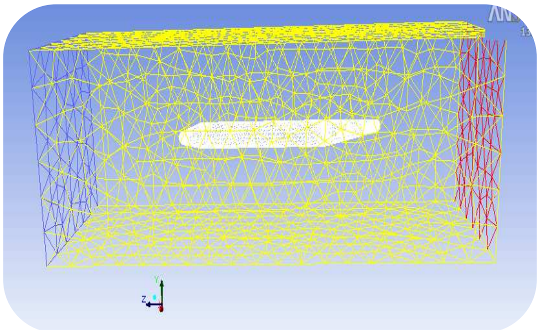
First, the fuselage drag forces were obtained through CFD simulations on the two configurations. The results obtained from simulations are tabulated as under:

Model	Fuselage drag (N)
A320.5	11287
A319-DD	12662

Table 4.2 Fuselage drag force



A319DD(+) Fuselage Profile Mesh



A320.5 Fuselage Profile Mesh

Figure 4.9

The total drag for model A320.5 is assumed to be same as that of A320 and its value is **43730N** (Reference**:** [4] **)**.The total drag from all other components other than fuselage is determined by deducting fuselage drag from total drag for A320.5 which came out to be **32443.7827 N**. This value is finally added to the fuselage drag of A319DD(+) to obtain the total drag on A319-DD. The total drag forces obtained through this approach are:

Model	Total drag (N)
A320.5	43730
A319DD(+)	45106

Table 4.3 Total drag force

Thus, drag force for A319DD(+) is slightly higher than that for A320.5. Other factors such as lift coefficient, total lift are assumed to be same as the major percentage of lift comes from the wings and the wing area for the double-decker model is same as that for A320.5.

4.2.2 Stability

CG Position

- We decided to place the module at a location such that there is a slight rightward longitudinal shift in C.G.
    - C.G. needs to be shifted right as the lift from wing would be higher in case of A319DD(+) as compared to A319DD(-) while the lift from tail would change only a bit. Hence to balance the moments, CG would have to be shifted slightly to the right to decrease the moment arm of wing lift.

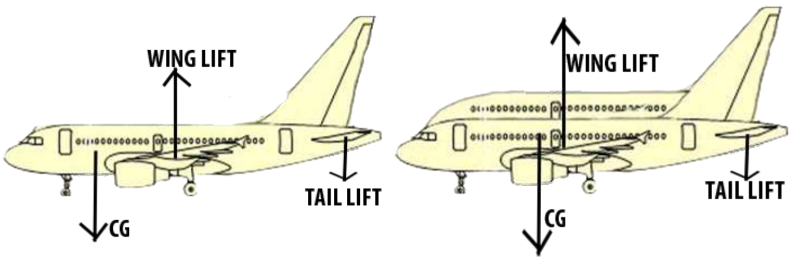


Figure 4.10 *(CG position has been exaggerated for clarity)*

- There would be shift in C.G in vertical direction, but that would not affect the aircraft stability during cruise. However, takeoff and landing characteristics would be modified due to the vertical shift.

Tail moments

The horizontal tail should be able to provide sufficient moments to A319DD(+) as well as A319DD(-). Further, the flow available to the vertical tail would be modified due to the deck. So the tail (elevator and rudder) should be optimized to perform its task.

4.3 Fuel Consumption Analysis

A319DD(+) will have different fuel consumption than the existing A320.5 because of two reasons:

- Difference in Drag
- Difference in Weight

We shall not bother about the fuel consumption of A319DD(-) since it can be safely assumed to be identical to A319.

4.3.1 Weight Estimation of Module

Due to the module, the weight may be different for A319DD(+) and A320.5 although the seating capacity is same. Since the module will not be taking very heavy loads as compared to main fuselage, it can be made of a lighter material and with thinner walls. Hence, it was argued that the weight of A319DD(+) would be slightly less than A320.5. However, for our analysis we take the weight to be same to account for the worst case.

4.3.2 Fuel Consumption

The fuel consumption of A319DD(+) model is expressed relative to that of A320.5 by comparing the total drag forces on the two models. This is justified by the fact that the thrust required for maintaining the same flight conditions viz. elevation, velocity etc. for the double-decker model varies directly as the total drag. Moreover, the weight remains same for the two models (*Section 4.3.1*). So, just by comparing drag we can compare the fuel consumption.

Hence, taking into account only the total drag, the fuel consumption of double-decker model increases relative to that of A320.5 by a factor of **: 45105/43730 = 1.031.**

Hence, A319DD(+) will consume 103.1% of the fuel consumed by A320.5. We can assume it to be 104% by allowing for inaccuracies in simulation and various assumptions we took. This value is used for fuel savings analysis done in Section5.2.

5. Benefit Estimation

This is done in two parts:

Best Configuration Analysis

- This provides us with the **best possible configuration** economically.

→

Fuel Savings

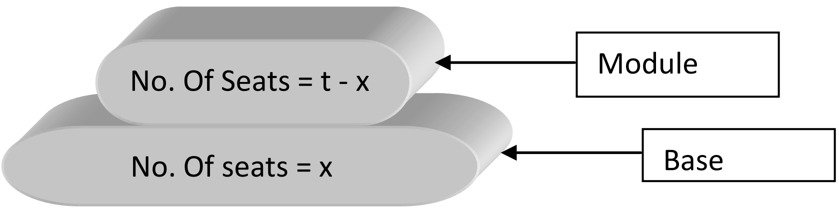
- Based on the best possible configuration obtained from previous analysis, we find out **net fuel savings** that the configuration will provide.
- We then estimated approximate **economic** and **environmental benefits**.

Refer **Appendix D** for more details.

Overview:

Our model can morph into two different seating capacities i.e.:

- Full Capacity ('t' seats)
- Base Model Capacity ('x' seats)



Total capacity = t
Base capacity = x
Module capacity = t - x

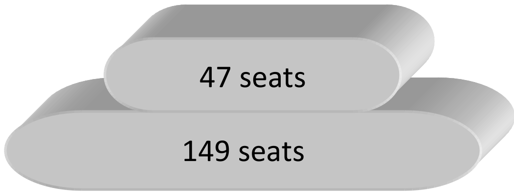
Best possible configuration means how much should be the **total capacity** and the **base capacity** of our aircraft so that it provides the most benefits.

5.1 Best Configuration Determination

5.1.1 Brief Procedure:

- Firstly, A320 is chosen as the base aircraft for our analysis.
  - ✓ We find all possible Passenger Demand Distribution Functions (PDDFs) for this aircraft.
- Then, coming to our modular design, we vary our total seat and base seat capacity, and calculate profits for each particular configuration. These profits are then compared to the existing aircraft (A320) profits.
- After comparing average profits for all the possible configurations, we find which configuration will provide us the best benefits.

5.1.2 Results:



- Best configuration was found to be:
  - Total capacity = 196
  - Base capacity = 149
- Based on these results, we used the following configuration for our analysis:
  - Total capacity = 200(A319DD+)
  - Base capacity = 156(A319DD-)

  **Note that base capacity is taken 156 instead of 149 so that A319DD(-) exactly resembles A319. This will ease our analysis. Correspondingly, we added 44 seats to get 200 total capacity.*

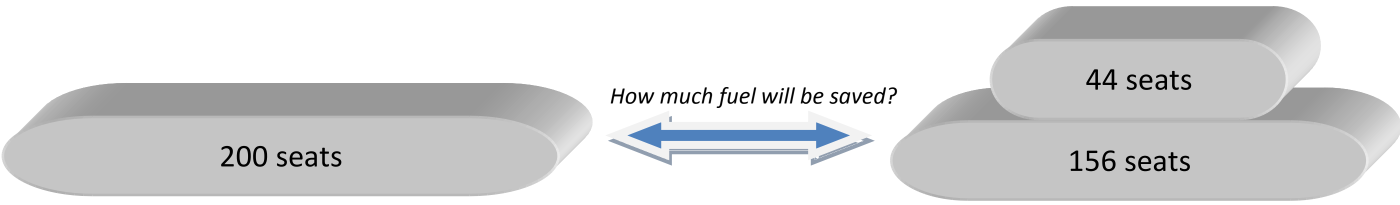
5.1.5 Remarks

Above analysis was based on several assumptions. But finally it estimated the best configuration. That was the main motive of this analysis.

Then, we did a fuel savings analysis (Section 5.2) without using any of the above assumptions and by using the best configuration provided by this analysis.

5.2 Fuel Savings Analysis

The suggested model configuration from above analysis is now taken to calculate the fuel savings when it is used as a replacement for a non-reconfigurable same capacity aircraft.



From technical fuel efficiency analysis, it was found that for a particular flight, our double-decker design(A319DD+) would consume more fuel as compared to the existing aircraft of the same capacity(A320.5). This factor was found to be approximately 104% (Section 4.3.2). However, when our design was incorporated to increase the passenger load factor, it was overall much more fuel efficient.

Incorporating the 104% factor and the passenger load factor in our MATLAB code, we found that our design saved fuel by an enormous factor of 7.24%.

- ✓ ***Appendix D is recommended for more insight into the method used to determine these values.***

5.3 Annual fuel savings

See appendix D for calculations.

Annual fuel savings = 3697 barrel per aircraft per year

Considering that the modular design replaces the entire 4,532 A320 models currently in operation. This would correspond to:

Annual fuel savings = 4532*3697 = 16,754,804 barrel per year.

5.4 Environmental Benefits

5.4.1 Reduction in CO_2 levels

See appendix D for calculations.

Reduction in CO_2 emission per year = 1448 tonnes per aircraft

Considering that the modular design replaces the entire 4,532 A320 models currently in operation. This would correspond to:

Reduction in CO_2 emission per year = 1448*4532 = 6,562,336 tonnes

5.4.2 Energy Saved

See appendix D for calculations.

Energy savings=5,590 MW-h per aircraft per year

This energy corresponds to a 638 KW power-plant generating energy throughout a year.

Considering the fuel savings if entire 4,532 A320 models are replaced,

Energy savings per year=25,334 GW-h.

This is equivalent to a 2892 MW power-plant generating energy in a year. Moreover, this is equivalent to setting up four largest wind farm power generating units*.

5.5 Assumptions

We have not considered the increased costs due to deployability at the airports. This will affect the revenues of the airlines however the fuel savings will still remains same since the energy consumed at the airports for reconfiguration will be insignificant as compared to our fuel savings.

*The largest wind farm in the world is Florida Power & Light's horse hollow wind energy centre located in Taylor County, Texas, with 421 turbines and a capacity of 735 Megawatts.

6. Conclusion

Above analysis reveals us that the concept, if implemented as the double-decker design replacing the A320 family, can provide us with the following benefits:

Environmental Benefits

- 6.56 million Tonnes of CO_2 emission reduction per year.
- Energy savings of 25.3 TW-h per year.
- The energy saved by our concept in a year can serve the world's energy needs for about half of a day, serve the European Union's needs for more than 3 days and serve the needs of a nation as big as India for more than 15 days!! (*Calculations based upon energy needs given on Wikipedia*)
- Due to increase in load factor, there will be reduction in air traffic. This will cause reduction in noise pollution.

Economic Benefits

- Annual savings of 151923.21€ per aircraft.
- Reduction in capital investment.
- Increased ability to land at different airports.
- Reduction in air-traffic.

7. Recommendations

When the concept was initially conceived, it was never thought that it might prove to be of such potential. However, the concept generated such enormous benefits that we sincerely think of a further research on this concept. We recommend following steps that can be taken by the industry to develop the concept:

- Develop a more aerodynamically efficient design. Our design had severe aerodynamic restrictions. Still it provided enormous benefits. An aerodynamically better design can be a chapter in airline history.
- A better and exhaustive economic analysis using survey data needs to be done for better estimation of benefits.
- With the introduction of modular aircraft, new methodologies need to be adopted for manufacturing. An intensive research needs to be done so that there are very little modifications in the current manufacturing process so as to minimize capital investment.

8. References

See Appendix-A for reference.

See Appendix-B for life-cycle analysis.

APPENDIX A

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1. References

[1] www.sciencedirect.com (Sustainable Air Transport-on track in 2050-Jonas Akerman 2005)

[2] www.airbus.com (Reference for aircraft Sales Records)

[3] 3ds max model

[4] www.lissys.demon.co.uk/pug/c05.html (See Appendix C for full details)

[5] http://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/Industry-Facts-March-2011.pdf

[6] http://www.iata.org/pressroom/Documents/IATAAnnualReport2010.pdf

[7] Airbus : A320 Family Performance Retention and Fuel Savings

[8] http://ocw.mit.edu/courses/aeronautics-and-astronautics/16-75j-airline-management-spring-2006/lecture-notes/lect4a.pdf

[9] http://en.wikipedia.org/wiki/Airbus_A320_family

[10] http://www.iata.org/whatwedo/economics/fuel_monitor/Pages/index.aspx

[11] http://en.wikipedia.org/wiki/Jet_fuel

[12] http://en.wikipedia.org/wiki/Power_station

2. Softwares Used

2.1 3-D Models for Double-decker design (Fig 4.1)

- Autodesk inventor
- Solidworks

2.2 Model rendered in flight gear for animation (Fig 4.1.b)

- 3ds-max

2.3 Joints Design (Fig 4.4, 4.5)

- Autodesk Inventor

2.4 Aerodynamic Simulations (Fig 4.9)

- Ansys Fluent

2.5 Double-decker Animation (Video)

- Flight-gear

APPENDIX B

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Contents

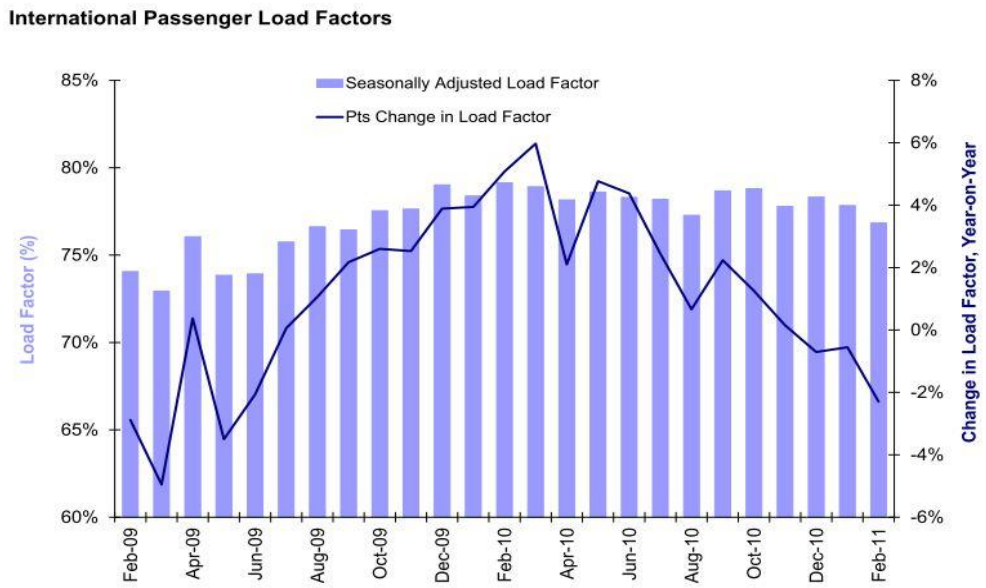
1. Indian Airports Survey

The following data shows which members of A320 family can land at different Indian airports. This data was obtained using the maximum runway lengths of different airports and comparing them with the runway length requirements of the different members of the family.

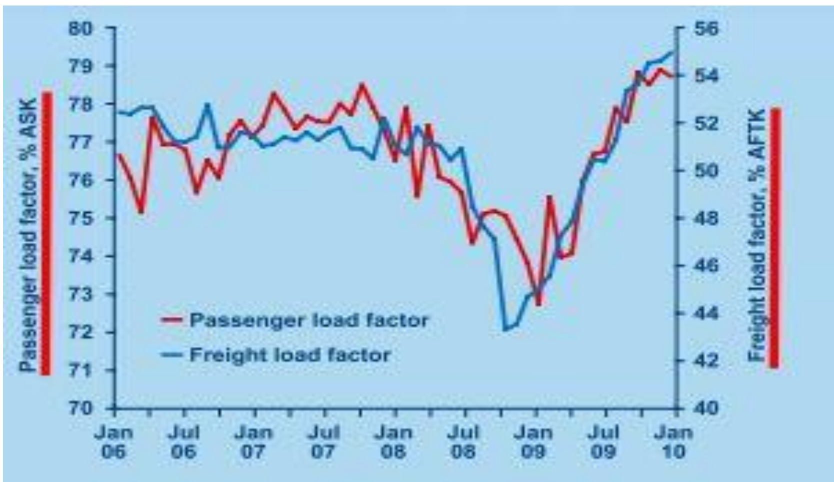
AIRPORTS	RUNWAY LENGTH (METRES)	A318 (1355m)	A319 (1950m)	A320 (2090m)	A321 (2180m)
Keshod	1372	Yes	--	--	--
Porbandar	1372	Yes	--	--	--
Pantnagar	1372	Yes	--	--	--
Latur	1372	Yes	--	--	--
Gandhinagar	1378	Yes	--	--	--
Ludhiana	1463	Yes	--	--	--
Kandla	1523	Yes	--	--	--
Bilaspur	1535	Yes	--	--	--
Rajahmundry	1740	Yes	--	--	--
Silchar Kumbhigram	1827	Yes	--	--	--
Shillong	1829	Yes	--	--	--
Rajkot	1841	Yes	--	--	--
Patna	1954	Yes	Yes	--	--
Raipur	1955	Yes	Yes	--	--
Jabalpur	1988	Yes	Yes	--	--
Sholapur	2009	Yes	Yes	--	--
Bhopal	2042	Yes	Yes	--	--
Jammu	2059	Yes	Yes	--	--
Dehrandun	2140	Yes	Yes	Yes	--
Belgaum	2190	Yes	Yes	Yes	Yes
Hosur	2195	Yes	Yes	Yes	Yes
Varanasi	2206	Yes	Yes	Yes	Yes
Chakulia	2220	Yes	Yes	Yes	Yes
Bhubaneshwar	2243	Yes	Yes	Yes	Yes
Khajuraho	2274	Yes	Yes	Yes	Yes
Udaipur	2281	Yes	Yes	Yes	Yes
Agartala	2286	Yes	Yes	Yes	Yes
Madurai	2286	Yes	Yes	Yes	Yes
Lilabari North Lakhimpur	2286	Yes	Yes	Yes	Yes
Tirupati	2286	Yes	Yes	Yes	Yes
Vijayawada	2286	Yes	Yes	Yes	Yes
Nanded	2300	Yes	Yes	Yes	Yes
Aurangabad	2351	Yes	Yes	Yes	Yes
Mangalore	2450	Yes	Yes	Yes	Yes
Vadodara	2469	Yes	Yes	Yes	Yes
Allahabad Bamrauli	2472	Yes	Yes	Yes	Yes
Tiruchirappalli	2480	Yes	Yes	Yes	Yes
Aizwal	2500	Yes	Yes	Yes	Yes
Bhuj	2501	Yes	Yes	Yes	Yes
Jamnagar	2512	Yes	Yes	Yes	Yes
Pune	2539	Yes	Yes	Yes	Yes
Ranchi	2699	Yes	Yes	Yes	Yes
Pathankot	2734	Yes	Yes	Yes	Yes
Jaisalmer	2742	Yes	Yes	Yes	Yes
Agra	2743	Yes	Yes	Yes	Yes
Gorakhpur	2743	Yes	Yes	Yes	Yes
Gwalior	2743	Yes	Yes	Yes	Yes
Jorhat	2743	Yes	Yes	Yes	Yes
Kanpur Chakeri	2743	Yes	Yes	Yes	Yes
Chandigarh	2744	Yes	Yes	Yes	Yes
Jodhpur	2745	Yes	Yes	Yes	Yes
Imphal Tulihal	2746	Yes	Yes	Yes	Yes
Tezu	2746	Yes	Yes	Yes	Yes
Indore	2750	Yes	Yes	Yes	Yes
Baghdogra	2754	Yes	Yes	Yes	Yes
Leh	2755	Yes	Yes	Yes	Yes
Jaipur	2797	Yes	Yes	Yes	Yes
Calicut	2860	Yes	Yes	Yes	Yes
Coimbatore	2990	Yes	Yes	Yes	Yes
Lucknow	3059	Yes	Yes	Yes	Yes
Guwahati	3110	Yes	Yes	Yes	Yes
Nagpur	3200	Yes	Yes	Yes	Yes
Vishakhapatnam	3200	Yes	Yes	Yes	Yes
Amritsar	3289	Yes	Yes	Yes	Yes
Port Blair	3290	Yes	Yes	Yes	Yes
Trivandrum	3398	Yes	Yes	Yes	Yes
Cochin	3400	Yes	Yes	Yes	Yes
Bombay	3445	Yes	Yes	Yes	Yes
Goa Navy	3458	Yes	Yes	Yes	Yes
Ahmedabad	3599	Yes	Yes	Yes	Yes
Calcutta	3627	Yes	Yes	Yes	Yes
Madras	3658	Yes	Yes	Yes	Yes
Srinagar	3685	Yes	Yes	Yes	Yes
Bangalore	4000	Yes	Yes	Yes	Yes
Hyderabad	4260	Yes	Yes	Yes	Yes
Delhi Indira Gandhi	4430	Yes	Yes	Yes	Yes

2. Passenger Load Factor

For the detailed economic analysis, the international passenger load factors were obtained on a yearly as well as monthly basis. The following two figures show the passenger load factor variation on monthly and yearly basis respectively:



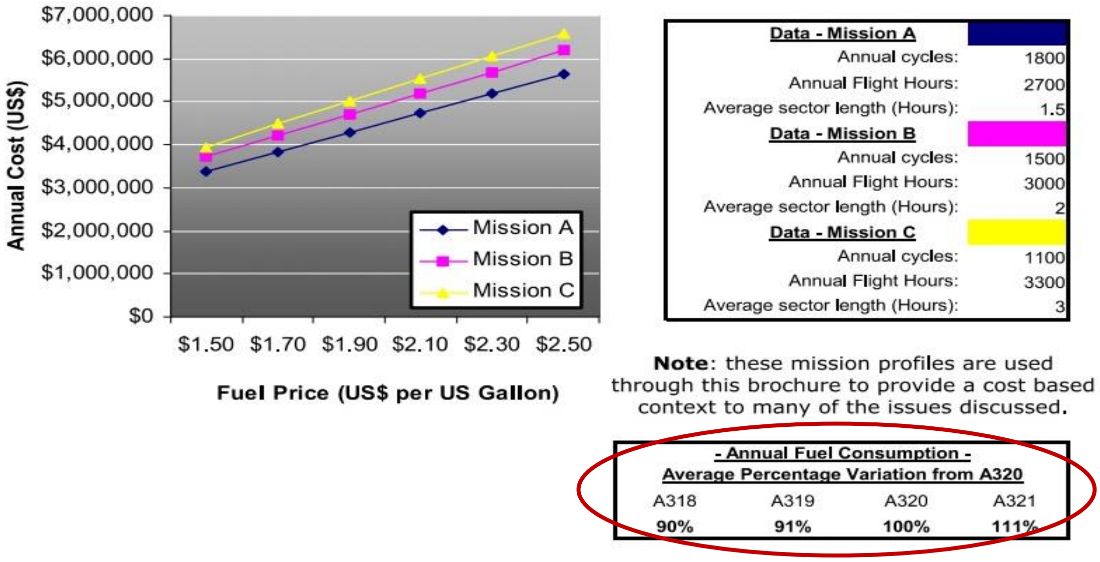
IATA monthly MIS traffic statistics [5]



Source: Platts, RBS [6]

3. Fuel Consumption Comparison

The following estimate helped us find the best transformation which could provide us with the maximum possible benefits. The fuel savings for each transformation within the family A320 is shown in the table as under:



A320 Family performance retention and fuel savings (Reference: [7])

-Annual Fuel Consumption- Average Percentage Variation from A320			
A318	**A319**	**A320**	**A321**
90%	91%	100%	111%

From the above data, we can directly compare the fuel consumption.

TRANSFORMATION	LOAD FACTOR (%)	FUEL SAVED (%)
A321 to A320	82	9.91
A321 to A319	71	18.02
A321 to A318	60	18.92
A320 to A319	87	9
A320 to A318	73	10
A319 to A318	85	1.1

The relative fuel consumption figures obtained here were also used in Detailed Benefit Estimation.

4. Energy Savings Calculation

4.1 Annual fuel savings

It was found that a reduction in fuel consumption by 3.5% corresponds to an annual savings about 151,923€ per aircraft (Reference: [9]). Consequently, a fuel savings of 7.24% would correspond to an annual savings of 314,264€ per aircraft. This led us to estimate the fuel savings using the following approach:

Current Fuel price = 85€ per barrel (Reference: [10]).
Annual fuel savings = 314264/85= 3697 barrel per aircraft per year

Considering that the modular design replaces the entire 4,532 A320 models currently in operation. This would correspond to:

Annual fuel savings = 4532*3697 = 16,754,804 barrel per year.

4.2 Environmental Benefits

4.2.1 Reduction in CO_2 levels

This is estimated considering the fact that a fuel savings by 3.5% reduces the CO_2 emission by 700 tonnes per aircraft per year (Reference [9]). Hence, a fuel savings by 7.24% led to the following result:

Reduction in CO_2 emission per year = 1448 tonnes per aircraft

Considering that the modular design replaces the entire 4,532 A320 models currently in operation. This would correspond to:

Reduction in CO_2 emission per year = 1448*4532 = 6,562,336 tonnes

4.2.2 Energy Saved

The energy savings are estimated using the following approach:

Specific energy of jet fuel= 42.80 MJ/kg (minimum value has been taken) (Reference: [11]).
Fuel savings = 3697 barrels (587,775 litres) per aircraft per year
Energy savings = 587775*0.80*42.80MJ (assuming fuel density to be 0.80kg/L) (Reference: [11]).
= 20,125 GJ
= 5,590 MW-h per aircraft per year

This energy corresponds to a 638 KW power-plant generating energy throughout a year.

Considering the fuel savings if entire 4,532 A320 models are replaced,
Energy savings per year = 4532*5590 MW-h
= 25,334 GW-h.

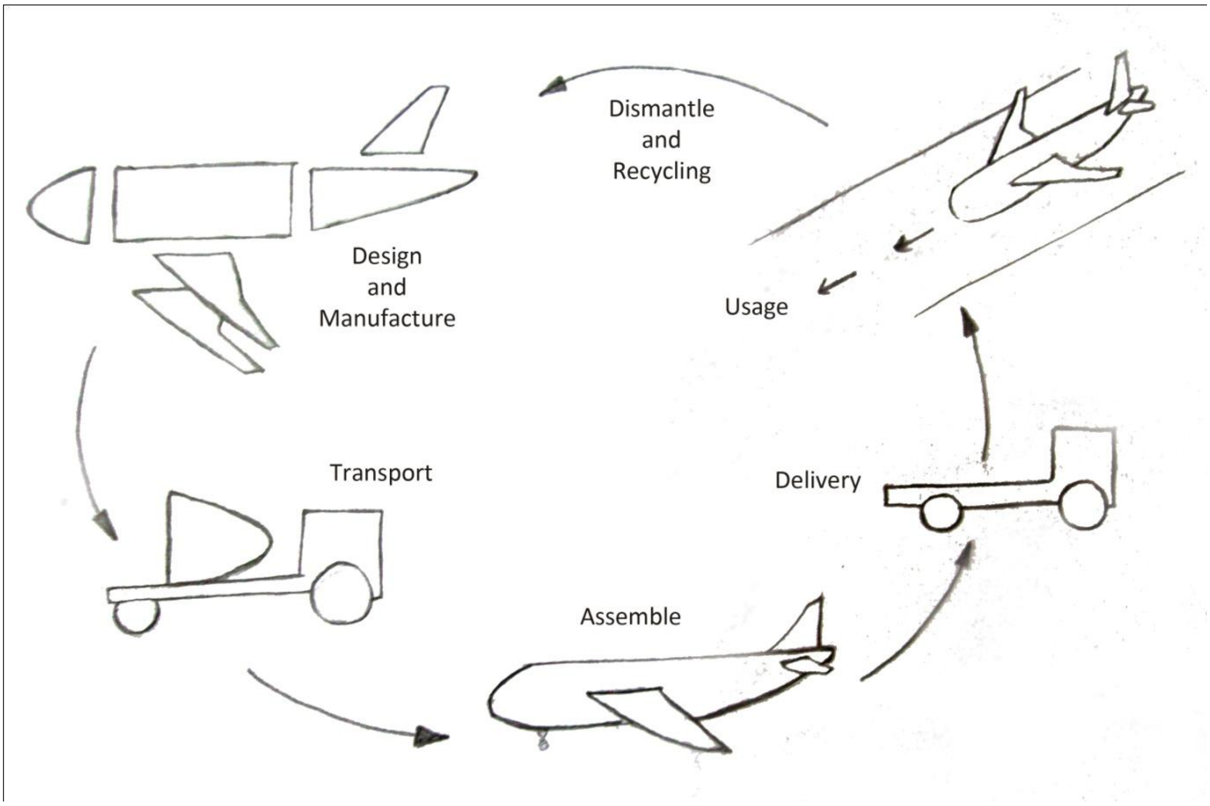
This is equivalent to a 2892 MW power-plant generating energy in a year. Moreover, this is equivalent to setting up four largest wind farm power generating unit(Reference: [12]).

5.Life Cycle Analysis

The life cycle of an aircraft starts with the design and manufacturing of its individual parts. These are then transported and assembled at one place to make the entire aircraft. The supply chain to various customers involves the safe transportation of the product to the airlines. Aircrafts typically undergo a usage life of around 25 years after some of the aircrafts are also used as a freighter for some time. They are then decommissioned, dismantled and put to recycling with taking out the spare parts (70%), testifying and reusing them.

From the recycling point of view our design would have the following advantages:

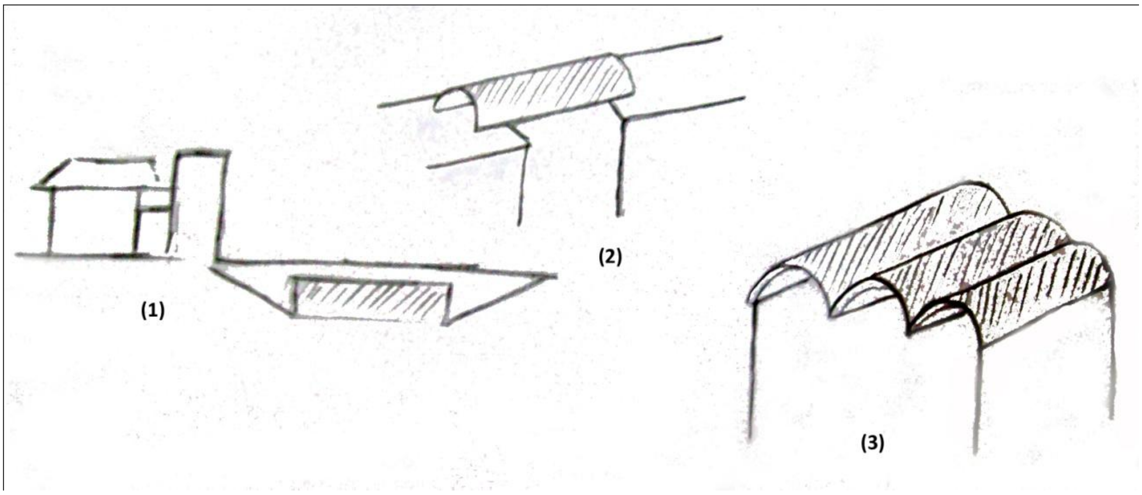
1) The life cycle of the upper module would be longer than that of the base.
2) The upper module would be easier to recycle as the amount of complexity in it would be lesser than the base.
3) The loads to be taken by the upper module will be lesser than the base and hence the change of material can be tried to make it more lighter but still strong.



A major concern for any product is the death of it and what will be its fate after that. We propose three possible uses of the upper module after its life cycle is over.

1) The fuselage can be emptied and modified to be used as a subway underground. Since the interior part of it would be anyways removed, the structure can be used to make the walls of a subway.

2) Similarly, overhead bridges on the airport itself could be made out of the fuselage structure.
3) Few of the upper module fuselages can be joined/welded together to make the roof of hangers at the airports. In this way, the dead aircrafts would not have to be taken anywhere else and can be put to use at the nearest.



APPENDIX C

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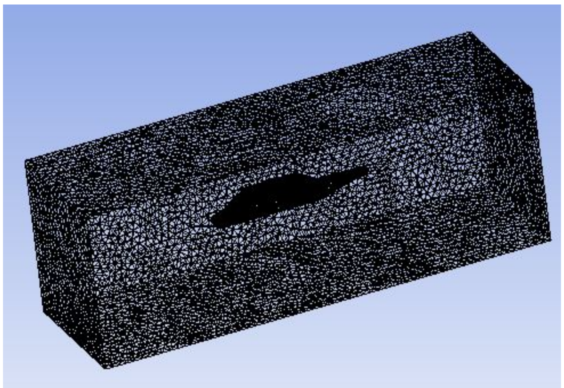
C. Aerodynamic and stability Analysis of Double-Decker

1. Aerodynamic analysis

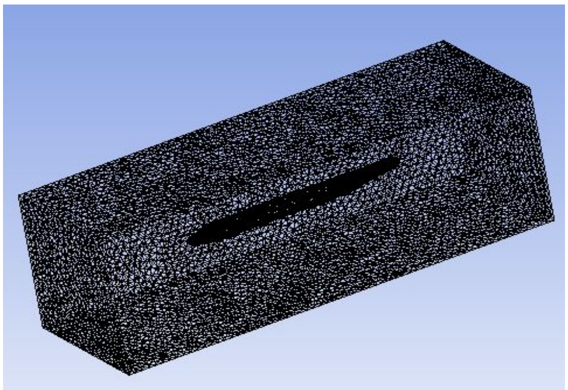
The following conditions were assumed for the aerodynamic analysis:

- Free air stream velocity: 241 m/s
- Mach no: 0.8
- Cruise altitude: 31000 ft. (9.45 km)
- Operating pressure: 28584 Pa
- Operating temperature: 226.5 k
- Air density= 0.43966 kg/m^3

For drag comparison, we determined fuselage drag forces through simulations on both the configurations: A320.5 and A319 Double-Decker.



A319-DD(+) Fuselage profile mesh



A 320.5 Fuselage Profile mesh

Further, we assumed: Total drag on A320.5 = Total drag on A320.
The total drag and the fuselage drag of A320 were found from a sample A320 aerodynamic report (see next page) as follows:

1. Total drag = 43730 N (9831 lbf)
2. Cd zero-lift = 67.1 %, fuselage &fairing Drag = 45.7% of zero-lift drag.
3. Fuselage drag on A320 = 43730*.671*.45 = 13410 N

The fuselage drag obtained from A320.5 simulation came out to be 11287N which is slightly less than the value we obtained in step (3). This value is then deducted from the total drag on A320 to get the drag contributions from rest of the components.

4. Drag from other components = 43730 - 11287= 32443 N.

Finally, the fuselage drag obtained for A319 DD (+) simulation is added to 32443 N to get the total drag on A319DD (+).

5. Total drag on A319DD(+) = 12662+32443 = 45105N

Note: The drag forces obtained through this analysis are only an estimate and not exact figures. These are evaluated just for a comparison of the aerodynamic efficiency of the double Decker configuration relative to that of the base configuration.

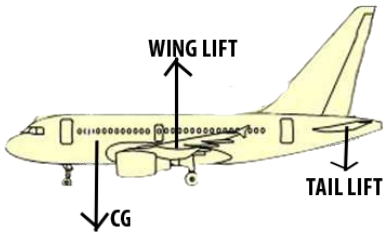
Sample Aerodynamic Report

```
AERODYNAMIC DRAG REPORT at:
---------------------------
MACH                    0.800
Altitude (pressure)     31000. feet
KTAS                    469.4
KEAS                    281.9
KCAS                    297.4
Reynolds number         2.202  millions per foot
Delta-ISA                 +0.  deg.C.

CL                      0.493  based on:
Reference Area        1207.20 sq.feet  (trapezoidal)

Drag Coefficients based on ref.area
-----------------------------------

Cd Zero-Lift                0.02033    (67.1 %)
Cd Lift-Induced             0.00905    (29.9 %)
Cd Compressibility          0.00078    ( 2.6 %)
Cd Trim                     0.00012    ( 0.4 %)
Delta Cd (polar-mod)        0.00000    ( 0.0 %)
                            -------    --------
Cd Total                    0.03028    ( 100 %)

Aerodynamic Boundaries:
-----------------------
Divergence Mach           0.774 {at the given CL 0.493}
Initial Buffet Mach       0.887 {at the given CL 0.493}
Initial Buffet CL         0.845 {at the given Mach 0.800}

Zero-Lift Component Breakdown (Drag Areas,= Cd*S = D/q)
-----------------------------

Wing                      7.803  sq.feet    (31.8 %)
Winglets                  0.105  sq.feet    ( 0.4 %)
Fuselage & fairing       11.225  sq.feet    (45.7 %)
Stabiliser                1.780  sq.feet    ( 7.3 %)
Fin                       1.609  sq.feet    ( 6.6 %)
Nacelles (total)          2.015  sq.feet    ( 8.2 %)
User CdS Increment        0.000  sq.feet    ( 0.0 %)
                        -------             --------
Total Cd0*S              24.536  sq.feet    ( 100 %)

Overall Lift / Drag Ratio = 16.27
=================================

Total Lift Force      160001. lbf.
Total Drag Force        9831. lbf. (4916.lbf. per engine)
```

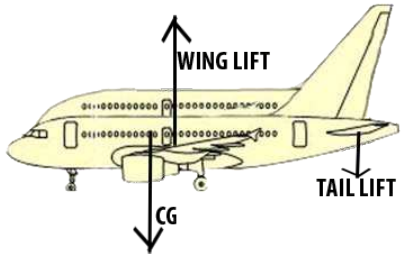
Reference: http://www.lissys.demon.co.uk/pug/c05.html

2. Stability Analysis

The modular deck increases the weight of the double-decker relative to the base version i.e. A319-dd (-). This means that more lift will be required for the higher version i.e. A319-dd (+) to maintain the same flight conditions. This would lead to increase in moment created due to lift which needs to be countered by the weight as well as negative lift from the tail.



A 319-DD(-)



A319-DD(+)

Since, the tail provides very low negative lift, it is suggested that the module be placed at a location such that there is a slight rightward longitudinal C.G shift. This would reduce the moment arm of lift force and hence, no tail modifications are required to maintain the stability during cruise conditions.

APPENDIX D

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Benefits Estimation Details

Here we are detailing the benefit estimation philosophy used in Section-5. This estimation is based upon standard benefit estimation procedures used by airline companies using passenger demand distribution functions. Reader is recommended to have a basic knowledge of probability theory.

Remarks

- The analysis is independent of the concept used. Hence, the analysis can be used for any modular concept in future.
- This analysis is better than a case-study that could have been done because:
  - Case study would have not been possible for such a new concept without proper data.
  - This analysis is based on probability theory which is fairly reliable and well-used in airline industry.

1. Best Configuration Determination

See attached MATLAB® codes main.m for the algorithm.

Reader can directly jump to the fuel efficiency analysis without understanding this part and consider this part as a black box which gives us the best configuration.

Further, reference for this section is MIT lecture series.

1.1 How to find Passenger Demand Distribution Function (PDDF)?

- It is assumed that distribution of passenger demand in aircraft industry is a **truncated normal distribution** for mathematical analysis.
- The ratio of standard deviation(σ) to mean(μ) is **coefficient of variation(k)**.
- Typical k values for airline industry demand distribution ranges between **0.20 & 0.40**. *This is based upon an extensive research in airline industry. (Ref: MIT Lecture* [8])
- The mean of the demand function of an aircraft can be calculated from its **passenger load factor(PLF)**. And if mean is found the whole demand distribution function is found(why?).

How to find mean(μ)?

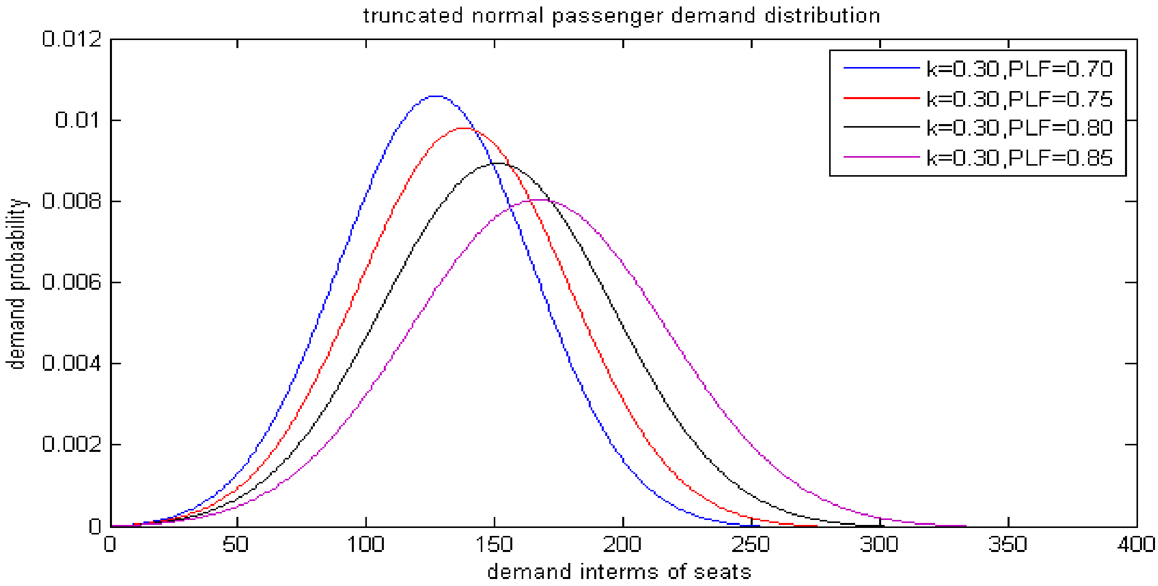
- Consider A320(180 seats) case.
- Let us assume k to be something between 0.2 and 0.4.
- The demand of an aircraft ranges from 1 seat to 2*μ seats.
- Let the demand probabilities are p1,p2,……,p180,p181,….,p2μ for seats 1,2,…180,181,…2*μ respectively. These demand probabilities are functions of mean μ.
- The average number of seats filled in an aircraft in this case is

$$(p1 * 1 + p2 * 2 + \cdots \ldots + p179 * 179 + (p180 + p181 + \cdots . p2\mu\ ) * 180)$$

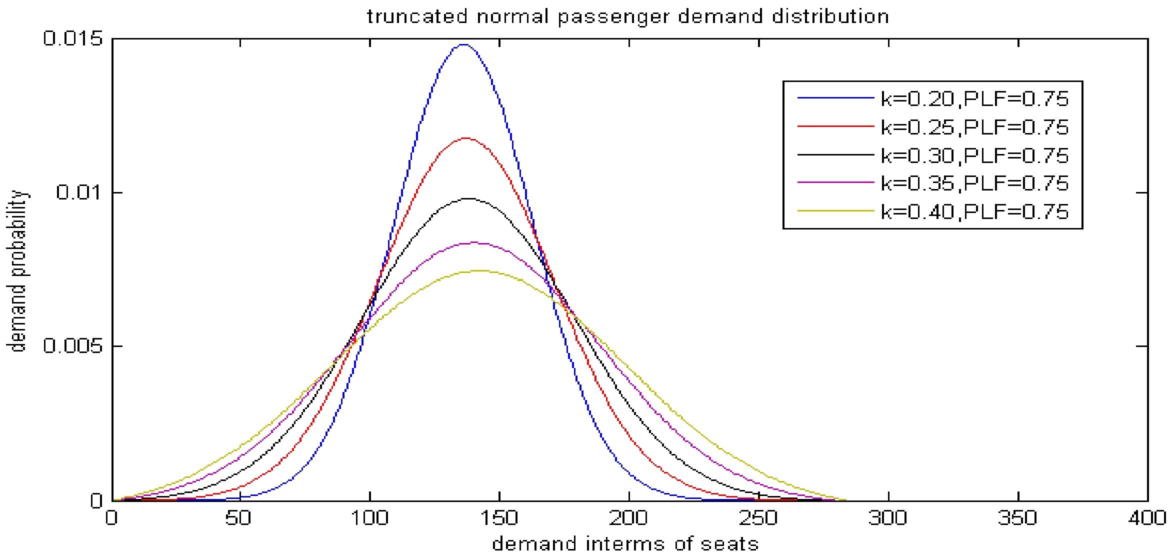
- Average number of seats occupied = Passenger Load Factor *Total number of seats
- From here μ is found.

Summary

- PDDFs are a function of 'k', 'PLF' and the aircraft concerned (i.e. the total capacity of the aircraft).
- For a particular aircraft chosen, there will be many PDDFs depending upon the 'k' and 'PLF'chosen.



A320 PDDF for constant 'k' and varying 'PLF'



A320 PDDF for varying 'k' and constant 'PLF'

1.2 How to calculate profits?

STEP1: ESTIMATION OF OPERATING COST

- Let p is probability of using base model (calculated from demand distribution)
- Let c1 is operating cost of base model aircraft
  - It is assumed that on an average for one aircraft seat 50$ is the operating cost
  - So, $c1 = 50\$ * x$
- Let c2 is operating cost of full capacity aircraft
  - For module, operating cost was assumed to be 60$ i.e. somewhat higher, to account for the increased fuel consumption, airport maneuvering etc.
  - So, $c2 = c1 + 60\$ * (t - x)$
- $\text{Average operating cost} = (p * c1) + (1 - p) * (c2)$

STEP 2: ESTIMATION OF REVENUE

- It is assumed that on an average for one aircraft seat 200$ is the revenue generated
- So $\text{average revenue} = 200\$ * \text{average number of seats filled}$.

STEP 3: ESTIMATION OF PROFITS

- Average profit = average revenue – average operating cost

STEP 4: Compare this profits with the existing profits

- The average profit of the actual A320 was calculated for comparison.

STEP 5 : Vary the base model and total seating capacities to find the best seating capacity

- This is done by repeating all the previous steps again for different combinations of base model and total seating capacities.

Different combinations of PDDFs

STEP 6:

- As the demand function changes with the day, month, location etc., so find the best seating capacity assuming all the possible demand functions as equi-probable
- Again, we will go back to all the previous steps and try different values of k (from 0.2 to 0.4)

STEP 7:

- Now we vary passenger load factor from 0.70 to 0.85 to encounter all possible cases. Again, we get different demand functions which are all assumed to be equi-probable.

STEP 8:

- Find the average revenue, cost, profits for this suggested model and compare with the existing values.

Remarks

- Above analysis reveals us the exact profits that this concept provides (step8). However, since there were certain assumptions taken such as 50$ and 60$ operating costs and 200$ revenue. So, we didn't report these profits in the main report. Hence, a more reliable analysis was done without these assumptions.
- Why was module operating cost taken to be 60$? To account for increased fuel consumption of A319DD(+) as compared to A320.5, increased maintenance costs at the airport etc.

2. Fuel Savings Analysis

See the attached MATLAB® code FuelEfficiency.m for algorithm.

Note that this analysis is totally independent from the previous analysis. Previous analysis just provides us the best configuration. This analysis finds out the exact fuel savings which we can further use to determine economic and environmental benefits as done in the report.

Explanation of Algorithm

1) First, we find out PPDFs based on the A320 market. Why A320? Because that's what is existing currently and is real.
2) Then, we plotted piecewise linear curve (Fuel consumption Vs Seat capacity) using the fuel consumptions of existing A320 aircraft. This was done to estimate the fuel consumption of an imaginary aircraft having seat capacity intermediate of the existing aircraft.
3) Then, we find out the fuel consumptions of the different models.
    - Fuel consumption of A319DD(-) = Fuel consumption of A319
    - Fuel consumption of A320.5 = From piecewise linear curve in (2)
    - Fuel consumption of A319DD(+) = 104% of that of A320.5
        - This 104% was found out from fuel consumption analysis in Section 4.3.2
4) Now, using the PPDF, we found out the probability of using A319DD(-) and A319DD(+).
    - Probability of using A319DD(-) is when the demand is less than (156+4) seats.
    - Probability of using A319DD(+) is when demand is more than (156+4) seats.
    - The number '4' appearing is used to account for the fact that the airline would not use the module(deck) unless there are more than 4 seats booked for the deck. It might be futile for the airline to carry the deck if only one person is travelling in it.
5) Then we found out the net fuel consumption based on the usage of A319DD(+) and A319DD(-). We also found the fuel consumption that A320.5 would ask for the same PDDF.

6) We compared the fuel consumption and found out the net savings our design provided.

3. Final Remarks

- One might argue why even the benefit estimation analysis was done. Best configuration could also have been found out using Fuel Savings analysis by trying different configurations. But this was done as the benefit estimation was based upon standard procedures used in airline industry. So it may have some worth.

MATLAB Codes

- Main.m is the main file for benefit estimation.
- FuelEfficiency.m depends upon main.m to calculate PDDFs. (mean is loaded from main.m). So first run main.m and then run FuelEfficiency.m.
- main2.m is now redundant. We haven't shown any results based on this. However, it is fully operational and produces results of economic benefits.

main.m

```
tic
clc
close all
clear all

%This code computes maximum profitable seating capacities of a
reconfigurable aircraft assuming all possible demand distributions are
%equiprobable.Here our modular aircraft profits are compard with existing
aircraft profits

RASC=180;      %RASC-Reference Aircraft Seat Capacity

kSize=size((0.20:0.01:0.40),2);          %k is the coefficient of
variation(ratio of standard deviation to its mean).
                                            %It ranges between 0.20 and 0.40
for aircraft industry

PLFSize=size((0.70:0.01:0.85),2);        %PLF-Passenger Load Factor.PLF
generally ranges between 0.70 & 0.85
TSCSize=size((1:RASC+25),2);             %TSC-Total Seat Capacity.Total
seating capacity is assumed to vary within 25 seats of actual seating
capacity


AEPCEP=zeros(TSCSize,TSCSize);  %AEPCEP-Average Extra Profits Compared to
Existing Profits in percentage

EPCEP=zeros(kSize,PLFSize);    %EPCEP-Extra Profits Compared to Existing
Profits in percentage

mean=zeros(kSize,PLFSize);     %here mean is the mean of the demand
distributions

kIndex=0;

 for k=0.20:0.01:0.40
    kIndex=kIndex+1;

    PLFIndex=0;

    for PLF=0.70:0.01:0.85
        PLFIndex=PLFIndex+1;


%finding the mean of the demand distribution assuming demand distribution
varies as normal distribution
```

```
ANSO=zeros(1,RASC);   %Average Number of Seats Occupied in aircraft

%The following two loops solve the transcdental equation given in the PPT
to find the value of mean of the demand distribution for a given k and PLF.

for mu=round(RASC*PLF):RASC                         %mu is the mean of demand
distibution.It is greater than RASC*PLF

    demdis=zeros(1,2*RASC);                         %Probabilities of demand
greater than 2*mu are zero

    Totalprobality=sum(normpdf((1:2*mu),mu,round(k*mu))-
normpdf((0),mu,round(k*mu)));     %finding total probability of
distribution for normalisation

    demdis(1:2*mu)=(normpdf((1:2*mu),mu,round(k*mu))-
normpdf((0),mu,round(k*mu)))/Totalprobality;         %Normalising the
distribution

    ANSO(1,mu)=sum(demdis(1:RASC).*(1:RASC))+(1-sum(demdis(1:RASC)))*RASC;
%Finding average number of seats occupied for all ppossible mu's
end

%finding mean of the demand distribution by comparing ANSO with PLF*RASC

previous=PLF*RASC;

for mu=round(RASC*PLF):RASC
    if(abs(ANSO(mu)-PLF*RASC)<previous)
        previous=abs(ANSO(mu)-PLF*RASC);
        mean(kIndex,PLFIndex)=mu;
    end
end

    end
 end

 %means of all demand distributions are stored in mean matrix for furthur
analyis

 %NOW STARTS THE GAME
 for TSC=RASC-25:RASC+25 %Total seating capacity is assumed to vary within
25 seats of actual seating capacity


    for BSC= round(TSC/2):TSC      %BSC-BASE Seat Capacity
        %here we have varied BSC from TSC/2 to TSC as BSC obviously can't
be less than TSC/2.

     kIndex=0;


for k=0.20:0.01:0.40

    kIndex=kIndex+1;
    PLFIndex=0;

    for PLF=0.70:0.01:0.85
        PLFIndex=PLFIndex+1;
```

```
 %This calculates for us the demand distribution curve for a particular k
and PLF
 demanddistribution=zeros(1,2*RASC);

Totalprobality=sum(normpdf((1:2*mean(kIndex,PLFIndex)),mean(kIndex,PLFIndex
),round(k*mean(kIndex,PLFIndex))-
normpdf((0),mean(kIndex,PLFIndex),round(k*mean(kIndex,PLFIndex))));

demanddistribution(1:2*mean(kIndex,PLFIndex))=(normpdf((1:2*mean(kIndex,PLF
Index)),mean(kIndex,PLFIndex),round(k*mean(kIndex,PLFIndex)))-
normpdf((0),mean(kIndex,PLFIndex),round(k*mean(kIndex,PLFIndex))))/Totalpro
bality;


 %Assumption:For 1000 seat miles
 %200$ is the revenue generated for one seat in airline industry
 %50$ is the operating cost of one seat in the base model
 %60$ is the operating cost of one seat in the attached module


  AOCEA=RASC*50;      %AOCEA-Average Operating Cost for Existing Aircraft
  ANSOEA=sum(demanddistribution(1:RASC).*(1:RASC))+(1-
sum(demanddistribution(1:RASC)))*RASC;    %ANSOEA-Average Number of Seats
Occupied for Existing Aircraft
  AREA=ANSOEA*200;     %AREA-Average Revenue for Existing Aircraft
  APEA=AREA-AOCEA;      %APEA-Average Profit for Existing Aircraft

  %Here we assumed module is attached only if demand >(BSC+4)

    probability1=sum(demanddistribution(1:BSC+4));   %probability1 is the
probability of using base aircraft

    if(TSC-BSC>4)
        AOCRA=probability1*BSC*50+((1-probability1)*(BSC*50+(TSC-BSC)*60));
%AOCRA-Average Operating Cost for Reconfigurable Aircraft


ANSORA=sum(demanddistribution(1:BSC).*(1:BSC))+sum(demanddistribution(BSC+1
:BSC+4))*BSC+sum(demanddistribution(BSC+5:TSC).*(BSC+5:TSC))+(1-
sum(demanddistribution(1:TSC)))*TSC;
        %ANSORA-Average Number of Seats Occupied for Reconfigurable
Aircraft
    else
        AOCRA=BSC*50;
        ANSORA=sum(demanddistribution(1:BSC).*(1:BSC))+(1-
sum(demanddistribution(1:BSC)))*BSC;
    end

    ARRA=ANSORA*200;    %ARRA-Average Revenue for Reconfigurable Aircraft
    APRA=ARRA-AOCRA;    %APRA-Average Profit for Reconfigurable Aircraft
    EPCEP(kIndex,PLFIndex)=(APRA-APEA)*100/(APEA);

    end
end

    AEPCEP(TSC,BSC)=sum(sum(EPCEP))/(kSize*PLFSize); %averaging the profits
over all the possible demand distributions

    end
 end
```

```
mesh(AEPCEP) %plot AEPCEP as function of TSC & BSC
xlabel('Base Seating capacity')
ylabel('Total Seating capacity')
zlabel('AEPCEP')

[AEPCEPM1,BSCM]=max(max(AEPCEP,[],1));   %BSCM-BASE Seat Capacity For
Maximum Profit Case
[AEPCEPM2,TSCM]=max(max(AEPCEP,[],2));   %TSCM-Total Seat Capacity For
Maximum Profit Case

BSCM %this will print the base seat capacity for maximum profit case
TSCM % this will print the total seat cpacity for maximum profit case

save mean
save AEPCEP

toc
```

main2.m

```
tic
 clc
 clear all
 close all

 %This code takes the best reconfigurable aircraft seating capacity and
calculates cost,revenue and profits for the reconfigurable and existing
aircrafts

 RASC=180;

 load mean
 load AEPCEP

 %FOR MAXIMUM PROFIT CASE

[AEPCEPM1,BSCM]=max(max(AEPCEP,[],1));   %BSCM-BASE Seat Capacity For
Maximum Profit Case
[AEPCEPM2,TSCM]=max(max(AEPCEP,[],2));   %TSCM-Total Seat Capacity For
Maximum Profit Case

kSize=size((0.20:0.01:0.40),2);         %k-Coefficient of Variation
PLFSize=size((0.70:0.01:0.85),2);       %PLF-Passenger Load Factor


 AOCRA=zeros(kSize,PLFSize);        %Average Operating Cost for
Reconfigurable Aircraft
 ANSORA=zeros(kSize,PLFSize);     %Average Number of Seats Occupied for
Reconfigurable Aircraft
 ARRA=zeros(kSize,PLFSize);          %Average Revenue for Reconfigurable
Aircraft
 APRA=zeros(kSize,PLFSize);          %Average Profit for Reconfigurable
Aircraft


 ANSOEA=zeros(kSize,PLFSize);       %Average Number of Seats Occupied for
Existing Aircraft
 AREA=zeros(kSize,PLFSize);           %Average Revenue for Existing
Aircraft
```

```
 APEA=zeros(kSize,PLFSize);            %Average Profit for Existing Aircraft

 EPCEP=zeros(kSize,PLFSize);           %EPCEP-Extra Profits Compared to
Existing Profits in percentage


 kIndex=0;

for k=0.20:0.01:0.40

    kIndex=kIndex+1;
    PLFIndex=0;

    for PLF=0.70:0.01:0.85
        PLFIndex=PLFIndex+1;



 %This calculates for us the demand distribution curve for a particular k
and PLF
 demanddistribution=zeros(1,2*RASC);

Totalprobality=sum(normpdf((1:2*mean(kIndex,PLFIndex)),mean(kIndex,PLFIndex
),round(k*mean(kIndex,PLFIndex)))-
normpdf((0),mean(kIndex,PLFIndex),round(k*mean(kIndex,PLFIndex))));

demanddistribution(1:2*mean(kIndex,PLFIndex))=(normpdf((1:2*mean(kIndex,PLF
Index)),mean(kIndex,PLFIndex),round(k*mean(kIndex,PLFIndex)))-
normpdf((0),mean(kIndex,PLFIndex),round(k*mean(kIndex,PLFIndex))))/Totalpro
bality;


 %Assumption:For 1000 seat miles
 %200$ is the revenue generated for one seat in airline industry
 %50$ is the operating cost of one seat in the base model
 %60$ is the operating cost of one seat in the attached module

  AOCEA=RASC*50;            %Average Operating Cost for Existing Aircraft
  ANSOEA(kIndex,PLFIndex)=sum(demanddistribution(1:RASC).*(1:RASC))+(1-
sum(demanddistribution(1:RASC)))*RASC;
  AREA(kIndex,PLFIndex)=ANSOEA(kIndex,PLFIndex)*200;
  APEA(kIndex,PLFIndex)=AREA(kIndex,PLFIndex)-AOCEA;


  probability1=sum(demanddistribution(1:BSCM+4));
  AOCRA(kIndex,PLFIndex)=probability1*BSCM*50+((1-
probability1)*(BSCM*50+(TSCM-BSCM)*60));

ANSORA(kIndex,PLFIndex)=sum(demanddistribution(1:BSCM).*(1:BSCM))+(sum(dema
nddistribution(BSCM+1:BSCM+4)))*BSCM+sum(demanddistribution(BSCM+5:TSCM).*(
BSCM+5:TSCM))+(1-sum(demanddistribution(1:TSCM)))*TSCM;
  ARRA(kIndex,PLFIndex)=ANSORA(kIndex,PLFIndex)*200;
  APRA(kIndex,PLFIndex)=ARRA(kIndex,PLFIndex)-AOCRA(kIndex,PLFIndex);
  EPCEP(kIndex,PLFIndex)=(APRA(kIndex,PLFIndex)-
APEA(kIndex,PLFIndex))*100/(APEA(kIndex,PLFIndex));

    end
end

              %averaging over all the possible demand distributions at
maximum profit case
```

```
AOCRAM=sum(sum(AOCRA))/(kSize*PLFSize)
ANSORAM=sum(sum(ANSORA))/(kSize*PLFSize)
ARRAM=sum(sum(ARRA))/(kSize*PLFSize)
APRAM=sum(sum(APRA))/(kSize*PLFSize)

AOCEAM=AOCEA
AANSOEA=sum(sum(ANSOEA))/(kSize*PLFSize)
AAREA=sum(sum(AREA))/(kSize*PLFSize)
AAPEA=sum(sum(APEA))/(kSize*PLFSize)

AEPCEPM=sum(sum(EPCEP))/(kSize*PLFSize)

toc
```

FuelEfficiency.m

```
%IMPORTANT: run the main.m before running this code as it loads mean from
%the main.m

tic
 clc
 clear all
 close all


%This code takes the best reconfigurable aircraft seating capacity and
%calculates the fuels required for reconfigurable and non-reconfigurable
%aircraft of same seating capacities

BSCM = 156; %Best base seating capacity
TSCM = 200; %Best total seating capacity


RASC=180;  %Reference Aircraft seat capacity
load mean   %mean of the demand distribution function



kSize=size((0.20:0.01:0.40),2);        %k-Coefficient of Variation
PLFSize=size((0.70:0.01:0.85),2);        %PLF-Passenger Load Factor

 %Y denotes the extra fuel consumption of full capacity model as compared
to the exisiting aircraft of the same capacity.
 %This was obtained by CFD simulations.

Y=1.04;

SeatCapacity=[132 156 180 220]; %aircraft seating capacities
FuelConsumption=[90 91 100 110];%aircraft fuel consumptions in terms of
A320 fuel consumption

AFRA=zeros(kSize,PLFSize);        %Average fuel for Reconfigurable Aircraft
in terms of A320 fuel consumption
```

```
kIndex=0;

for k=0.20:0.01:0.40

    kIndex=kIndex+1;
    PLFIndex=0;

    for PLF=0.70:0.01:0.85
        PLFIndex=PLFIndex+1;



 demanddistribution=zeros(1,2*RASC);

 %Total sum of all the demand probabilities (which is not equal to one)

Totalprobality=sum(normpdf((1:2*mean(kIndex,PLFIndex)),mean(kIndex,PLFIndex
),round(k*mean(kIndex,PLFIndex)))-
normpdf((0),mean(kIndex,PLFIndex),round(k*mean(kIndex,PLFIndex))));

 %The demand distribution curve. This is obtained by dividing the
individual probailities by the Totalprobability obtained above.

demanddistribution(1:2*mean(kIndex,PLFIndex))=(normpdf((1:2*mean(kIndex,PLF
Index)),mean(kIndex,PLFIndex),round(k*mean(kIndex,PLFIndex)))-
normpdf((0),mean(kIndex,PLFIndex),round(k*mean(kIndex,PLFIndex))))/Totalpro
bality;

 %probability of using base model at maximum profit case.
 probability1=sum(demanddistribution(1:BSCM+4));

 %fuels for different seat capaity aircraft are  obtained from linear
 %interpolation

AFRA(kIndex,PLFIndex)=probability1*interp1(SeatCapacity,FuelConsumption,BSC
M,'linear')+(1-
probability1)*interp1(SeatCapacity,FuelConsumption,TSCM,'linear')*Y;

   end
end


TAFRA=sum(sum(AFRA))/(kSize*PLFSize) %Total average fuel for reconfigurable
aircraft in terms of A320 fuel consumption by assuming all the demand
distribution curves to be equi-probable`

AFEA=interp1(SeatCapacity,FuelConsumption,TSCM,'linear')       %Average
fuel for existing Aircraft in terms of A320 fuel consumption

fuelefficiency=(AFEA-TAFRA)*100/AFEA

toc
```