Significance of Modifications for Development of Passenger Airplanes

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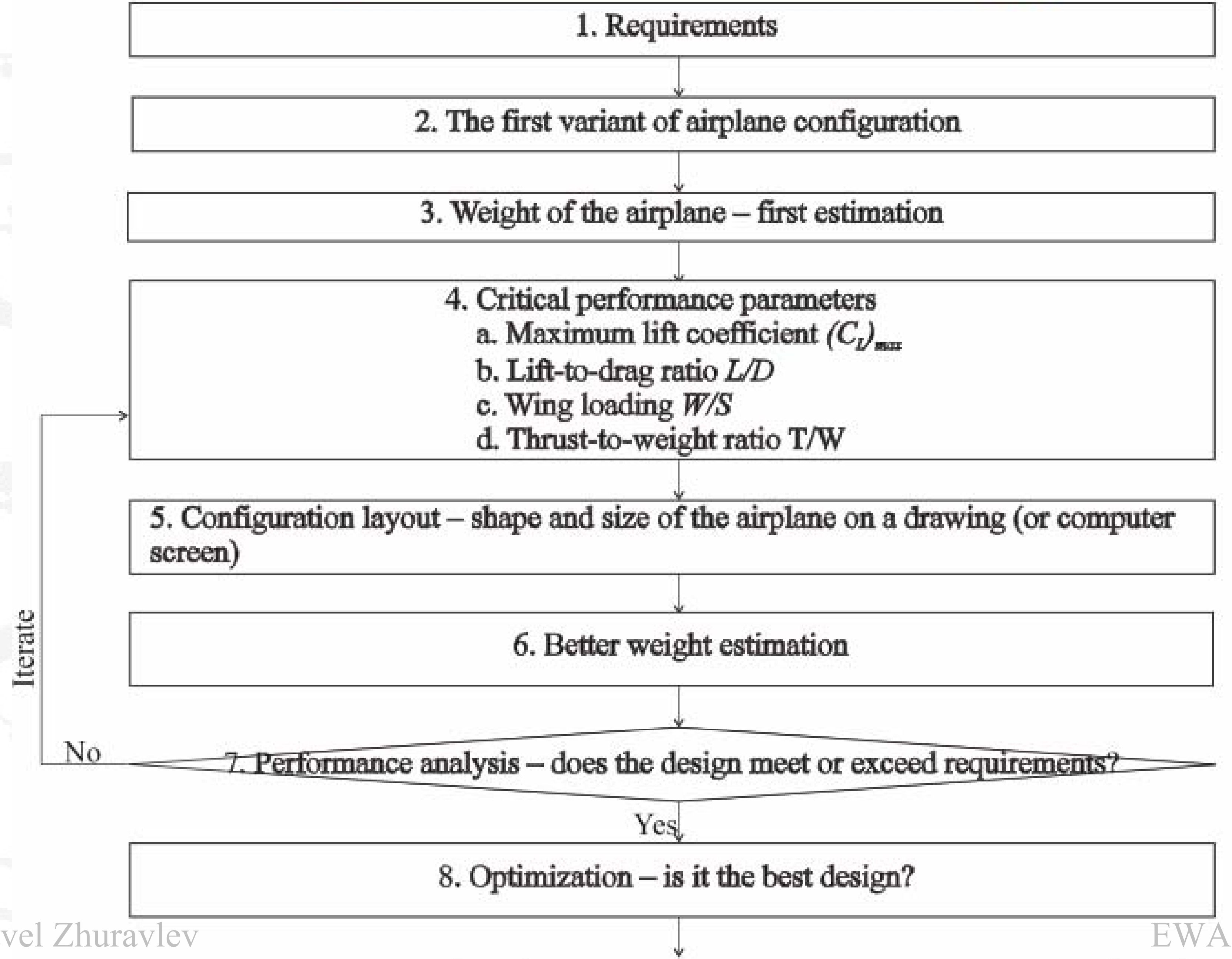
The Main Pivot Points for Conceptual Design (J. Anderson - Aircraft Performance and Design)



1. Requirements

2. The first variant of airplane configuration

3. Weight of the airplane – first estimation

4. Critical performance parameters
    a. Maximum lift coefficient $(C_L)_{max}$
    b. Lift-to-drag ratio L/D
    c. Wing loading W/S
    d. Thrust-to-weight ratio T/W

5. Configuration layout – shape and size of the airplane on a drawing (or computer screen)

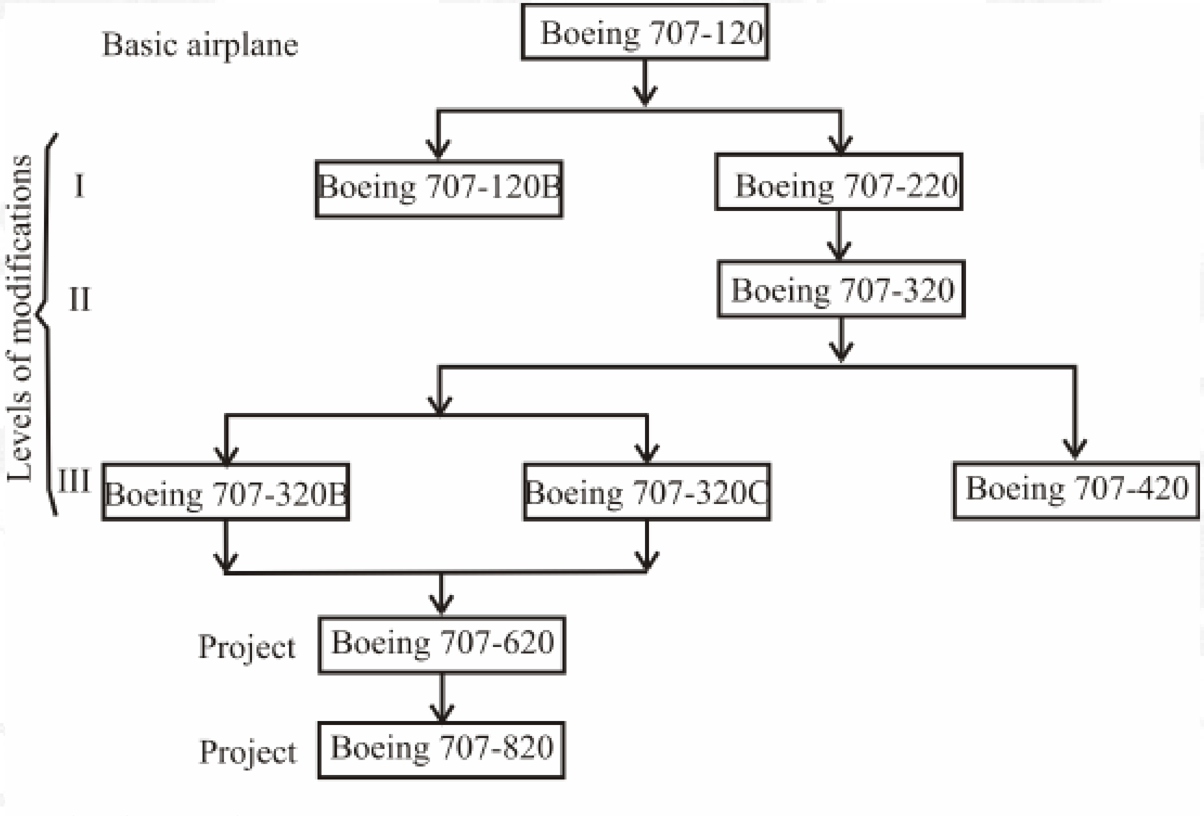
6. Better weight estimation

7. Performance analysis – does the design meet or exceed requirements?

8. Optimization – is it the best design?

Introduction

- During the last 50 years there is a clear trend for development of families of trunk-route passenger airplanes.
- Number of variants has reached up to 9 for some airplane families (for example, for Boeing 707).



Family of Boeing-707 airplanes

Introduction

- “Theory of aircraft modifications (variants)” was formed in Russia within the “Aircraft Design” scientific area.
- Foundations of this theory were laid by scientists, who worked in aviation industry (e.g. Ilyushin) and at universities (e.g. MAI);

ОСОК

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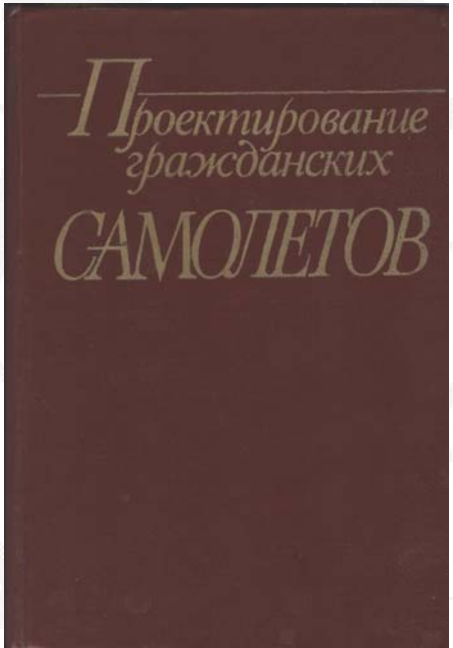

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МОСКОВСКИЙ ОРДЕНА ЛЕНИНА
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С УЧЕТОМ МОДИФИКАЦИЙ

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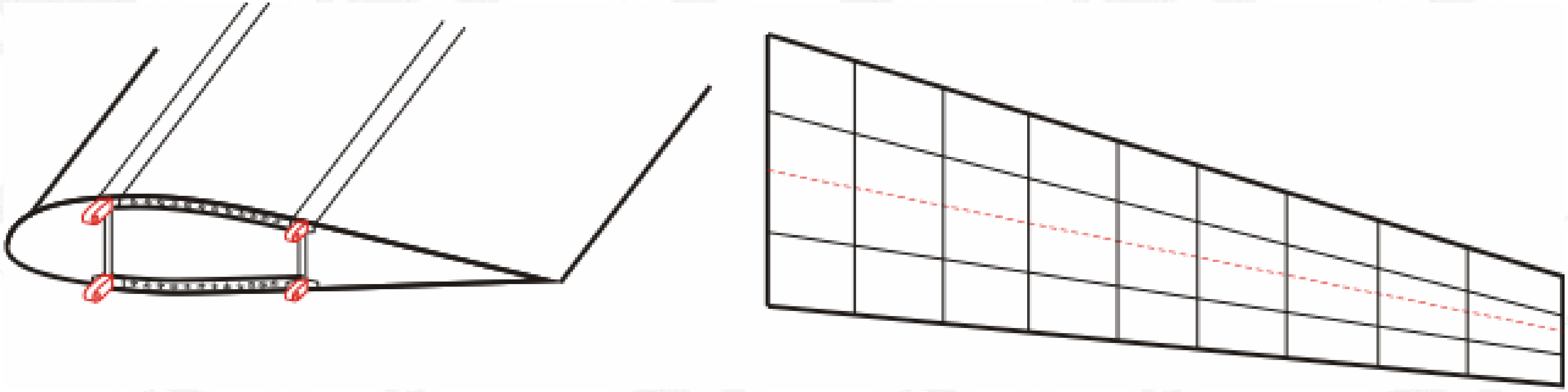
Difference between new types of airplanes and airplane variants (modifications)

- "**Modifications (variants) of existing airplanes**" differ from "**new types of airplanes**" by the degree of novelty of main units and onboard subsystems.
- A new variant (modification), which would incorporate any of the changes listed below can be considered as a **"new type"**:
  - **new wing;**
  - **new fuselage;**
  - **new number and position of engines.**

All other changes lead to creation of airplane modifications (variants)

New wing

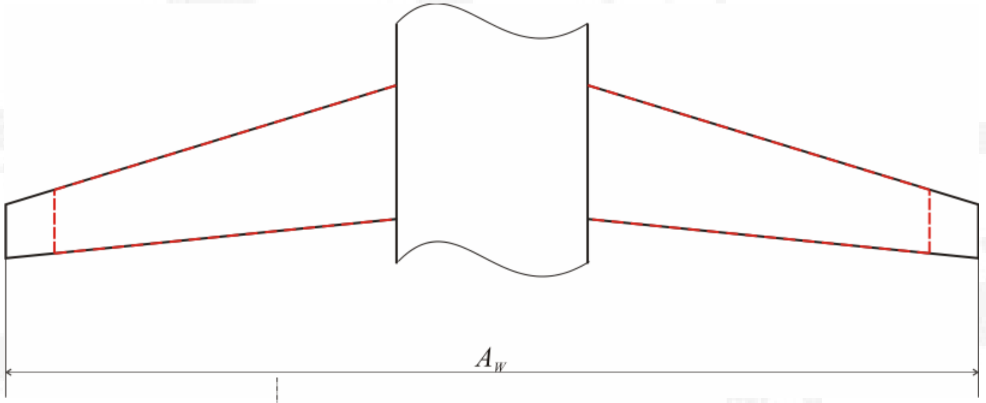
- **“New wing”** should have the following changed:
  - set of airfoils;
  - type of structure of wing box;
  - structure materials of main load-bearing elements;
  - types of connection of wing box elements;
  - main geometrical parameters.

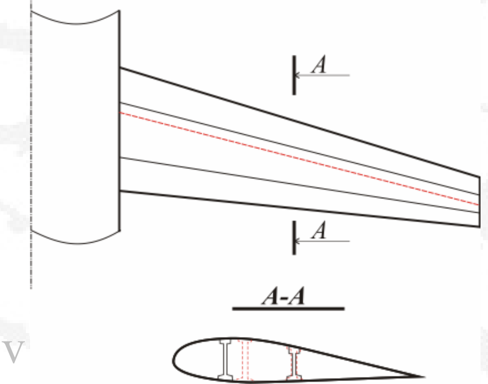


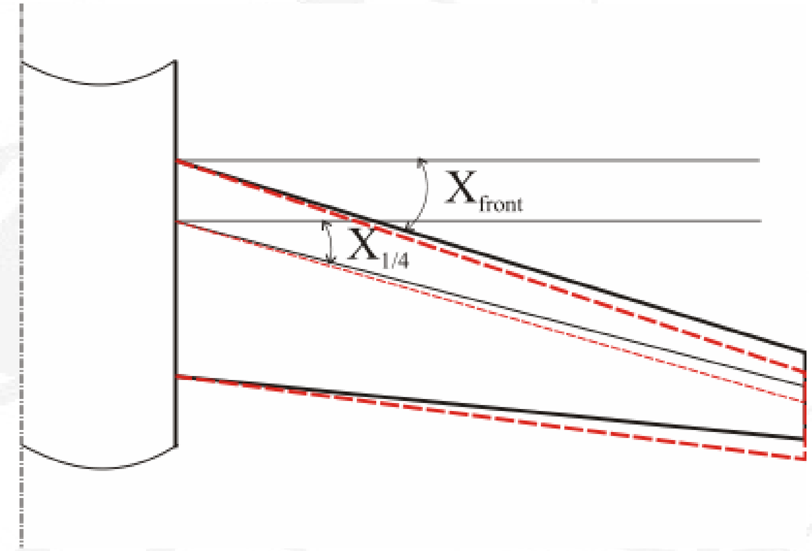
New wing

Main geometrical parameters of **“new wing”** :

- wing span;
- sweep angles of leading edge and quarter-of-wing-chord line;
- length of airfoil chords with taking into account their distribution along the wing span;
- wing box dimensions, including shape and dimensions of cross sections of elements.

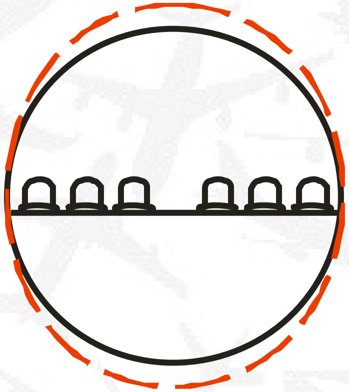


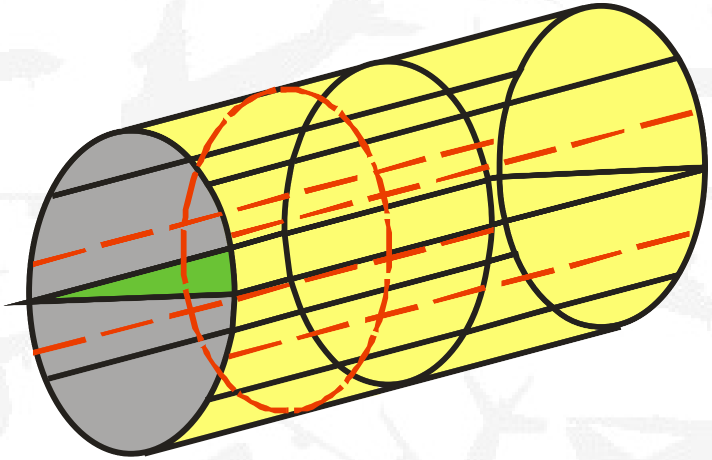




New fuselage

- "**New fuselage**" should have the following changed:
  - shape of cross section;
  - type of structure;
  - structure materials of main load-bearing elements;
  - types of elements connection;
  - main geometrical parameters.

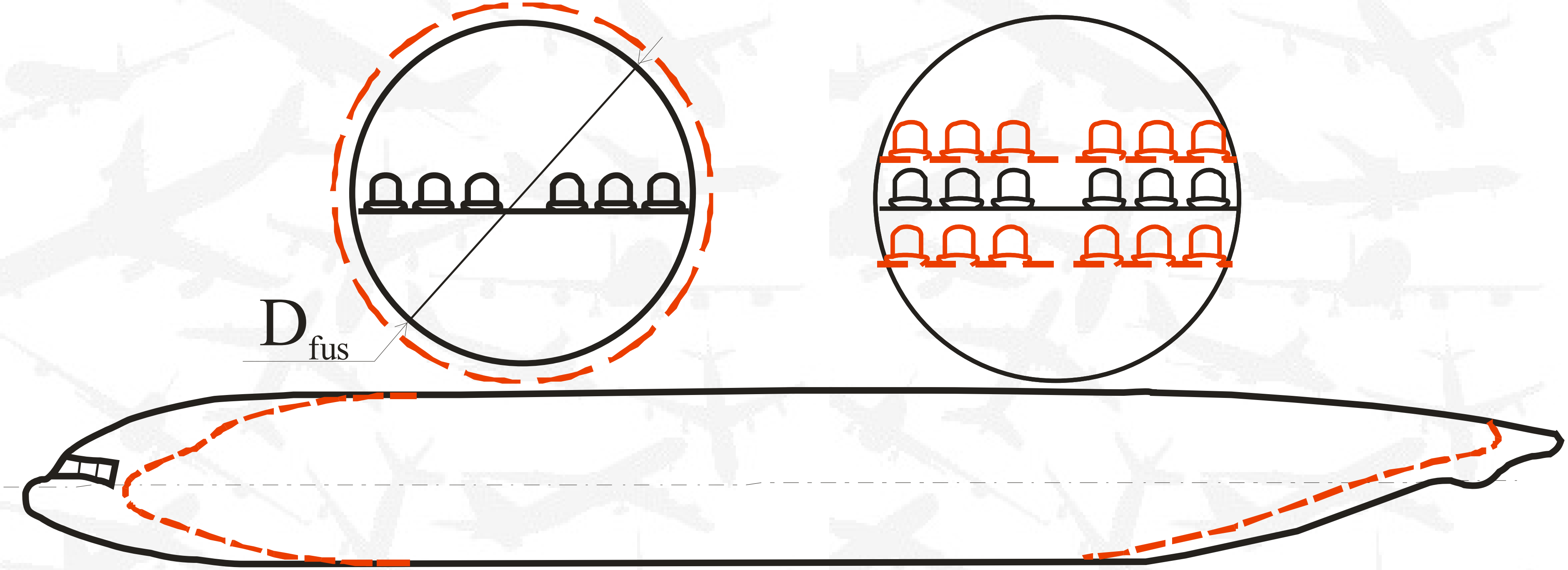




New fuselage

Main geometrical parameters of **“new fuselage”** :

- diameter;
- number of decks of passenger cabin and their positions;
- geometry and dimensions of nose and tail parts.



Types of variants

- Two main groups of variants of passenger trunk-route airplanes:

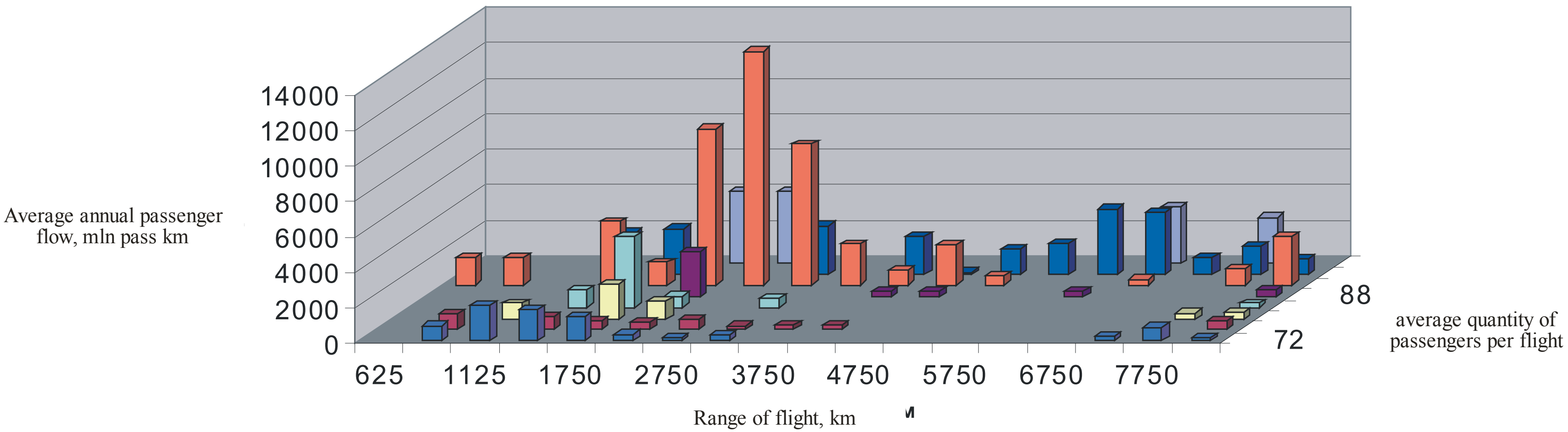
I. Specialized variants, which differ from basic airplane by type of mission (cargo, cargo-passenger, military) (not considered);

II. Variants with different maximum quantity of passengers and maximum payload range of flight (considered).

A320-family aircraft in flight

Reasons behind creation of passenger airplane families

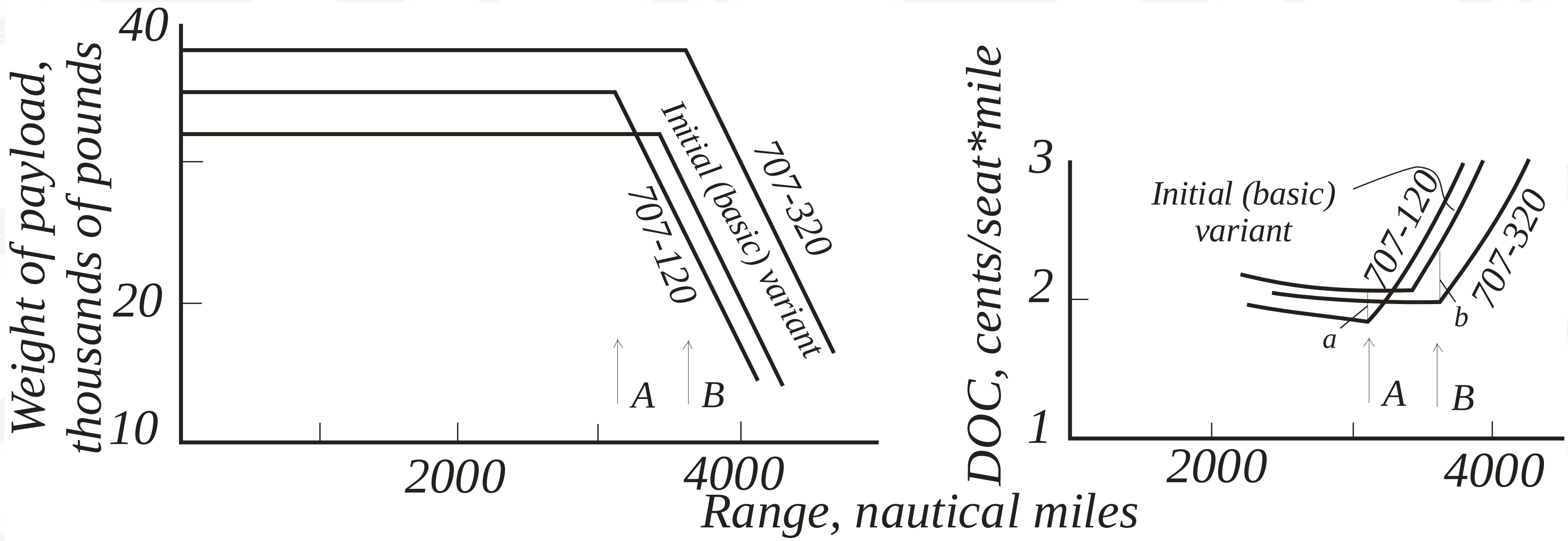
- More flexible response to demand of airline companies;



Transportation network in Russian Federation (example)

Reasons behind creation of passenger airplane families

- More flexible response to demand of airline companies;

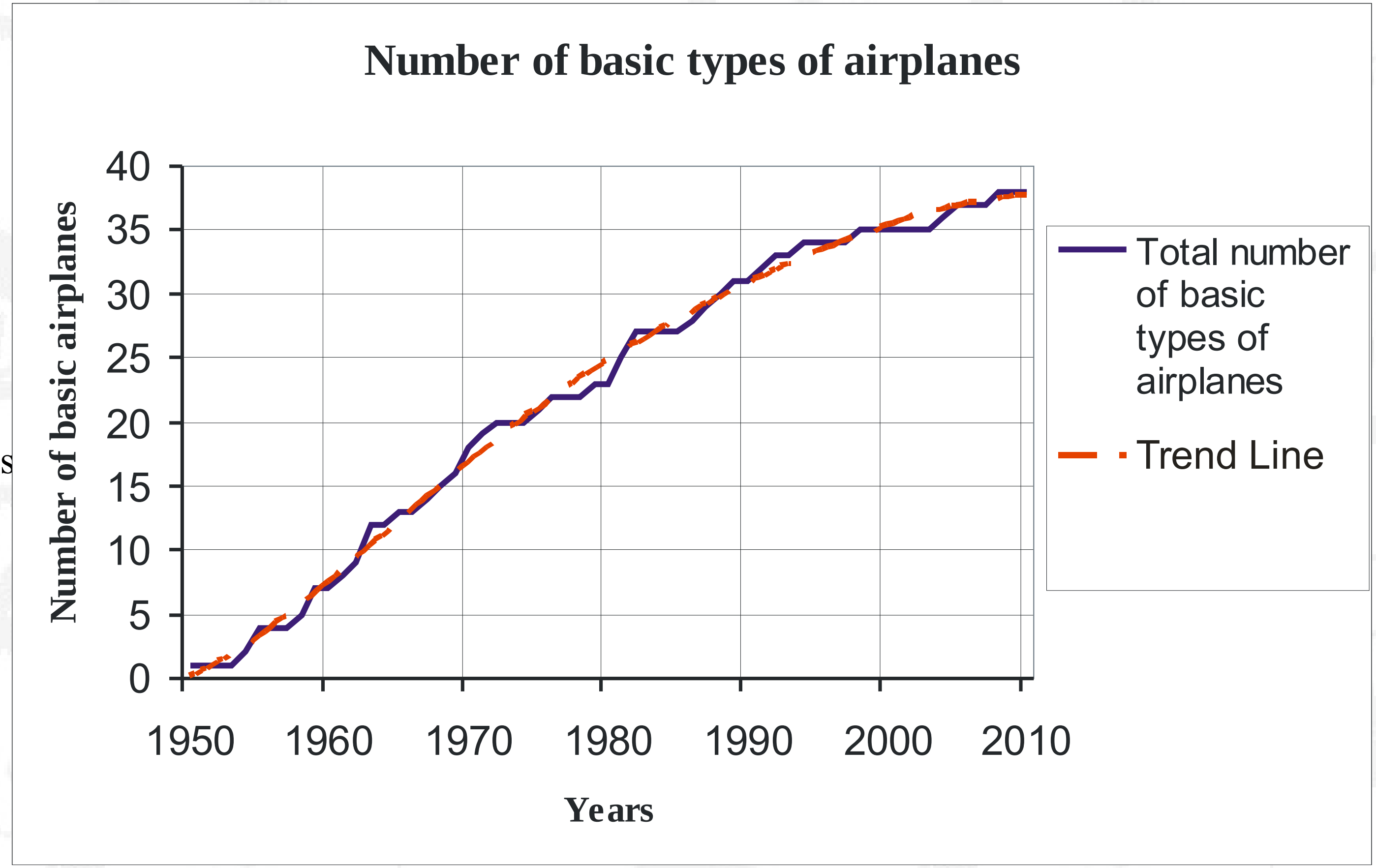


Variants of Boeing 707 and their effectiveness
Decrease of Direct Operating Costs for 707-120 (*a*) and 707-320 (*b*) compared to the basic variant

Reasons behind creation of passenger airplane families

- Compensation for considerable decrease in number of new basic versions of passenger airplanes (e.g. due to shrinking number of aircraft design companies);

- Antonov
- Ilyushin
- Sukhoi
- Tupolev
- Yakovlev
- British Aerospace
- Fokker
- Airbus
- Boeing
- Lockheed
- McDonnell-Douglas
- Convair
- de Havilland
- Vickers
- Dassault
- Sud-Aviation



- **Average number of variants per basic airplane is 4.8 (excluding the last 10 years)**

Reasons behind creation of passenger airplane families

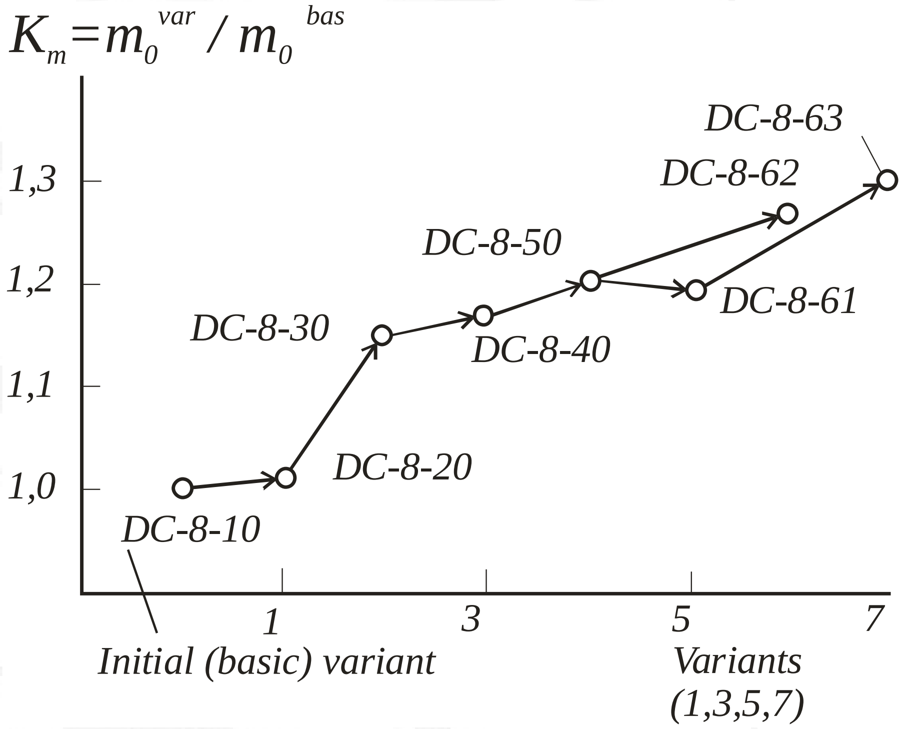
- Relatively lower requirements for labor, complexity, costs and terms of creation of new variants compared to basic versions.

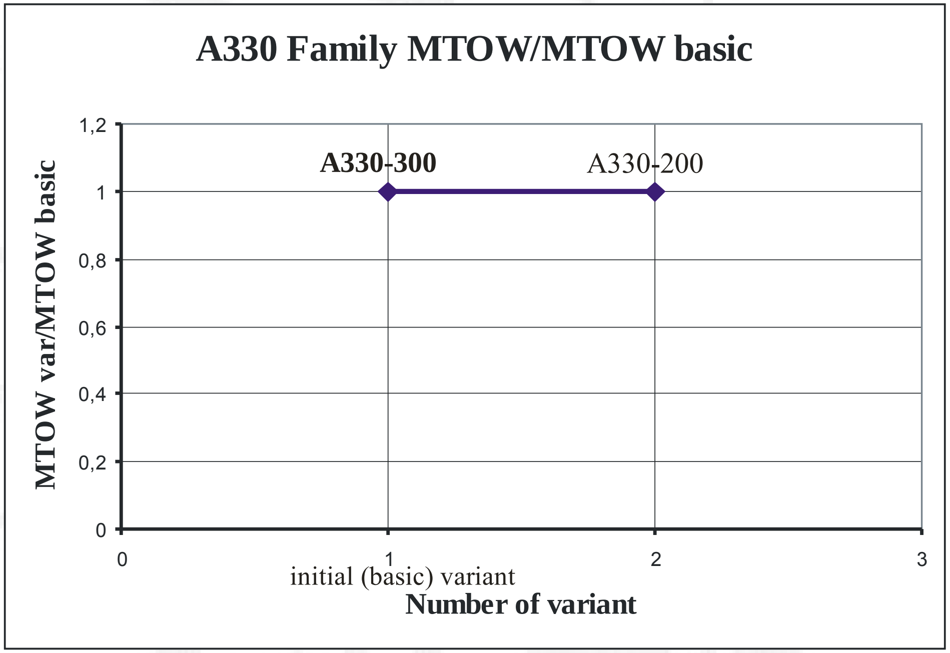
Company	Airplane	Type of airplane	First year of operation	R&D Cost, mln USD
Douglas	DC-3	Piston	1936	0.3
Vickers	Vickount	Turboprop	1953	11.2
Douglas	DC-8	Jet	1959	112.0
Boeing	Boeing-747	Wide-body	1970	650.0
Aerospatiale-BAC	Concord	Supersonic jet	1976	2400.0

- **Cost of R&D for a new variant usually does not exceed 30% of that for basic airplane.**

Consecutive airplane modifications

- Each new variant is the base for the next one.
- This sequence was common for passenger airplanes of 1st and 2nd generations

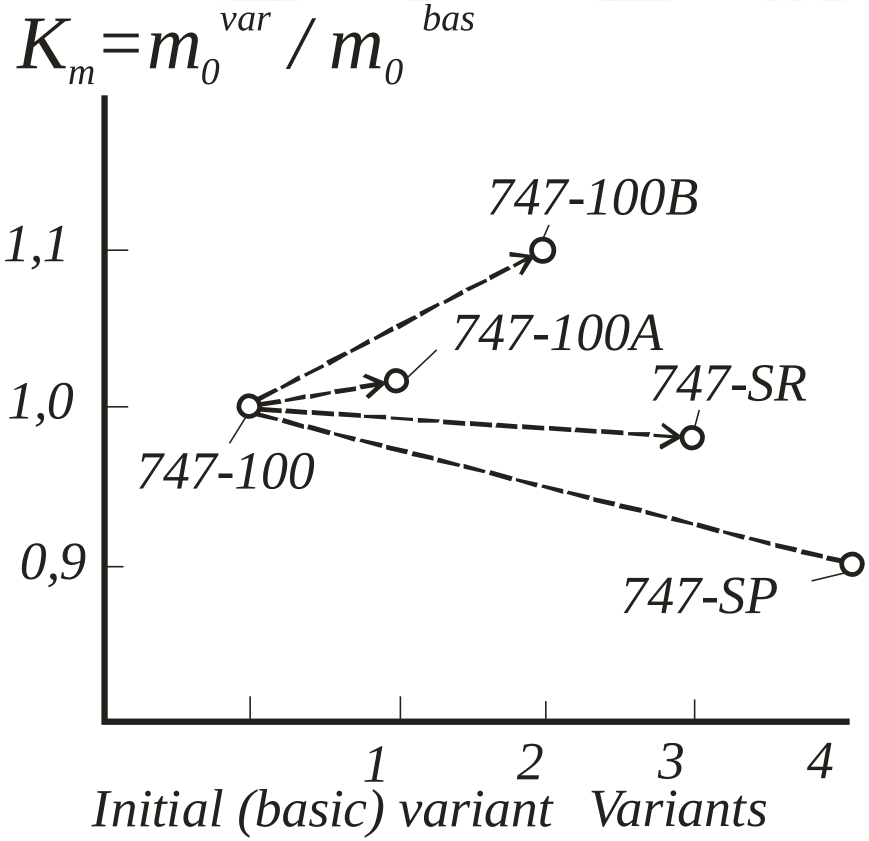




Consecutive development of variants

Parallel airplane modifications

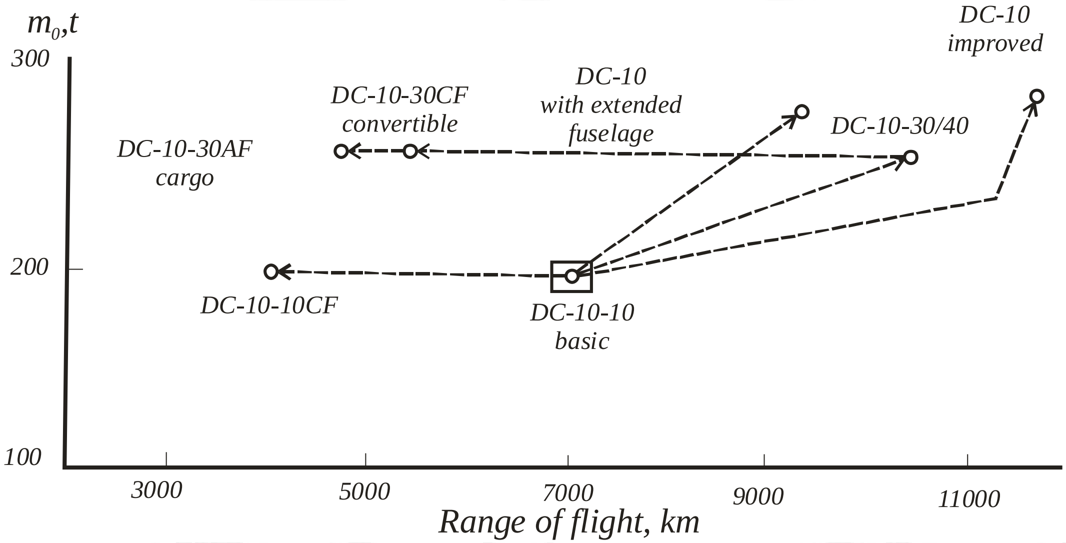
- A single unified base for all variants.
- Parallel development became a standard for families of 3rd and 4th generations.



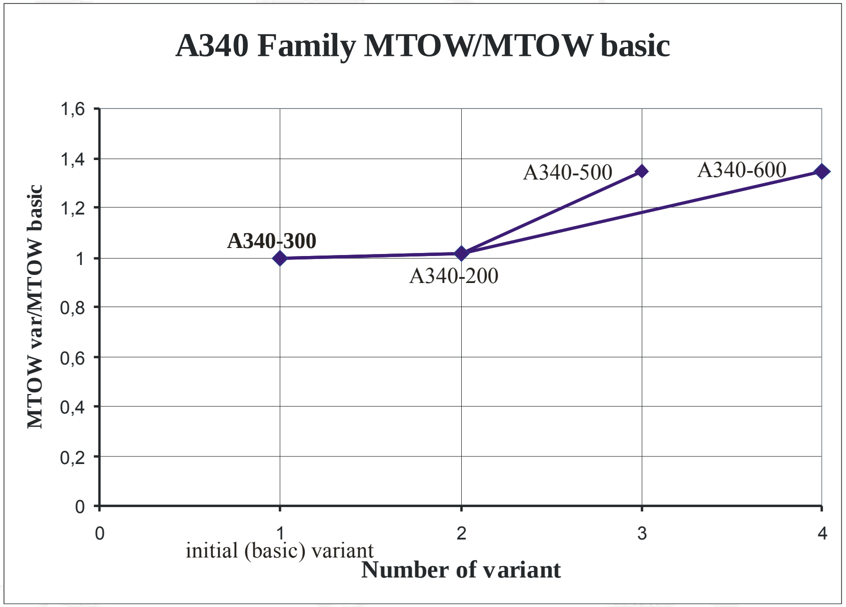
Parallel development of variants

Parallel-consecutive airplane modifications

- Interchange of two previously mentioned methods.
- Can be spotted in families of all generations.



Parallel-consecutive development of variants



Unscheduled (unplanned) and planned modifications

- Analysis of modification development shows that
    - some variants were made according to plans formulated during design of basic aircraft;
    - others were unplanned.
  - Recently the development of planned modifications starts almost at the same time with design of basic version.

Unscheduled (unplanned) and planned modifications

- For scheduled variants precise values of parameters and performance are known beforehand.
- For unplanned variants only ranges of possible values of parameters and performance are known.
- Degree of predictability of emergence of new unplanned modifications is very low. Partial prediction can be made basing on statistics (trends) and other forecasts. However, some modifications cannot be predicted at all.

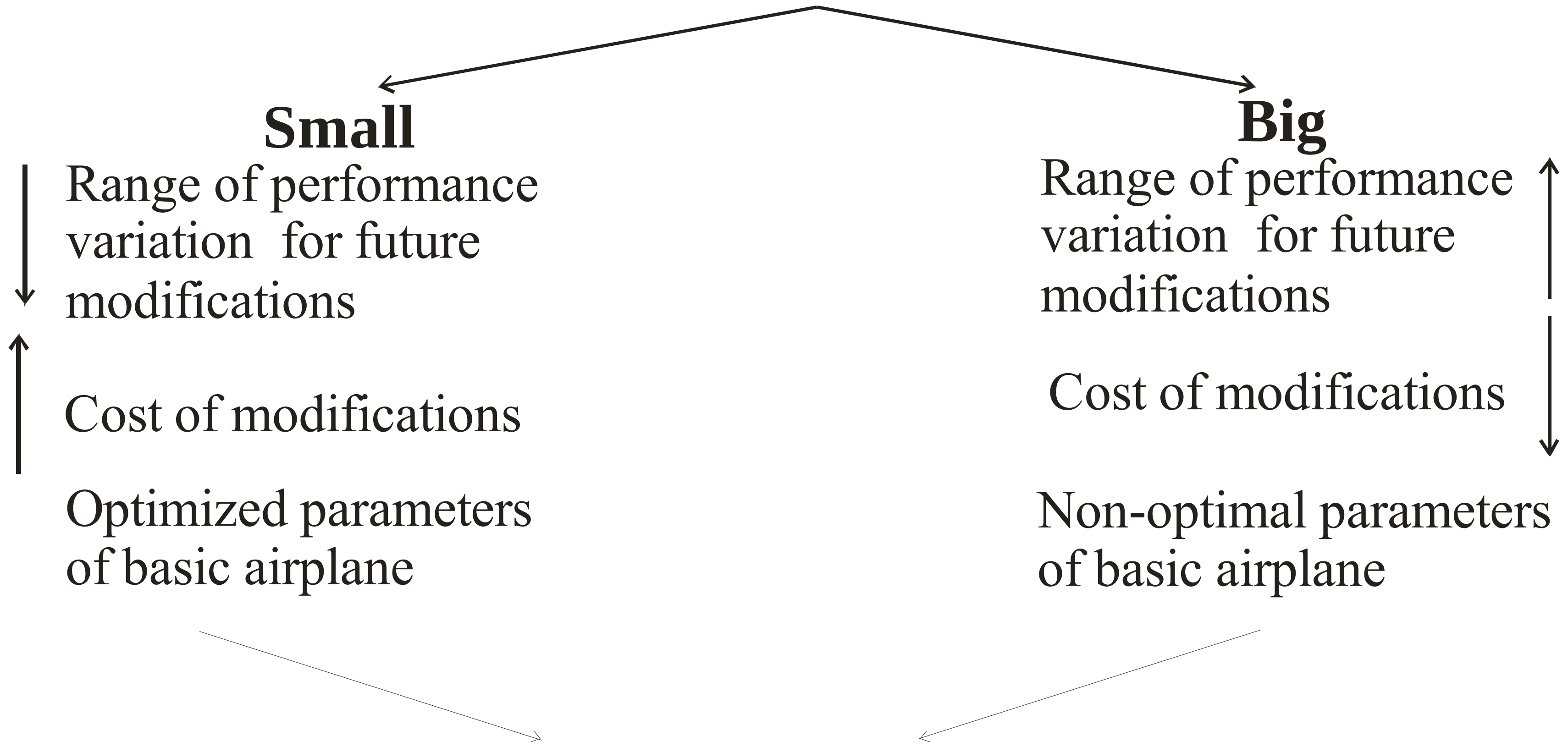
Unscheduled (unplanned) and planned modifications

Necessity for creation of new unplanned variants is defined by:

- changing conditions of the passenger air transportation market during operation of basic aircraft;
- general economic processes (e.g., increase of fuel prices results in the demand for increase of the number of modifications for various flight ranges);
- trends of development of new aviation technologies;
- political decisions (e.g. national security of the state and its transportation network);
- personal decisions of the creators.

Unscheduled (unplanned) and planned modifications

Special reserves (e.g. in structure) for implementation of modifications



Small

Range of performance variation for future modifications

Cost of modifications

Optimized parameters of basic airplane

Big

Range of performance variation for future modifications

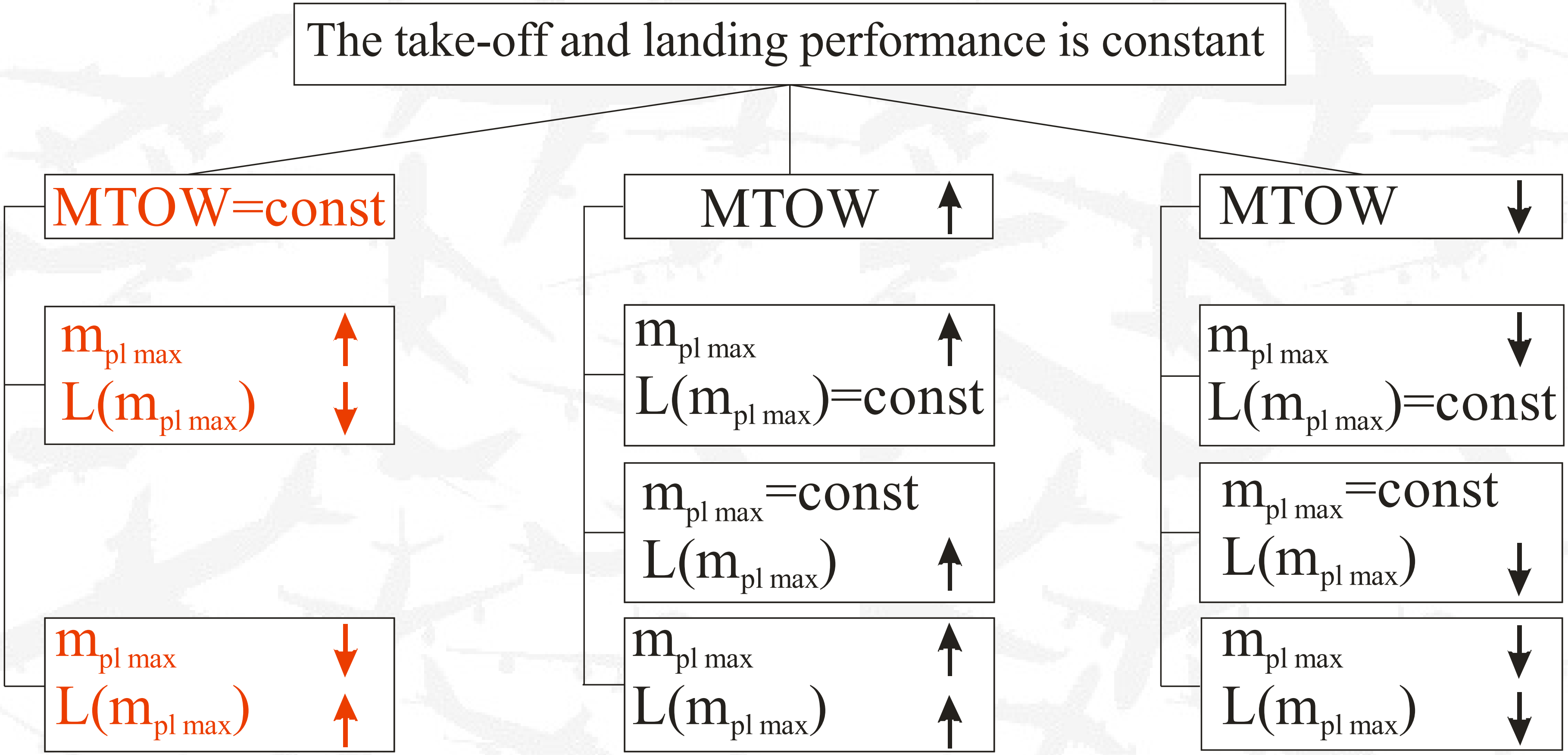
Cost of modifications

Non-optimal parameters of basic airplane

New design variables:

- parameters, which define the “reserve” in the structure of the basic version;
- parameters, which define the possibility of creation of unplanned modifications and implementation of their required performance.

Change of main performance during creation of variants



The take-off and landing performance is constant

MTOW=const

$m_{pl\,max}$ ↑
$L(m_{pl\,max})$ ↓

$m_{pl\,max}$ ↓
$L(m_{pl\,max})$ ↑

MTOW ↑

$m_{pl\,max}$ ↑
$L(m_{pl\,max})$=const

$m_{pl\,max}$=const
$L(m_{pl\,max})$ ↑

$m_{pl\,max}$ ↑
$L(m_{pl\,max})$ ↑

MTOW ↓

$m_{pl\,max}$ ↓
$L(m_{pl\,max})$=const

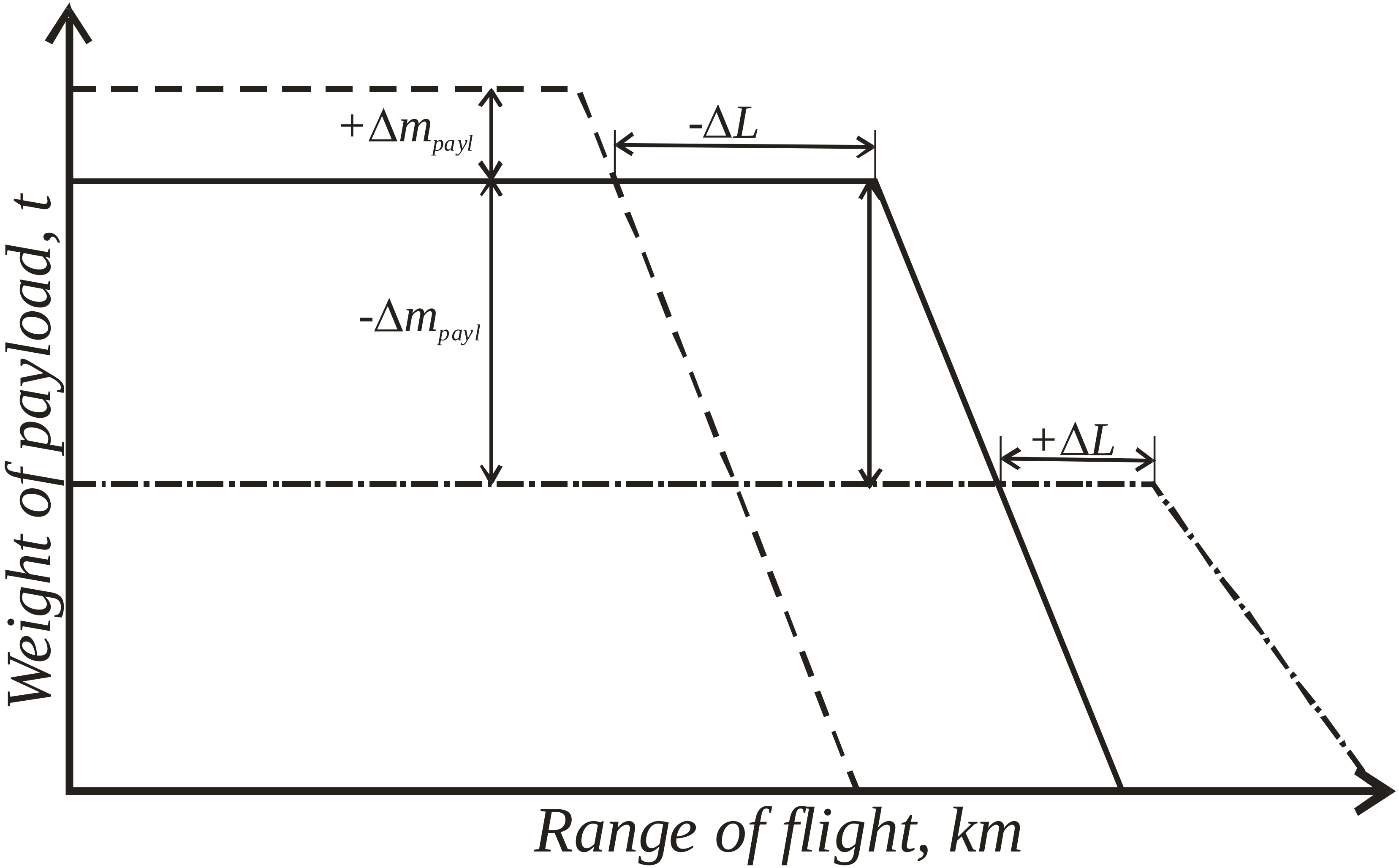
$m_{pl\,max}$=const
$L(m_{pl\,max})$ ↓

$m_{pl\,max}$ ↓
$L(m_{pl\,max})$ ↓

Trends of change in performance and parameters during the development of the variants (modifications)

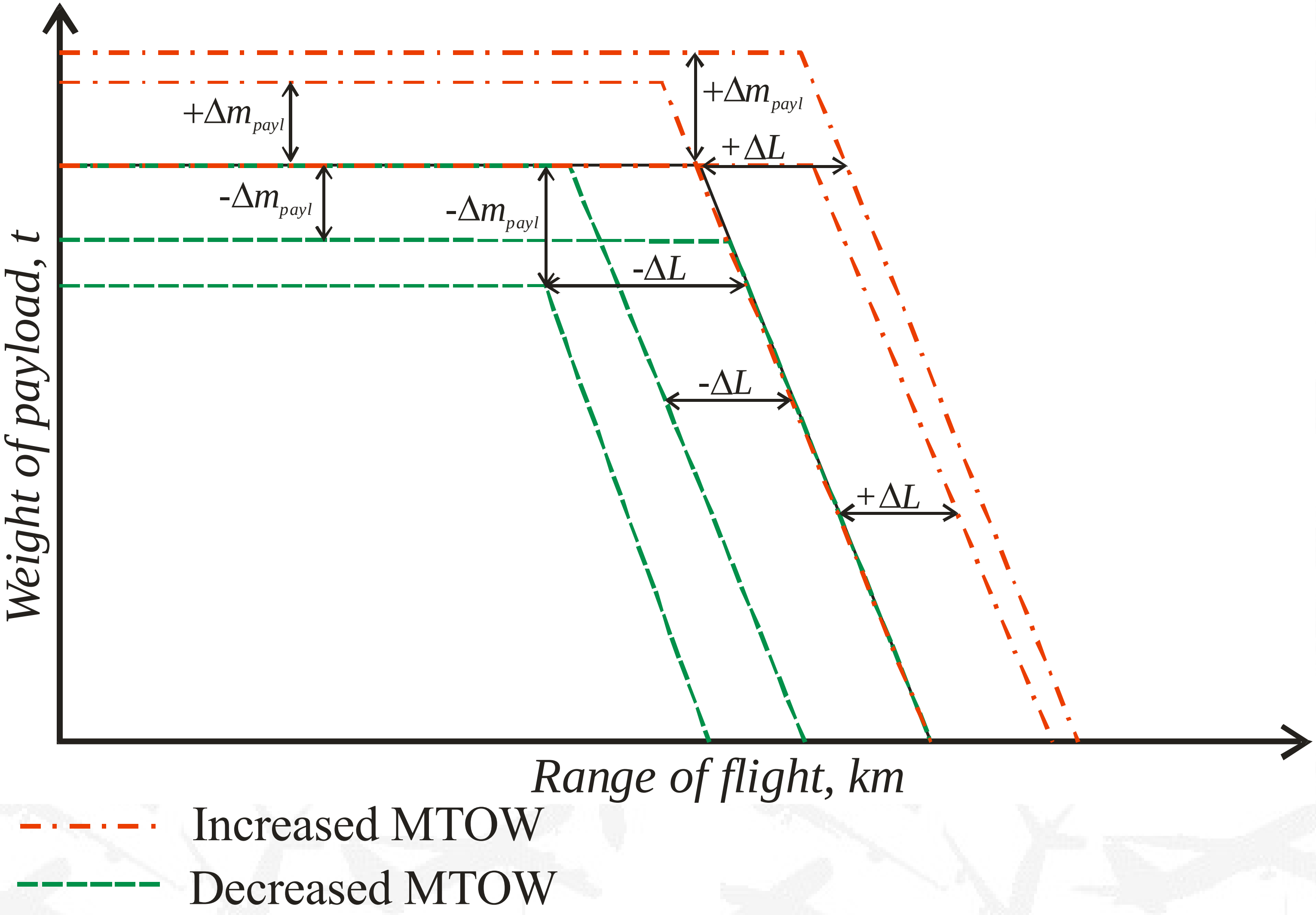
- One of the important limitations during creation of airplane variants is **preservation of take-off and landing performance;**
- **Takeoff and landing performance within one family of the most recent generations mostly vary within the limits of 10%;**
- This is due to:
  - increase of the wing area
  - usage of the more advanced high-lift devices
  - usage of engines with higher thrust at take-off and in reverse mode

Various variants.
Same take-off weight.



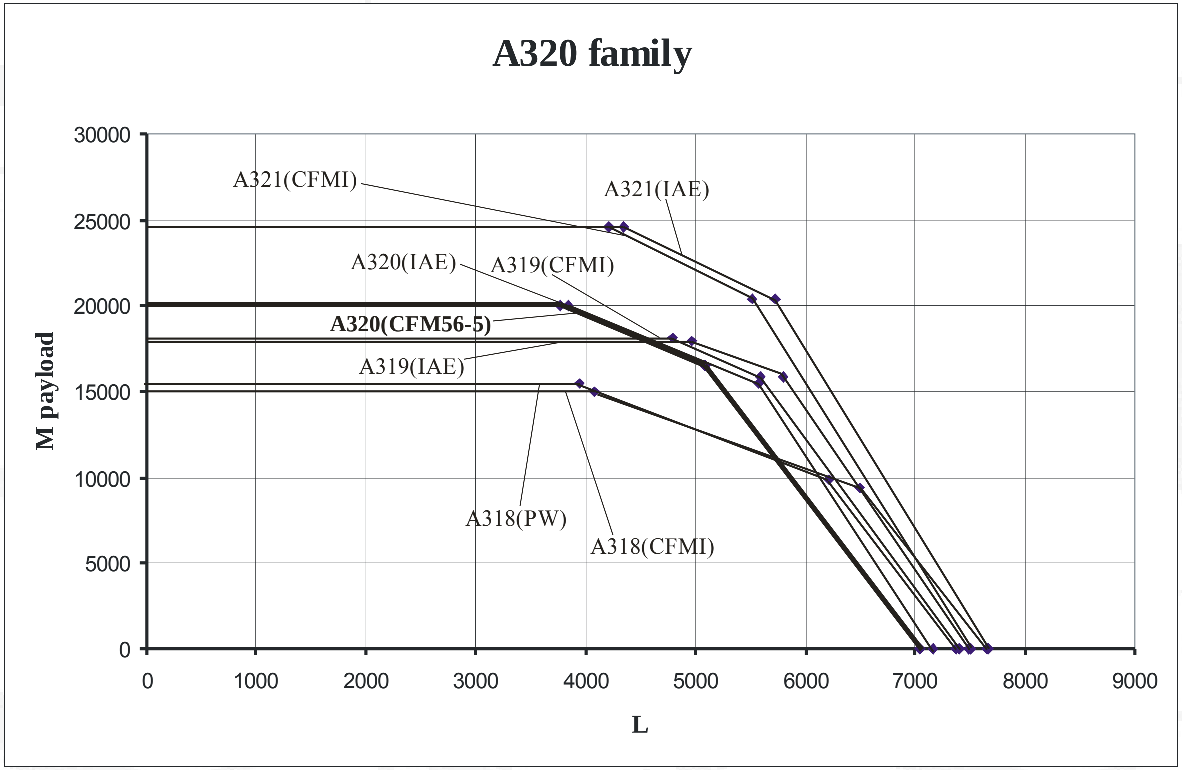
Variants of airplane with constant maximum take-off weight

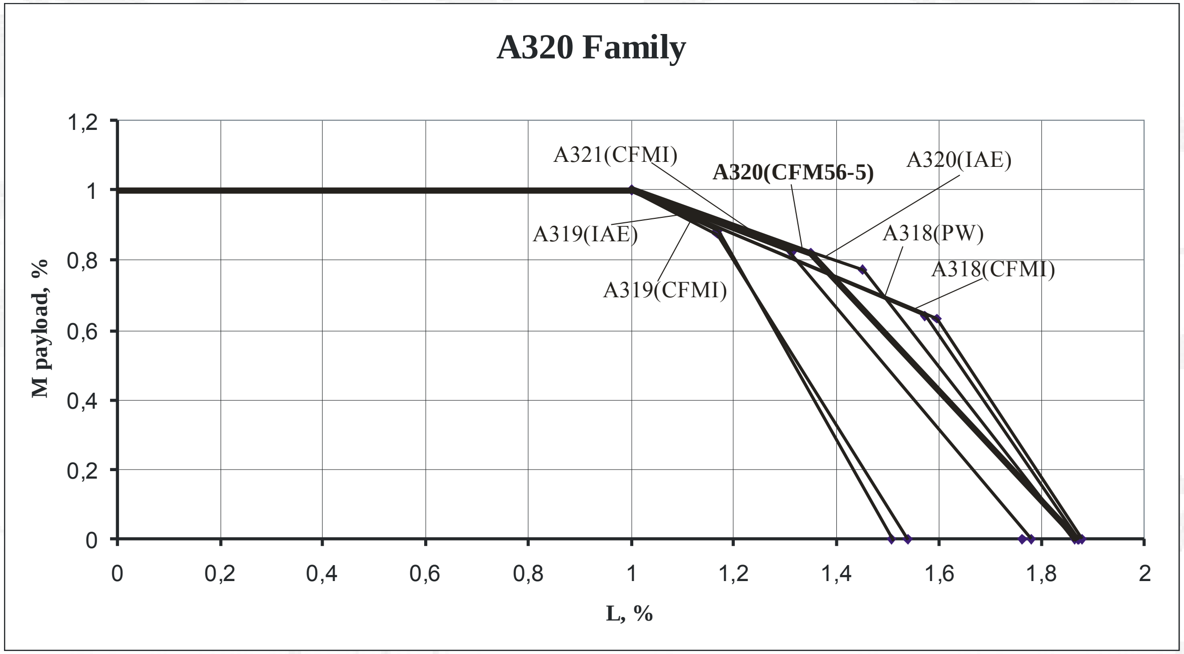
Various variants. Changing take-off weight.

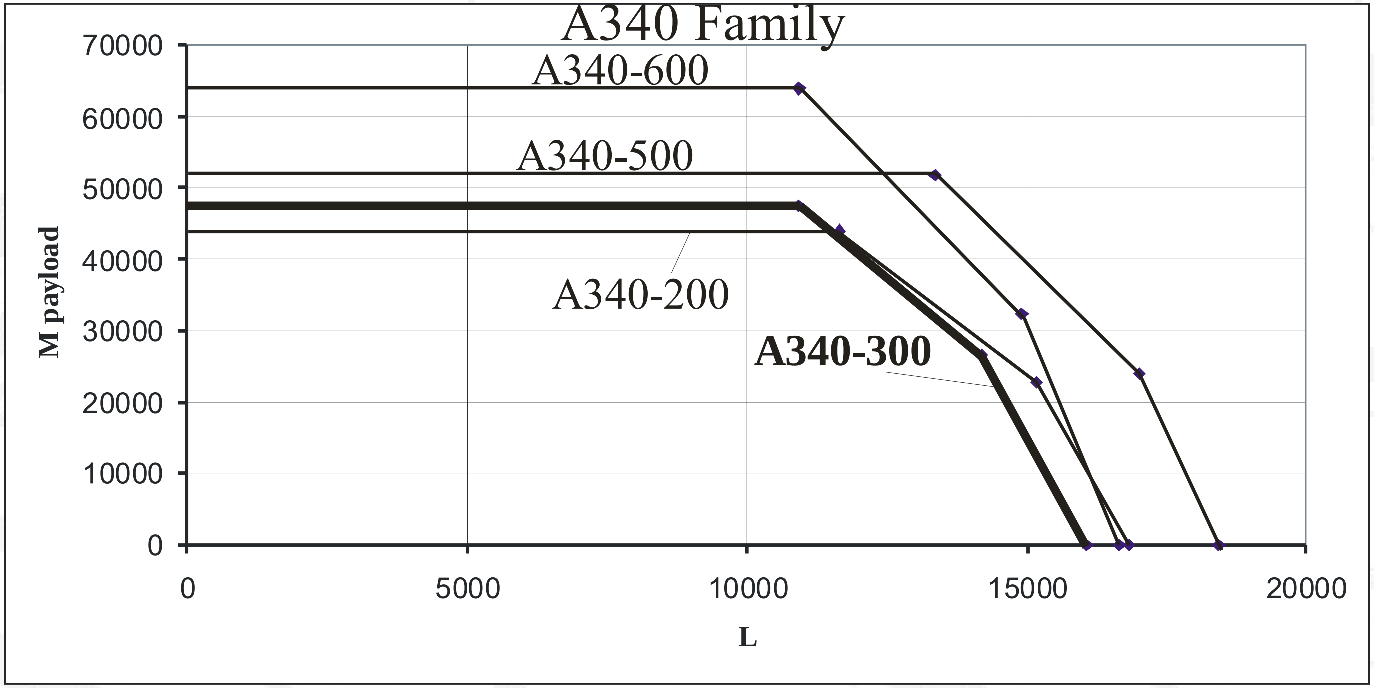


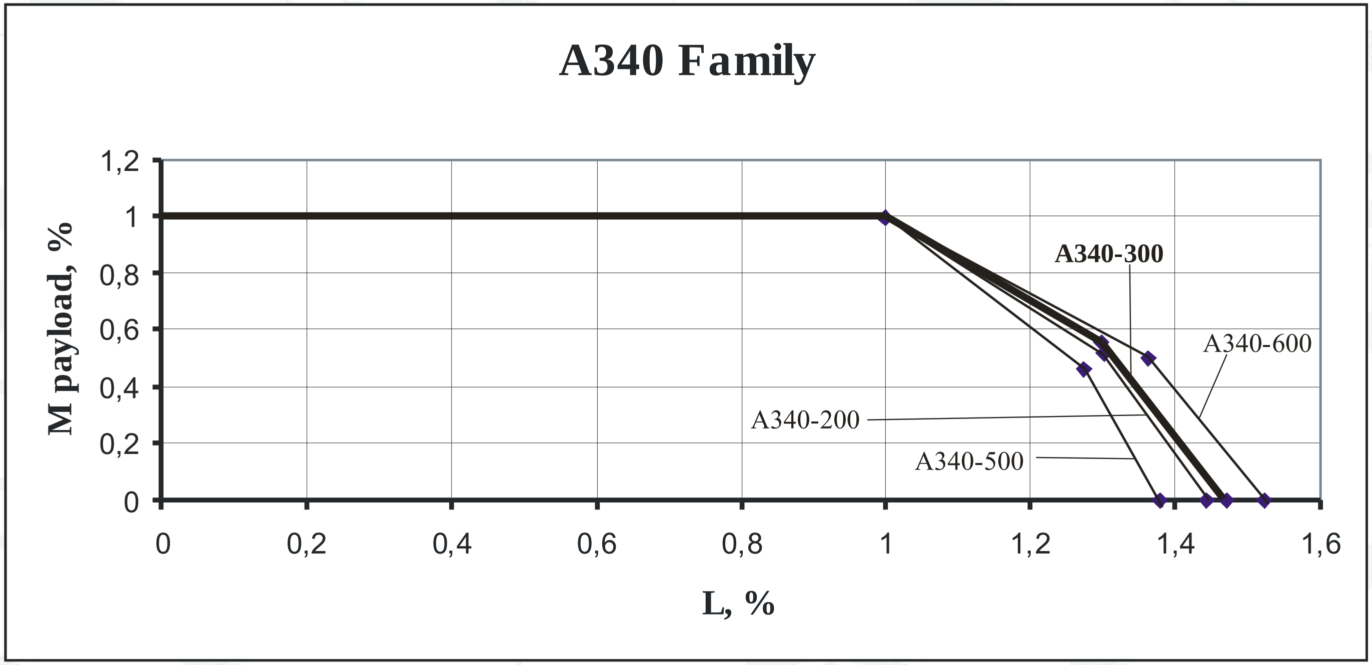
Typical variants of airplane with varied maximum take-off weight

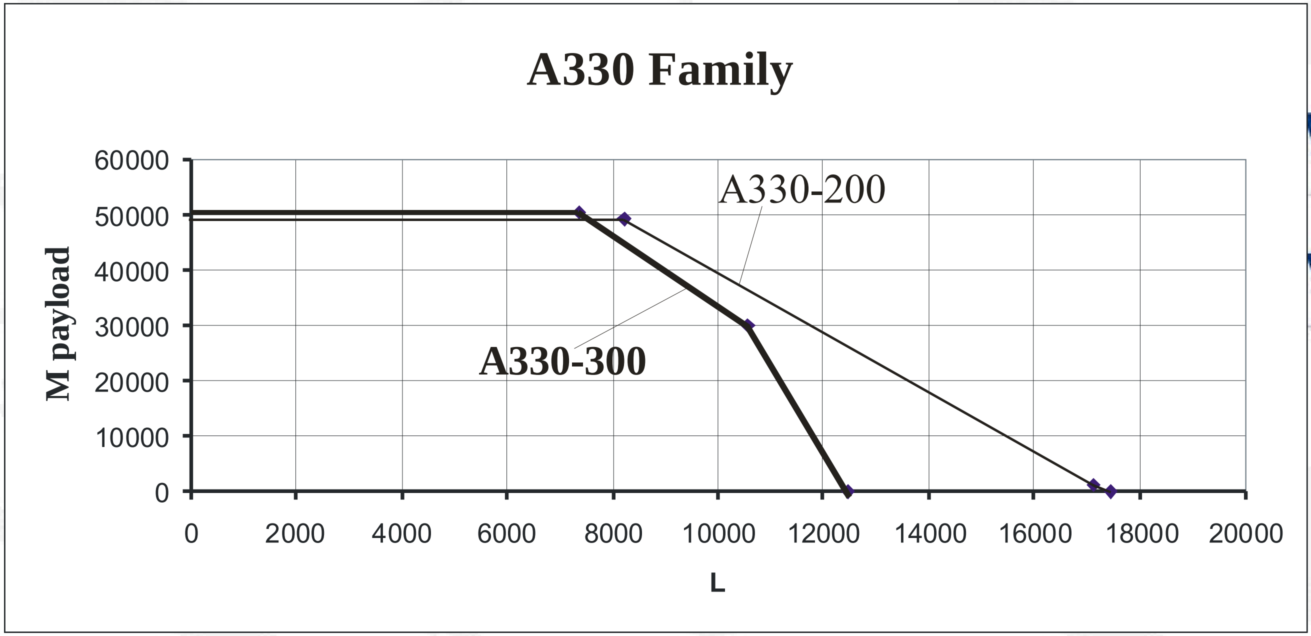
Change of the maximum weight of the payload ($m_{pl\ max}$) depending on the maximum payload range of flight ($L(m_{pl\ max}$))	**Change of weight performance of airplane variants in comparison with basic airplane**			
	maximum take-off weight	maximum weight of the airplane without fuel	maximum landing weight	empty weight of the airplane + undrainable liquids and crew
$m_{pl\ max}$ increases without change of fuselage length (spare internal volume) and $L_{d\ max}$ constant	constant	increases	increases	Constant, if spare structural strength; can increase, if reinforcement needed
$m_{pl\ max}$ increases with increase of fuselage length and decrease of $L_{d\ max}$	constant	increases	increases	increases
$m_{pl\ max}$ constant with increase of $L_{d\ max}$	increases	remains constant	remains constant	Constant, if spare structural strength and engine thrust
Simultaneous increase of $m_{pl\ max}$ and $L_{d\ max}$	increases	increases	increases	increases
$m_{pl\ max}$ decreases (decrease of fuselage length) $L_{d\ max}$ increases	decreases	decreases	decreases	decreases


A320 family
M payload
30000
25000
20000
15000
10000
5000
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
L
A321(CFMI)
A321(IAE)
A320(IAE)
A319(CFMI)
A320(CFM56-5)
A319(IAE)
A318(PW)
A318(CFMI)

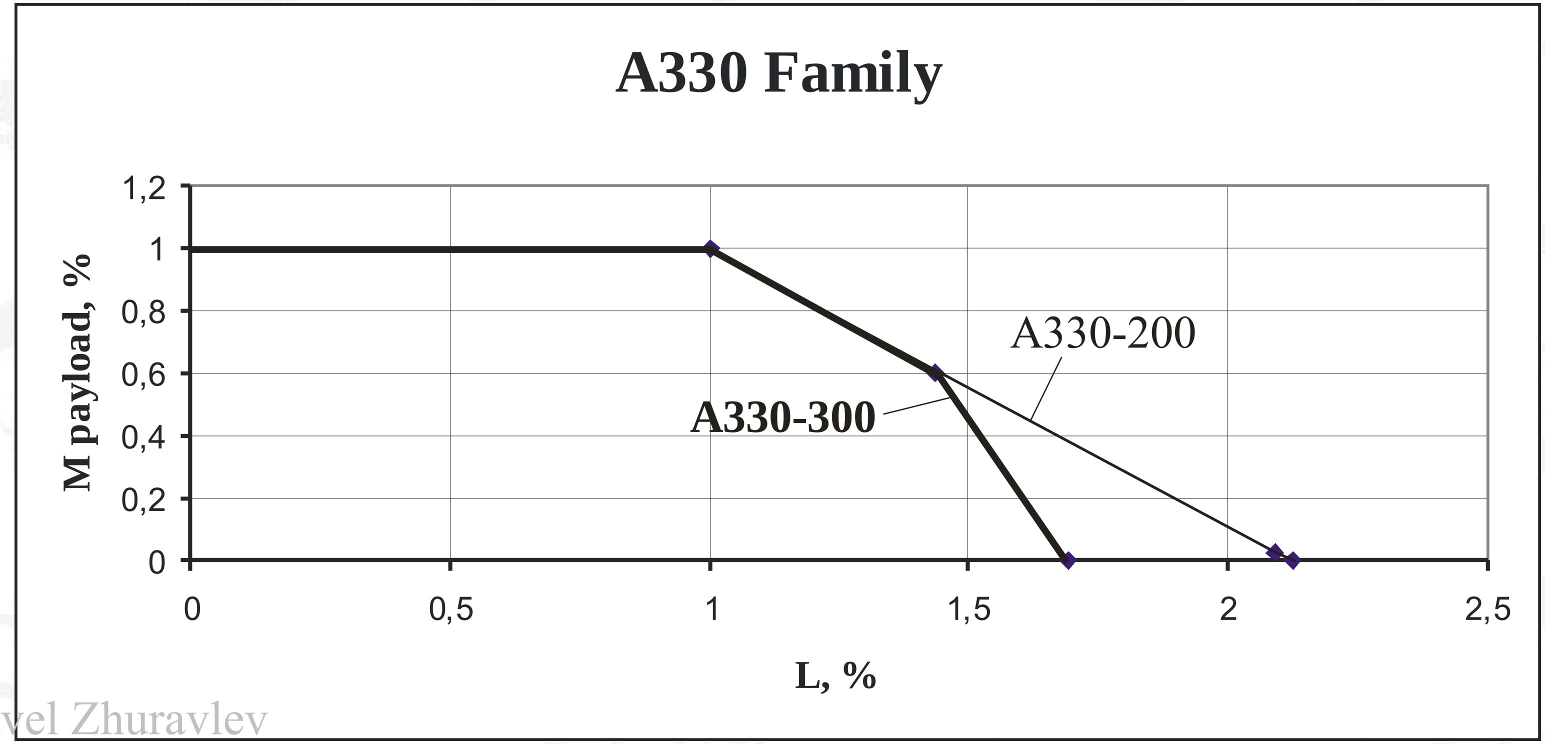

A320 Family
M payload, %
1,2
1
0,8
0,6
0,4
0,2
0
0
0,2
0,4
0,6
0,8
1
1,2
1,4
1,6
1,8
2
L, %
A321(CFMI)
A320(CFM56-5)
A320(IAE)
A319(IAE)
A318(PW)
A319(CFMI)
A318(CFMI)


A340 Family
A340-600
A340-500
A340-200
A340-300
M payload
L
70000
60000
50000
40000
30000
20000
10000
0
0
5000
10000
15000
20000


A340 Family
A340-300
A340-600
A340-200
A340-500
M payload, %
L, %
1,2
1
0,8
0,6
0,4
0,2
0
0
0,2
0,4
0,6
0,8
1
1,2
1,4
1,6

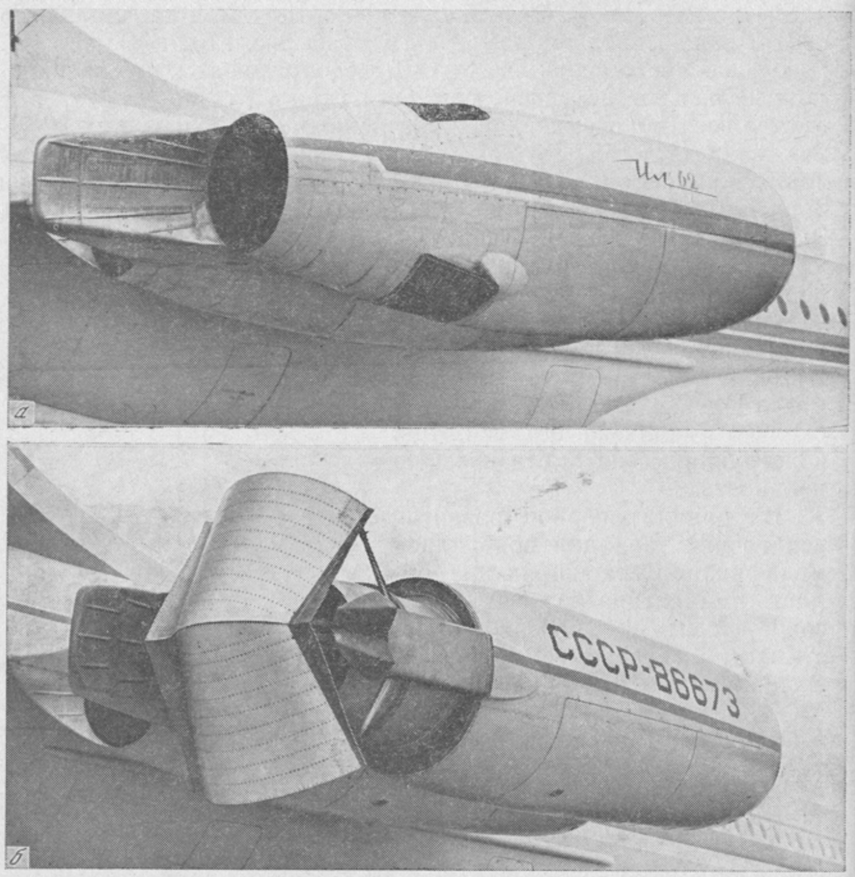

A330 Family
A330-200
A330-300
M payload
60000
50000
40000
30000
20000
10000
0
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
L


A330
A330
AIRBUS
AIRBUS


A330 Family
A330-200
A330-300
M payload, %
1,2
1
0,8
0,6
0,4
0,2
0
0
0,5
1
1,5
2
2,5
L, %

Ways of creating variants

- Modernization and change of engines;
- Lengthening or shortening of fuselage;
- Change of the surface area of tail units;
- Modernization of landing gear (increased leg length, wheels with bigger diameter) etc.

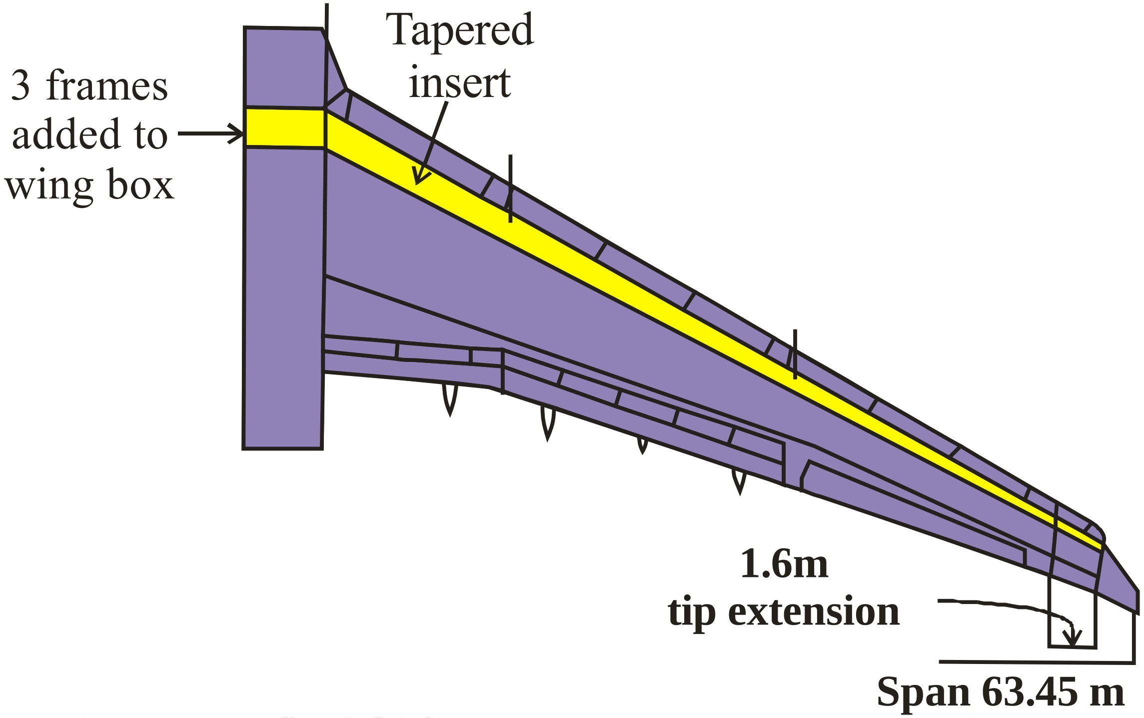


Thrust reversers on Il-62 and Il-62M

Ways of creating variants

- Increase of wing area (additional wing tip and root sections; increase of leading- and trailing-edge extensions; increase of wing chord length);
- Reworking high-lift devices (new and/or modernized leading-edge slats, complication or simplification of flaps);

A340-500 / -600 wing

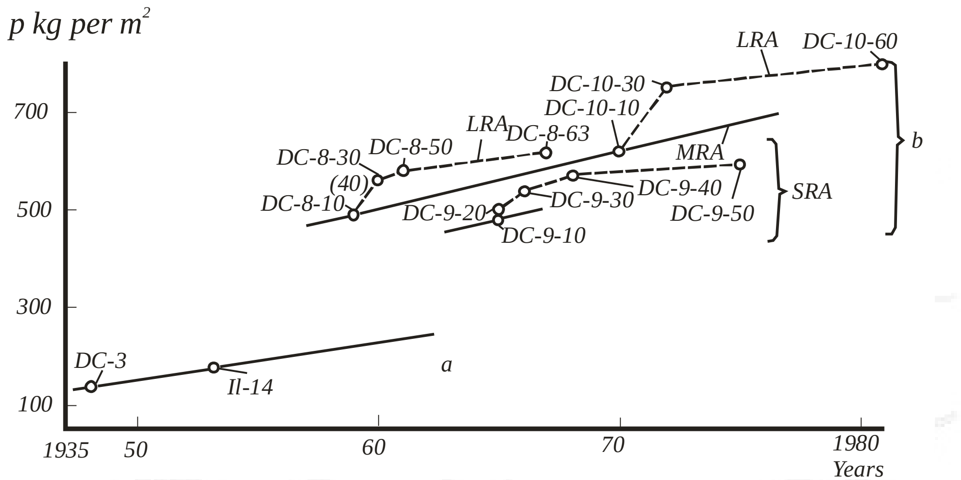


Design of variants based on reserves

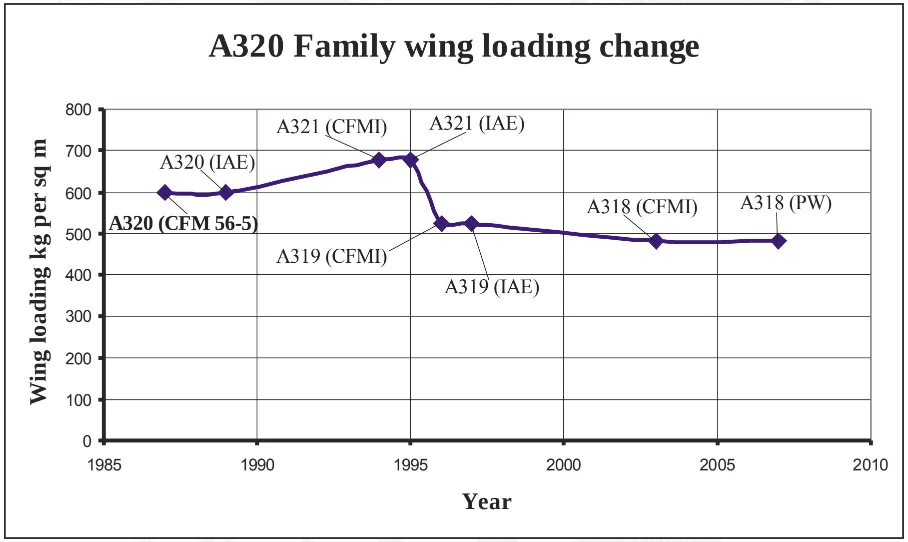
- Technically and economically substantiated reserves are made in basic airplane to create future variants.
- Usually reasonable to make reserves of:
  - wing area,
  - height of landing gear legs;
- Usually not reasonable to make reserves of:
  - fuel tank capacity,
  - engine thrust,
  - fuselage volume,
  - structure strength.

Reserves in wing area

- Reserves in wing area. Significant increase of wing area for created variants is very difficult as increases of loads and requires significant reinforcement of wing structure. Thus **basic airplanes normally are created with bigger wing area (lower wing loading) than optimum**.



Wing loading of basic airplane variants and their modifications
a - airplanes with piston engines; *b*- airplanes with turbojet and turbofan engines

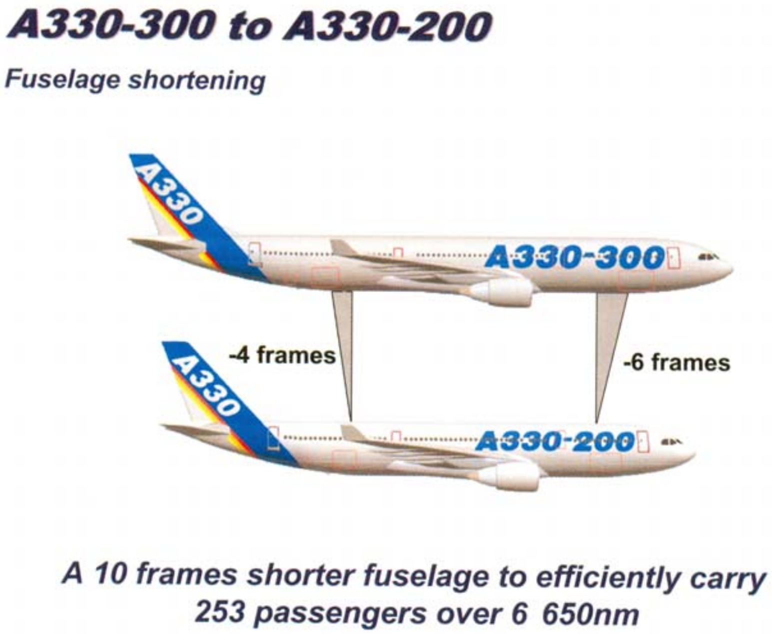


Design of variants based on reserves

- Reserves in fuselage length are not reasonable.

– Increase of fuselage length leads to reinforcement of fuselage structure, which is easy to make.

– Decrease of fuselage length leads to significant changes of the fuselage structure, which are harder to make.

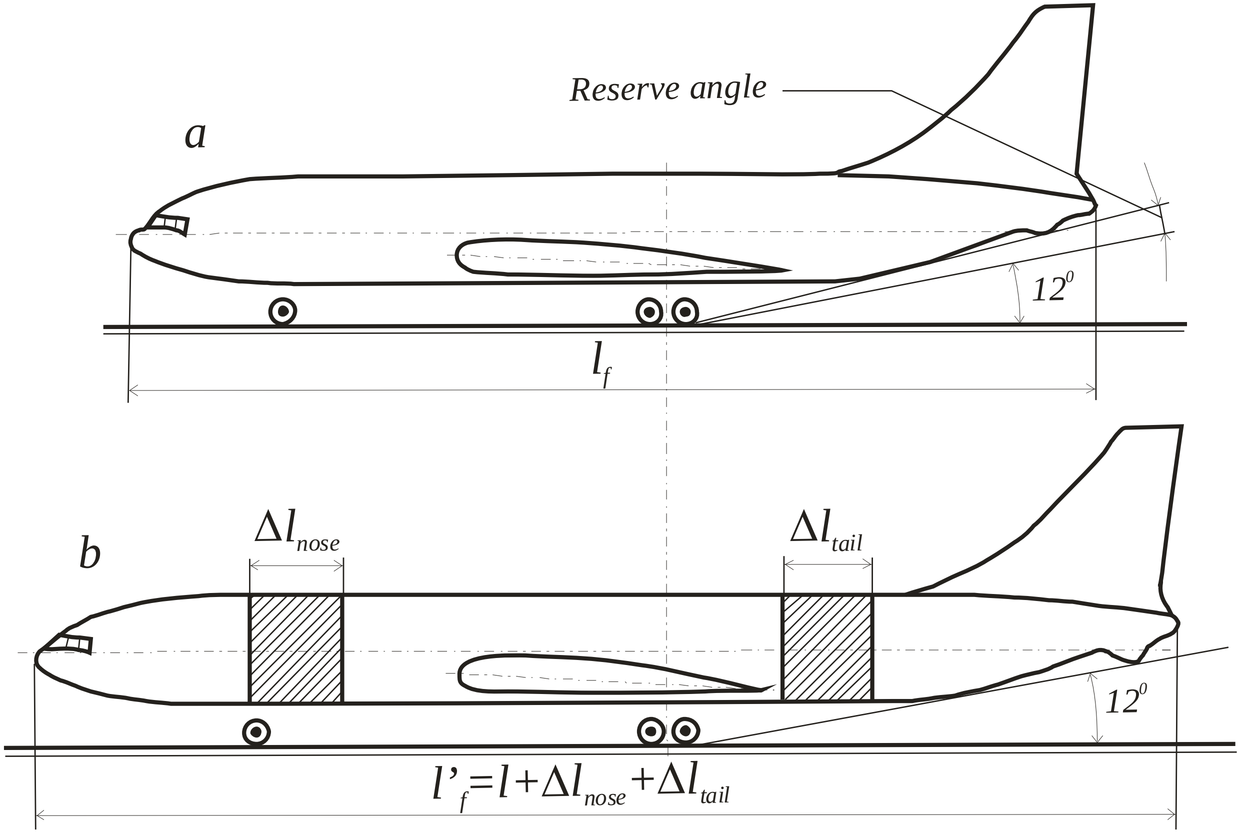


Design of variants based on reserves

Increase of fuselage length does not affect stability and controllability, because the distance of tail units from the centre of gravity increases.

The unplanned increase of fuselage is limited by height of landing gear legs (landing angle).

Thus it is reasonable to make reserves of height of landing gear legs.

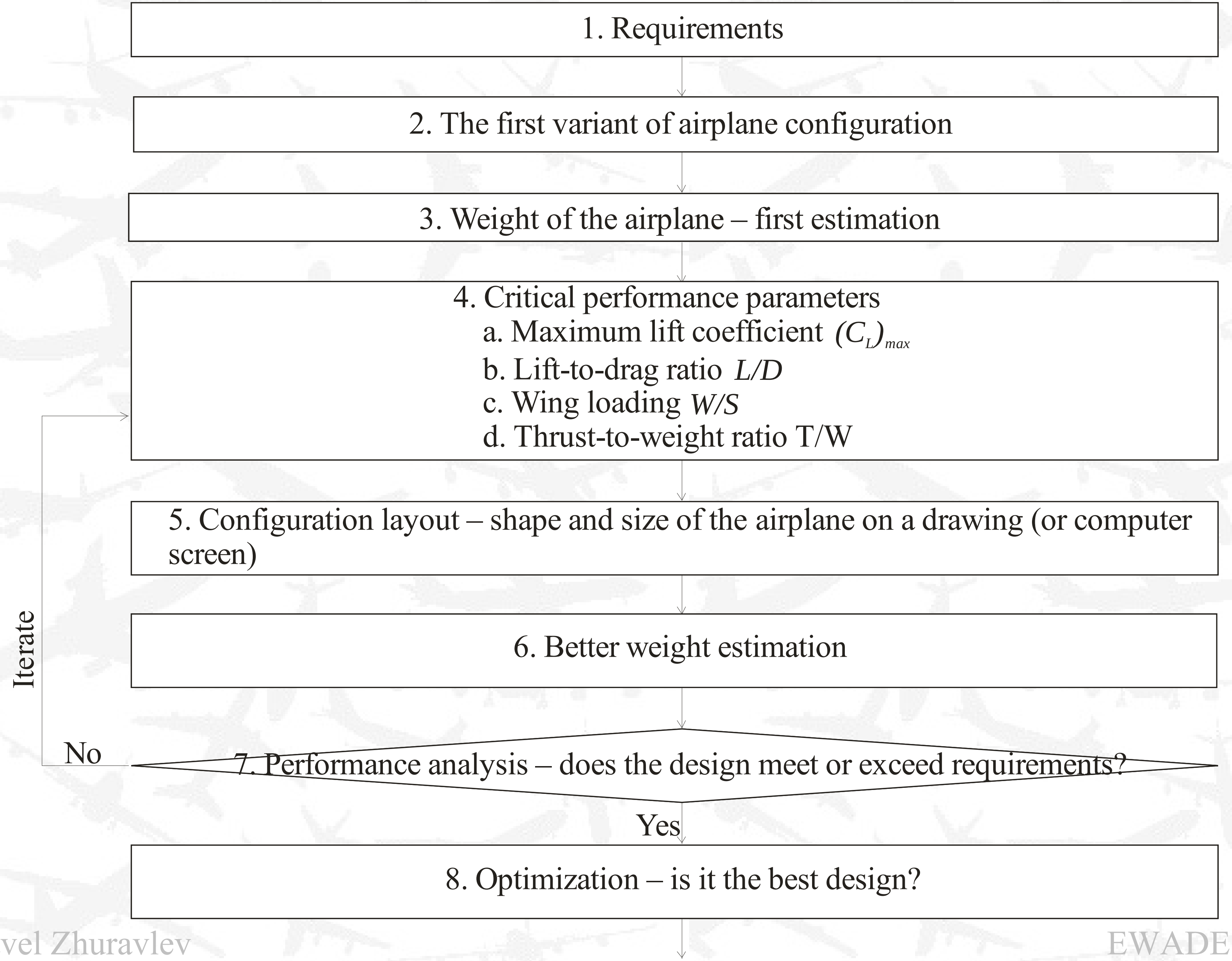


Reserve of landing angle and length of landing gear legs for creation of variants

Design of variants based on reserves

- ***Reserves of fuel tank capacity are not reasonable.*** Usually there are reserves of internal capacity (first of all, in the wing). They can be used as additional fuel tank after the minimum change.
- ***Reserves of structure strength are not reasonable.*** Experience shows that rational structure should be designed according to undersized loads. Static tests reveal the places, which need reinforcement. Local reinforcement usually is easy to implement.

The Main Pivot Points for Conceptual Design (Anderson)



1. Requirements

2. The first variant of airplane configuration

3. Weight of the airplane – first estimation

4. Critical performance parameters
   - a. Maximum lift coefficient $(C_L)_{max}$
   - b. Lift-to-drag ratio L/D
   - c. Wing loading W/S
   - d. Thrust-to-weight ratio T/W

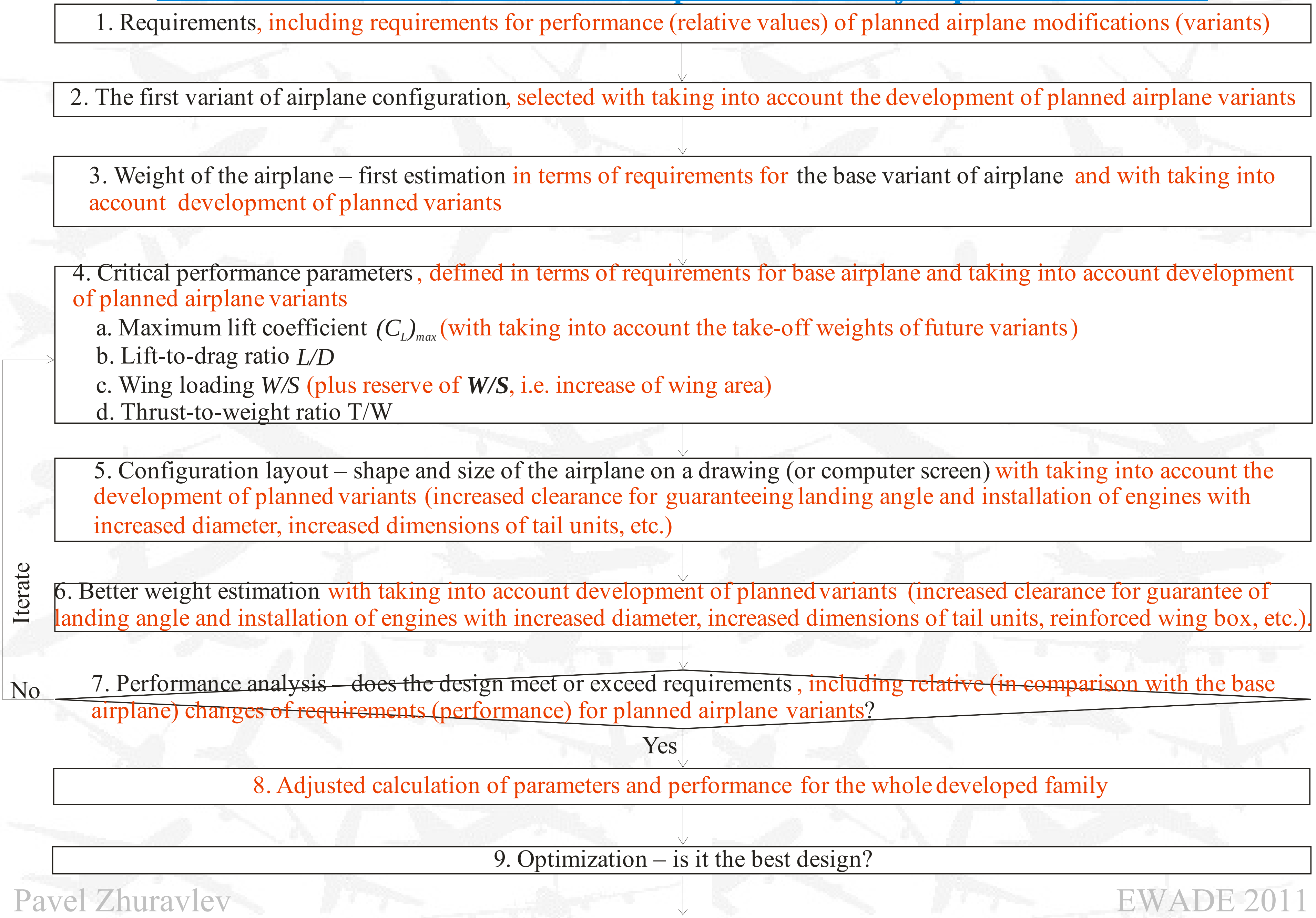
5. Configuration layout – shape and size of the airplane on a drawing (or computer screen)

6. Better weight estimation

7. Performance analysis – does the design meet or exceed requirements?

8. Optimization – is it the best design?

Flow-Chart of Conceptual Design of base variants of passenger airplanes with taking into account the reserves for development of family of planned variants



1. Requirements, including requirements for performance (relative values) of planned airplane modifications (variants)

2. The first variant of airplane configuration, selected with taking into account the development of planned airplane variants

3. Weight of the airplane – first estimation in terms of requirements for the base variant of airplane and with taking into account development of planned variants

4. Critical performance parameters, defined in terms of requirements for base airplane and taking into account development of planned airplane variants

   a. Maximum lift coefficient $(C_L)_{max}$ (with taking into account the take-off weights of future variants)

   b. Lift-to-drag ratio *L/D*

   c. Wing loading *W/S* (plus reserve of ***W/S***, i.e. increase of wing area)

   d. Thrust-to-weight ratio T/W

5. Configuration layout – shape and size of the airplane on a drawing (or computer screen) with taking into account the development of planned variants (increased clearance for guaranteeing landing angle and installation of engines with increased diameter, increased dimensions of tail units, etc.)

6. Better weight estimation with taking into account development of planned variants (increased clearance for guarantee of landing angle and installation of engines with increased diameter, increased dimensions of tail units, reinforced wing box, etc.).

7. Performance analysis – does the design meet or exceed requirements, including relative (in comparison with the base airplane) changes of requirements (performance) for planned airplane variants?

8. Adjusted calculation of parameters and performance for the whole developed family

9. Optimization – is it the best design?

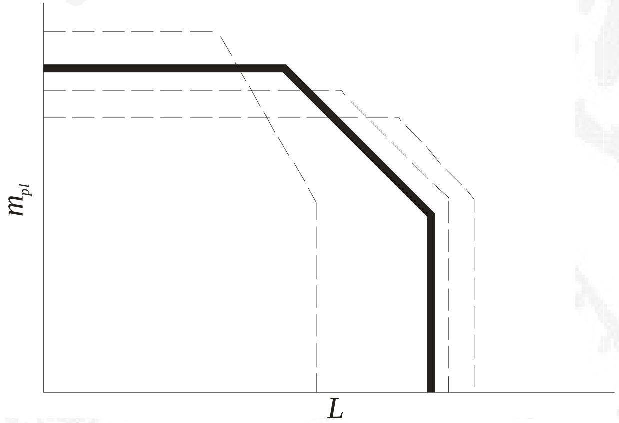
Problem of definition of optimal reserves

Bigger reserve (e.g. lower wing loading)

More expensive operation of basic airplane

Cheaper and more flexible creation of variants

“Too much reserve would lead to expensive operation of basic airplane, while “too little” would complicate creation of modifications. Optimum can only be found in case of evaluation of operation of the whole aircraft family (airplane fleet creation problem - this task requires using Pre-Design methods during design of any new passenger airplane).



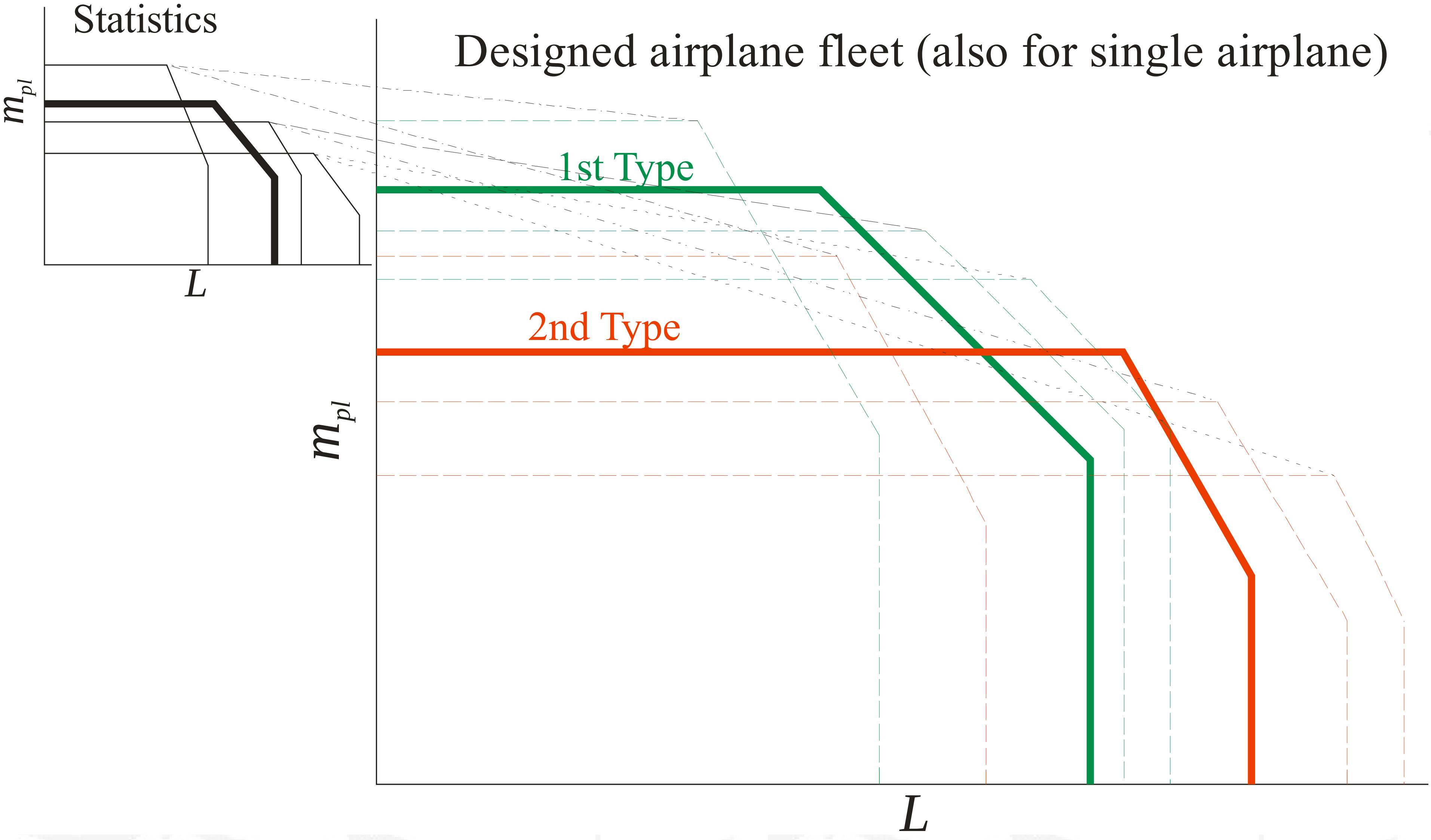
3 ways of selection of main performance and parameters of airplane variants (with taking into account their operation within fleet)

1. For Static Problem of Fleet Creation (during one given year).

From known statistics we define:

- average number of variants,
- average percent of change of parameters and performance for every variant relative to basic airplane, i.e. change of:
  - maximum payload weight,
  - flight range,
  - take-off weight,
  - geometrical dimensions, etc.
- Based on the assumed changes, we add the appropriate variants and estimate the expedience of creation of airplane family and estimate optimum reserves within the basic airplane.

Static problem of airplane family creation

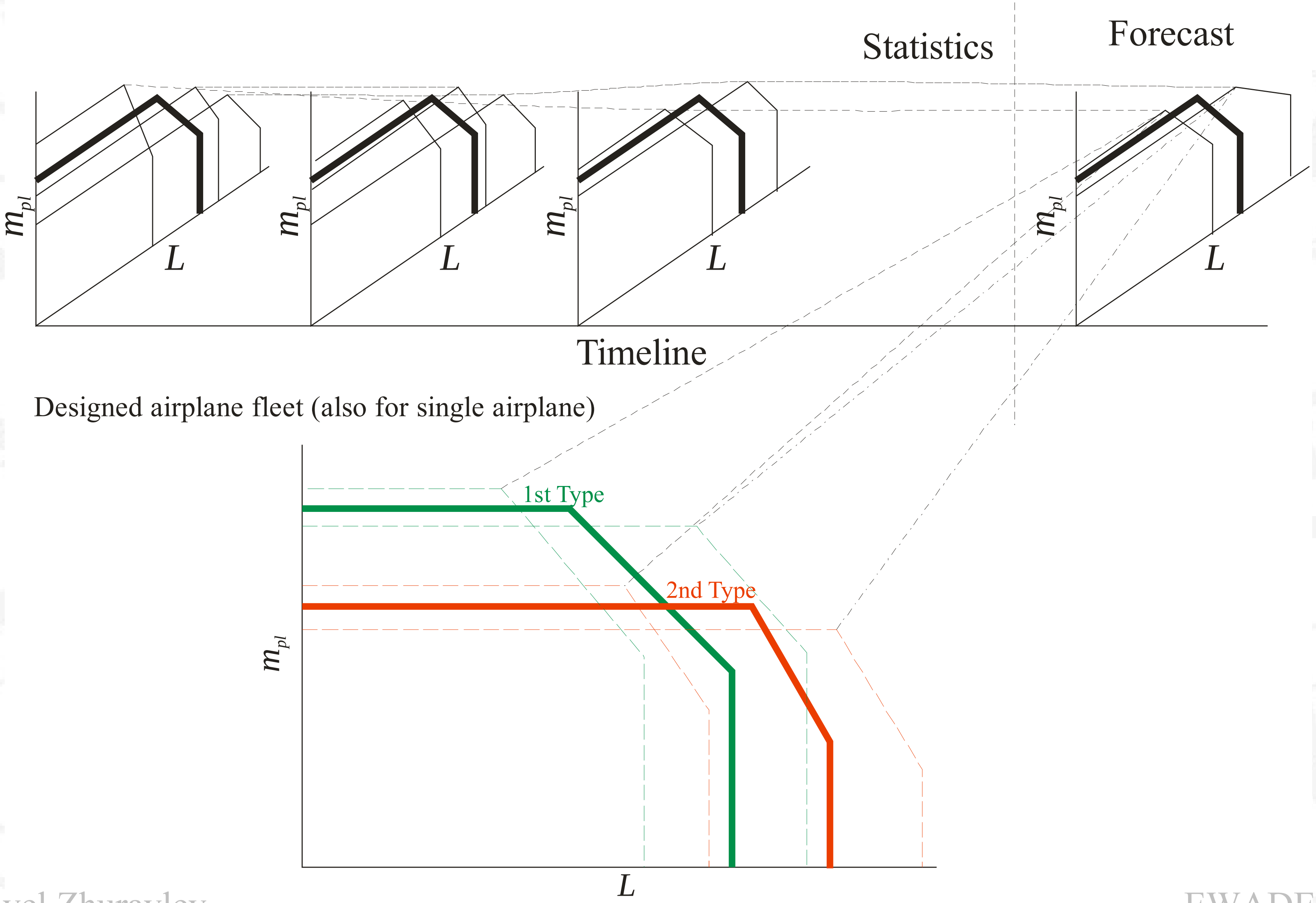


3 ways of selection of airplane variants

2. For Dynamic Problem of Fleet Creation with usage of past experience and statistics (during a given period of time).

- The number of variants, maximum and average percent of changes in parameters and performance of every variant vary over a long time interval.
- Therefore we define the trend line, which describes these changes over the years. This trend is than used to correct the number of variants and the appropriate changes of their parameters and performance.
- This data is also used to define optimum reserves of the performance and parameters of the basic airplane.

Dynamic problem of airplane family creation



3 ways of selection of airplane variants

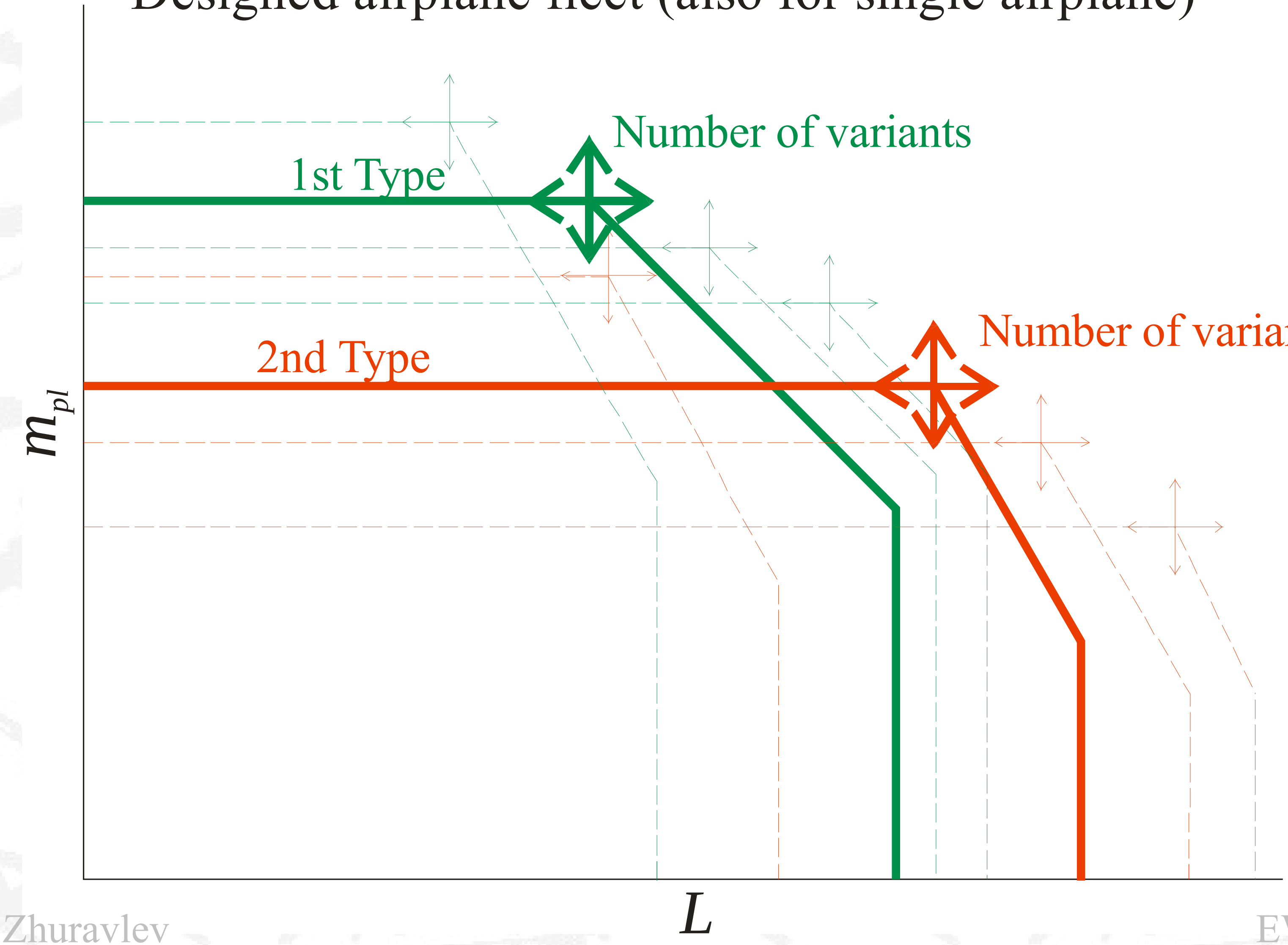
3. For solution of the Problem of Fleet Creation together with the Problem of Optimization of Airplane Families.

During the process of solution of this task we define:

- Parameters and performance of basic airplane;
- Optimal number of variants within the family;
- Optimal values of parameters and performance for each variant (with respect to given limits);
- Optimum reserves of performance and parameters of the basic airplane.

Problem of fleet creation and airplane family optimization

Designed airplane fleet (also for single airplane)



Conclusions

1. **Actual experience of airplane design shows that it is necessary to take into account the problem of development of “airplane family”** both during design of single airplanes and creation of advanced airplane fleet. √
2. **To define the reserves** for the newly designed airplane **it is necessary to consider operation of the whole family** (solve a fleet creation problem by using Pre-Design methods). √
3. It is useful **to teach students**, who study Aircraft Design, **basics of family creation methods** including some elements of Pre-Design of airplanes. √


A321
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A319
A319
F-WWDB
A318
A318
F-WWBD
A340
A340-300 AIRBUS
A340
A340-200 AIRBUS
A330
A330-300 AIRBUS
A330-200 AIRBUS
Monarch
G-MONS
A340
A330

Thank you