MULTIOBJECTIVE MULTIPARAMETRIC OPTIMIZATION OF PROPULSION SYSTEM FOR ADVANCED CIVIL AIRCRAFT IN DISTRIBUTED ENVIRONMENT OF COLLABORATIVE MDO SYSTEM DEVELOPED IN AGILE PROJECT

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Abstract

The paper describes the procedure of organization of optimization studies with required mathematic models of aircraft and engine using commercial software Optimus (Noesis), which allow to implement all main phases of investigations, required for optimal Propulsion System (PS} generation, including input data preparation, parametric studies, optimization, postoptimization analysis, assessment of the risk to reach declared data due to impact of random factors and recommendation delivery.

Solution of multiobjective tasks on optimal PS path generation for initial design phases is appropriate to carry out in accordance with well-known Pareto efficiency concept, i.e. the area of design space, in the scope of which it is impossible to reach improvement of any one criterion without making at least one of the other criterion worse off, should be defined.

The solutions are obtained in the scope of distributed environment of collaborative MDO system developed in AGILE Project.

1 Introduction

To integrate a lot of interdisciplinary links which are characterized modern aviation projects, as well as to perform researches and design of whole aircraft, low cost technologies providing effective design of air vehicles and their systems are needed. Demand of the technologies is also concerned with the fact that to meet more and more stringent environmental (noise and emission) requirements implementation of effective search and optimization of new solutions on Propulsion System (PS) architectures as well as aircraft configurations.

Many international projects of FP6 and FP7 programs in Europe (including projects with Russia participation) such as NACRE, DisPURSAL, etc. were dedicated to solving of the tasks.

Multidisciplinary analysis and optimization (MDAO) is central component of joint aircraft and PS design system, allowing to overcome mentioned above complex design problems. Nowadays MDAO systems could implement multilevel and multidisciplinary status of the system and provide multiobjective analysis and optimization, effectively combine analytical models located on the different computers and obtain optimal solutions. In the same time, new incipient design problems require the development of new more advanced MDAO systems. Expecting technical and economic effect from new MDAO system application consist in the providing significantly reduction of aircraft and its PS development costs due to obtaining of more efficient solutions on earlier design phases and exchange of experience with leading aviation companies. It is assumed to reduce time of MDAO tasks solutions on earlier aircraft and its PS design phases by 20%.

Main phases of design and optimization (problem statement, task solutions and selection of optimal solutions are shown on the Fig.1.

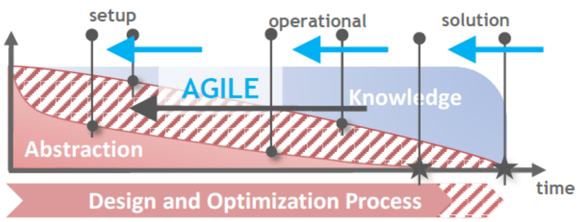


Fig.1 – Phases of MDO based processes

According to [1] based on the last 20 year MDO tasks in 3-5 years R&D setup problem phase spends 60-80% of total design and optimization time.

Main goal of AGILE project (its paradigm) includes 3 tasks:

– Acceleration of setup problem phase of design process;

– Automation of MDAO workflow generation;

– Effective integration of distributed competencies in one center.

New 3rd generation MDO system are oriented to solve the tasks.

The 3rd generation MDO system are characterized by following features:

– Reduction of the complexity of management of distributed design processes;

– Management of huge amount of input/output connections;

– Visualization and decision making technics for support of design groups;

– Flexible integration of new competencies or simplicity of reconfiguration of design processes;

– Extension of collaboration and knowledge modelling;

– High level of variety and experience formalization on each level;

– Availability of interdisciplinary capabilities and multinet structure.

Inclusion in the design process of new members besides of disciplinary experts, i.e. system architect, system integrator and collaborative engineer was required for effective implementation of all capabilities of new generation MDO systems (Fig. 2).

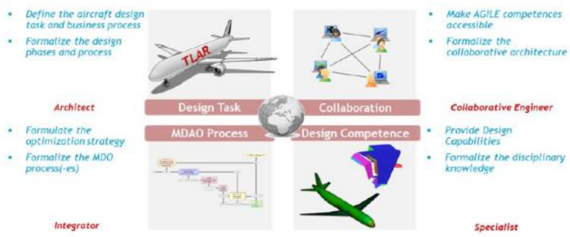


Fig.2 – Stakeholders within the Collaborative Architecture of MDO system in AGILE project.

The architect is responsible for specification of the design case in the AGILE framework, such as collecting the required competences, defining the design phases and the dimensionality of the design space to be explored, integrator is responsible for the deployment of the design and optimization (sub-) processes, and for the management of such processes within the AGILE framework and collaborative engineer is responsible for providing the integration within the framework, necessary to connect the various competences and making them accessible to the framework..

General structure of design process organization in AGILE project are presented om the Fig. 3. Main systems (RCE, Brics, CPACS), providing link between separate competences (models) in a common MDAO process are shown in the figure [1].

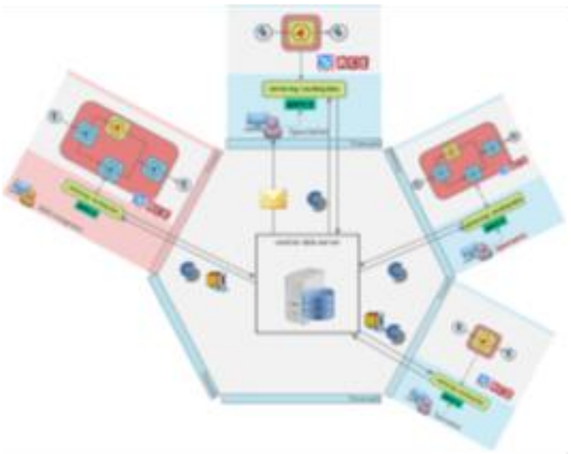


Fig.3 - General structure of design process organization in AGILE project

2 Problem statement

The aim of the activity is solution of debug task on studies using improved MDAO system by example of optimal design of PS based on the turbofan with takeoff thrust class of 30 tf for long range widebody jet (LRWBJ). Advanced level of engine parameters as well as level of weight and aerodynamic efficiencies for baseline LRWBJ were adopted in the activity.

Mathematical problem statement of indicated task consists of generation of Pareto-optimal solutions resulting of investigation of design space of variable parameters , vector of which consist of aircraft &PS matching parameters (i.e. takeoff wing and thrust loading - G/S and R/G) and engine cruise cycle parameters at fixed takeoff gas temperature: FPR_{CR} and $T4_{CR}$ (BPR is selected to obtain minimal SFC at fixed combination of the parameters) for criteria vector, which includes cruise flight range at optimal flight level, required runway length and fuel efficiency (L_{LRWBJ}, L_{runway} , q_{fuel}), i.e.:

– vector of design variables – **x** = (G/S, R/G, FPR_{CR}, $T4_{CR}$);

– vector of design objectives – **y** = (L_{LRWBJ}, L_{RUNWAY}, q_{FUEL}).

Variation range and baseline level of parameters are presented in the Table 2.

Table 2 - Variation range of parameters for baseline aircraft and PS

Parameter	Variation range	Baseline value
G/S, kg/m^2	600…750	700
R/G	0.25…0.3	0.275
$T4_{CR}$, K	1500…1575	1550
FPR_{CR}	1.4…1.6	1.45

In general case task of optimal choice of engine parameters for commercial aircraft requires much more problem statement: besides of indicated criteria environmental, costs, engine life, reliability and other parameters should be taking into account. Main goal of the activity is implementation of optimization studies of task using required models of aircraft and PS, in distributed collaborative design environment Optimus, which allow to perform all needed phases of PS design study, including preparation of input data, parametric studies, postoptimization analysis, estimation of influence of risk of reaching of required parameters values due to impact of random factors and recommendations delivery.

Complex of CIAM models, which interconnections are shown on the Fig.4, is developed to solve the task of optimal design of PS for LRWBJ using Optimus.

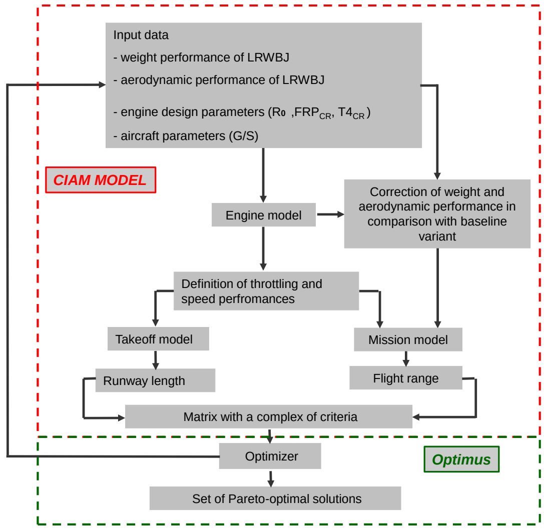


Fig..4 – Complex of models for optimal design of PS using of Optimus

After the input of initial data, including weight and aerodynamic performances, wing loading and engine cycle parameters, the program to run engine model to define speed and throttling performance. Optimal BPR is also defined in the block at given combination of FPR_{CR} and $T4_{CR}$ is also defined in the block.
At design engine cycle parameters variation (FPR_{CR}, $T4_{CR}$), engine specific weight γ_{eng} is defined as function of BPR.

Change of onboard fuel weight at change of PS weight was taken into account at fixed takeoff weight of aircraft using following formula:

$$\Delta G_{fuel} = K_{eng} \cdot K_{PS} \cdot \big(\gamma_{eng\,baseline} \cdot R_{0\,baseline} - \gamma_{eng} \cdot R_0\big)$$

where K_{eng} is engine number (=2);

K_{PS} is PS weight coefficient (=1.6);

R_0 is takeoff thrust.

At change of wing area in given range correction of available fuel weight was taken into account by following way:

$$\Delta G_{fuel} = \left(\frac{G_w}{S_w}\right) \cdot (S_{w\,baseline} - S_w)$$

where $\left(\frac{G_w}{S_w}\right)$ is weight of 1 m^2 of wing structure (=55 kg/m^2);

$S_{w_{baseline}}$ is baseline wing area (=307 m^2).

Taking into account of influence of change of wing area on aerodynamic performance in model is implement by following way

$$\Delta C_{x0} = C_{x\,F}^{F_F} \cdot \left(\frac{F_{F\,baseline}}{S_w} - \frac{F_{F\,baseline}}{S_{w\,baseline.}}\right) ?$$

where $C_{x\,F}^{F_F}$ is drag coefficient corrected with fuselage area (=0.06);

$F_{F\ baseline}$ is baseline fuselage area (=21.4 m^2).

After correction of weight and aerodynamic performance in comparison with baseline aircraft and PS, flight range and required runway length are defined using mission and takeoff models.

Calculation of flight range is performed for simple flight profile, which include flight segments such as climb, cruise with fixed Mach number M_H = const and descent. At that cruise flight is implemented for fixed angle of attack α and lift coefficient c_y with increase of flight altitude (flight "on ceiling"). Besides choice of optimal altitude providing maximum flight range is carried out.

Calculation of runway length with takeoff model is performed according to airworthiness standards [2] up to altitude of 10.7 m in design atmospheric conditions (ambient air temperature T_{amb}=+30°C, ambient air pressure P_{amb} = 760 Hg mm). It is assumed that during continued takeoff the rating of operating engine is not changed when other engine is inoperative.

Later on, optimizer selects Pareto-optimal solutions from obtained set of object variants with combination of selected criteria to further elaboration.

Computational results on main mission performance for baseline LRWBJ, carried out with described model, are presented in Table 3.

Table 3 - Mission performance for baseline LRWBJ

Cruise flight range L_{CR} (Altitude=11 km, M=0.85), km	12230
Fuel efficiency q_{FUEL}, g/(pax·km)	22.5
Runway length L_{RUNWAY}, m	2800

3 Parametric studies

Adjustment of assigned task in collaborative environment Optimus consists in generation of workflow, indicating set of required models, specification of variation range of selected optimized parameters and choice of objectives for further consideration (Fig. 5).

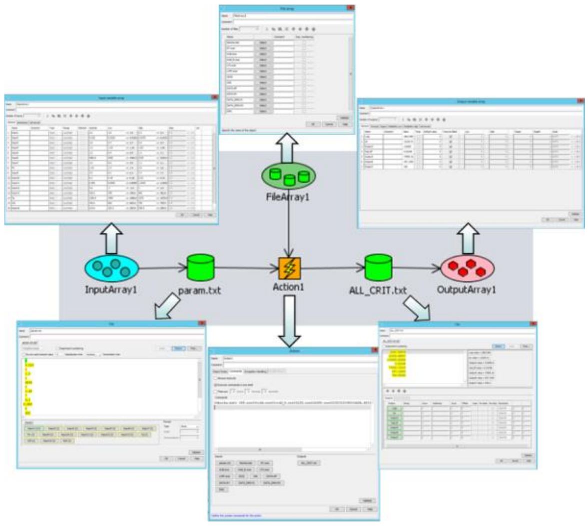


Fig.5 - Workflow generation in Optimus

Parametric studies using developed CIAM program complex are carried out with designing of experiments to select of design points in design space of variable parameters. Thereto uniform distribution as well as other planes of experiments (full-factor, orthogonal, lπ-τ) could be applied for [3, 4].

In the activity estimation of impact of factors on selected objectives are carried out with full-factor plan of experiment of 3rd level (43 experiments) (Fig.6).

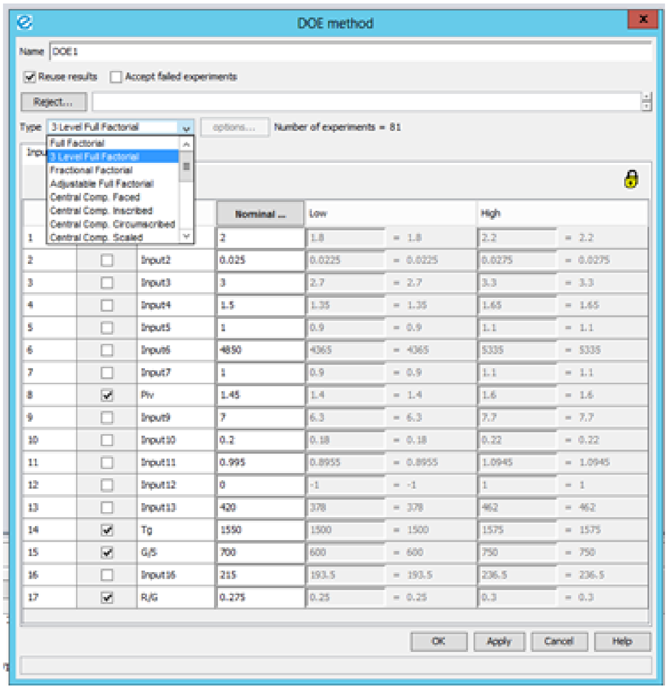


Fig. 6 - Method of plan of experiment, selected for parametric studies

Results of the studies are presented in graphic view: level lines of selected objective functions in the field of two design parameters at fixed values of other factors. Influence of variables on 3 criteria are shown on the Fig. 7.

Increase of FPR_{CR} together with decrease of gas temperature leads to improvement of speed performance of LRWBJ at rolling, and therefore to decrease of balanced runway length.

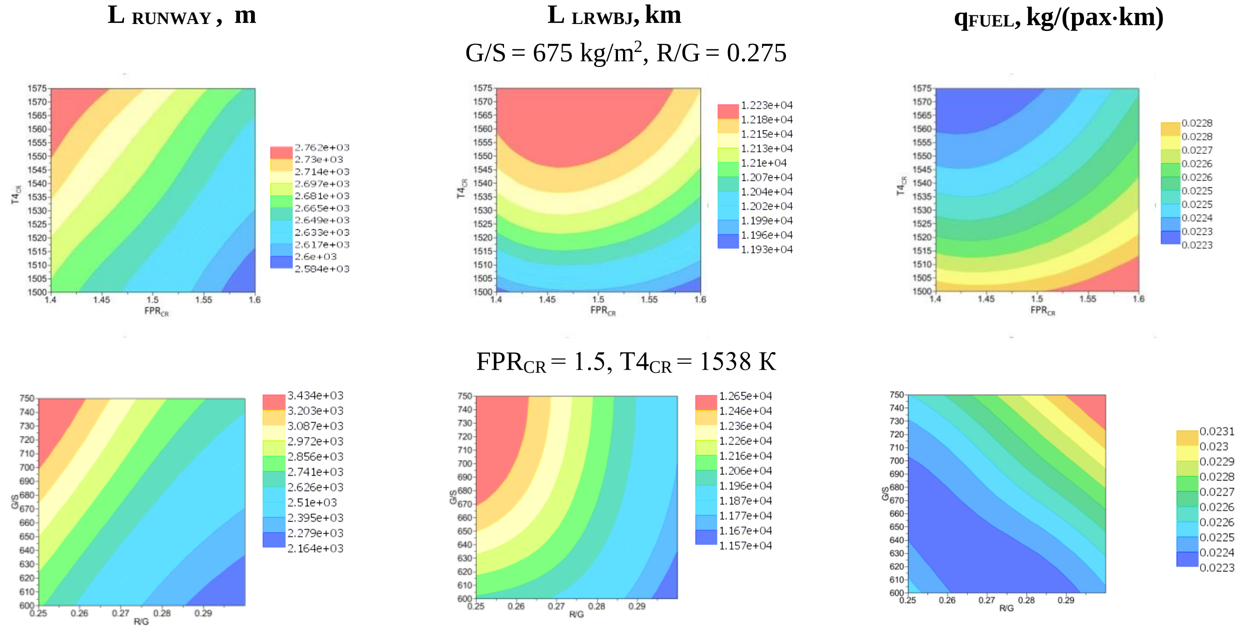
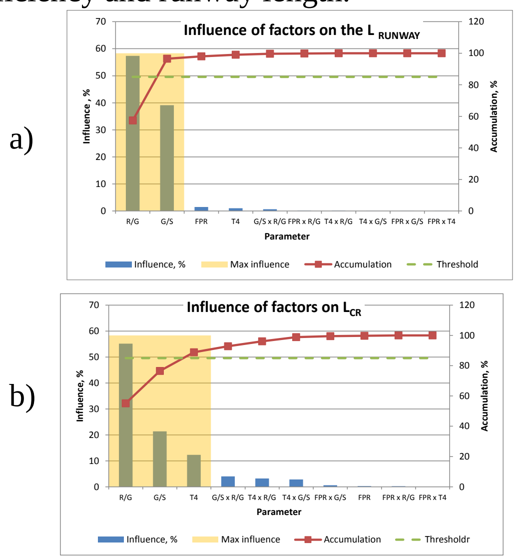


Fig.7 - Results of parametric studies for LRWBJ

Decrease of wing loading and increase of thrust loading promote improvement of LRWBJ takeoff performance due to rise of wing area and takeoff thrust, in the same time it leads to reduction of fuel consumption which despite of some improvement of aerodynamic efficiency (due to decrease of drag coefficient C_{x0}) leads to losses of flight range.

If cruise gas temperature is increased, SFC is decreased and flight range as well as fuel efficiency are improved. Optimum of FPR_{CR} from point of view of maximum flight range and minimum of fuel efficiency is explained in that with rise of FPR_{CR} despite of some degradation of SFC (due to decreasing of optimal BPR) engine weight also is decreased increasing of fuel weight. Quantitative assessment of impact of selected optimized variables on criteria are presented as columns along on the Fig.9. Contribution of variables and their combinations in change of criterion are indicated as columns along axis of abscissa. Percentage of change of criterion and accumulation on influence of factors on criterion are indicated on left and right axes of coordinate accordingly. For further studies only factors, which total impact on selected criteria is not higher than threshold value (yellow background on the Fig.9), which is equal to 80…85%.

It is seen, that takeoff thrust loading, wing loading and cruise gas temperature have most influence on the cruise flight range, fuel efficiency and runway length.



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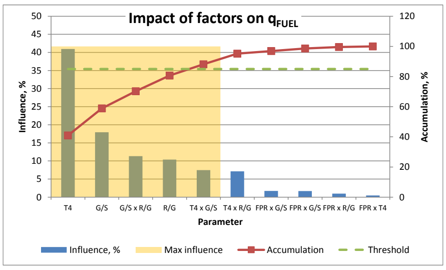


Fig.8 - Influence of optimized variables on criteria Lrunway (a), L $_{LRWBJ}$ (b) and q_{FUEL} (c)

At that FPR_{CR} variation has low impact on selected criteria. Therefore for further studies the number of optimized variables could be reduced in comparison with initial problem statement.

4 Multiparametric multicriterial optimization of PS for LRWBJ

Solution of assigned task of multicriterial mulrifactor optimization with 4 variable parameters and 3 criteria (cruise range at optimal altitude, balanced field length and fuel efficiency of LRWBJ) are shown on the Fig. 10, where Pareto-optimal solutions are presented. Each of the solutions in some relation (at least for one of the criteria) is better than the remaining and selection of best rational solution requires comprehensive nonformalized analysis.

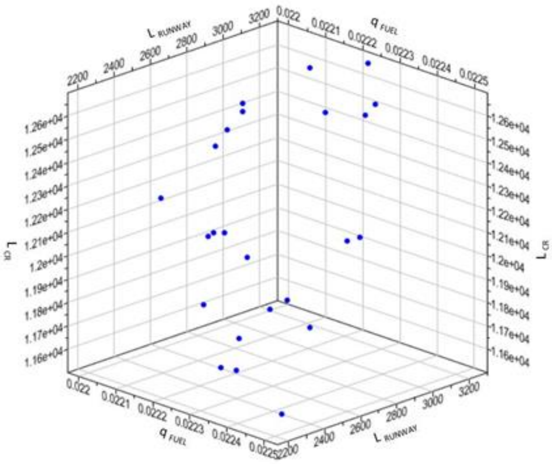


Fig.9 - 3D Pareto set in the field of selected criteria

Optimization is performed with one of the multicriterial method available in Optimus environment and based on the genetic algorithm. Parameters of the method such as population size, weight factor, maximal iteration number, etc. are presented on the Fig. 11 [5].

23 Pareto-optimal solutions for design variables and objectives, obtained with optimization, are described in the Table 4.

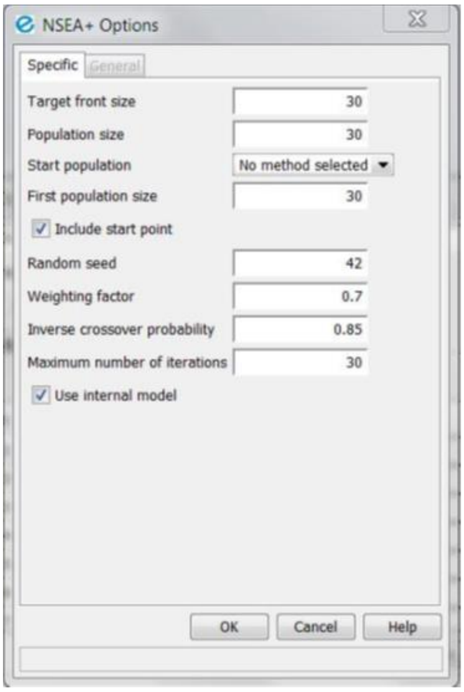


Fig.10 - Parameters of optimization algorithm, adopted for implementation of optimization studies

Table 4 - Results of 3-objectives 4-parametric optimization of LRWBJ and PS at flight range for optimal altitudes, runway length and fuel efficiency

№	FPR_{CR}	$T4_{CR}$	G/S	R/G	q fuel	L_{runway}	L_{LRWBJ}
1	1.45	1570	690	0.253	22.1	3173	12611
2	1.45	1549	704	0.255	22.3	3165	12557
3	1.59	1560	687	0.252	22.3	3072	12543
4	1.50	1561	687	0.257	22.2	3033	12519
5	1.53	1571	653	0.255	22.1	2926	12494
6	1.50	1566	654	0.256	22.1	2905	12470
7	1.53	1569	643	0.258	22.1	2819	12415
8	1.50	1561	628	0.258	22.1	2775	12349
9	1.57	1532	656	0.264	22.5	2710	12205
10	1.53	1537	609	0.251	22.4	2765	12143
11	1.41	1570	616	0.270	22.0	2595	12141
12	1.48	1548	615	0.268	22.2	2560	12106
13	1.43	1556	627	0.274	22.2	2559	12089
14	1.43	1550	610	0.268	22.2	2553	12071
15	1.52	1541	611	0.268	22.3	2523	12056
16	1.55	1573	647	0.286	22.4	2456	11964
17	1.43	1545	639	0.287	22.4	2443	11908
18	1.49	1554	654	0.291	22.5	2438	11892
19	1.51	1571	617	0.288	22.2	2341	11883
20	1.58	1554	607	0.285	22.4	2295	11816
21	1.49	1572	620	0.300	22.4	2256	11697
22	1.44	1552	611	0.297	22.3	2254	11686
23	1.45	1529	613	0.299	22.5	2219	11597
BASELINE							
	1.45	1550	700	0.275	22.5	2803	12330

5 Posoptimization analysis

Correlation analysis is one of the main methods of postoptimization analysis. It is based on the graphical representation and calculation of elements of correlation matrix of influence design parameters on objectives and degree of interconnection of selected objectives (correlation coefficients).

Correlation matrix with values of matrix elements is presented on the Fig. 12. Correlation coefficients values close to 1 characterizes high direct correlation (rise of one variables leads to rise other variable), values close to -1 characterizes inverse correlation (rise of one variable leads to decrease of other variable). Intermediate values of the correlation coefficients show that despite of trend of rising of one variable leads to insignificant rise (fall) other one, but some correlation between the variables is observed.

Presented on Fig.12 data confirms results of parametric studies concerning fact that most impact on the cruise flight range and runway length have wing loading, increase of which leads to rise of criteria (direct correlation) and thrust loading, which is inversely correlated with the criteria.

Cruise gas temperature has most impact on the fuel efficiency, rise of which leads to decrease of the objective function.

To analyze variation, range of optimized variables distribution bar chart for all calculated variants and Pareto-optimal solutions obtained during optimization are constructed (Fig. 12).

Pearson (Spearm	FPR_{CR}	$T4_{CR}$	G/S	R/G	q_{FUEL}	L_{RUNWAY}	L_{CR}
FPR_{CR}	1.000 (1.000)	-0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.113 (0.133)	-0.121 (-0.160)	0.002 (-0.008)
$T4_{CR}$	-0.000 (0.000)	1.000 (1.000)	0.000 (0.000)	0.000 (0.000)	-0.611 (-0.620)	0.101 (0.112)	0.341 (0.346)
G/S	0.000 (0.000)	0.000 (0.000)	1.000 (1.000)	0.000 (0.000)	0.389 (0.431)	0.625 (0.598)	0.441 (0.445)
R/G	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	1.000 (1.000)	0.291 (0.300)	-0.751 (-0.762)	-0.737 (-0.735)
q_{FUEL}	0.113 (0.133)	-0.611 (-0.620)	0.389 (0.431)	0.291 (0.300)	1.000 (1.000)	-0.067 (-0.048)	-0.483 (-0.432)
L_{RUNWAY}	-0.121 (-0.160)	0.101 (0.112)	0.625 (0.598)	-0.751 (-0.762)	-0.067 (-0.048)	1.000 (1.000)	0.874 (0.862)
L_{CR}	0.002 (-0.008)	0.341 (0.346)	0.441 (0.445)	-0.737 (-0.735)	-0.483 (-0.432)	0.874 (0.862)	1.000 (1.000)

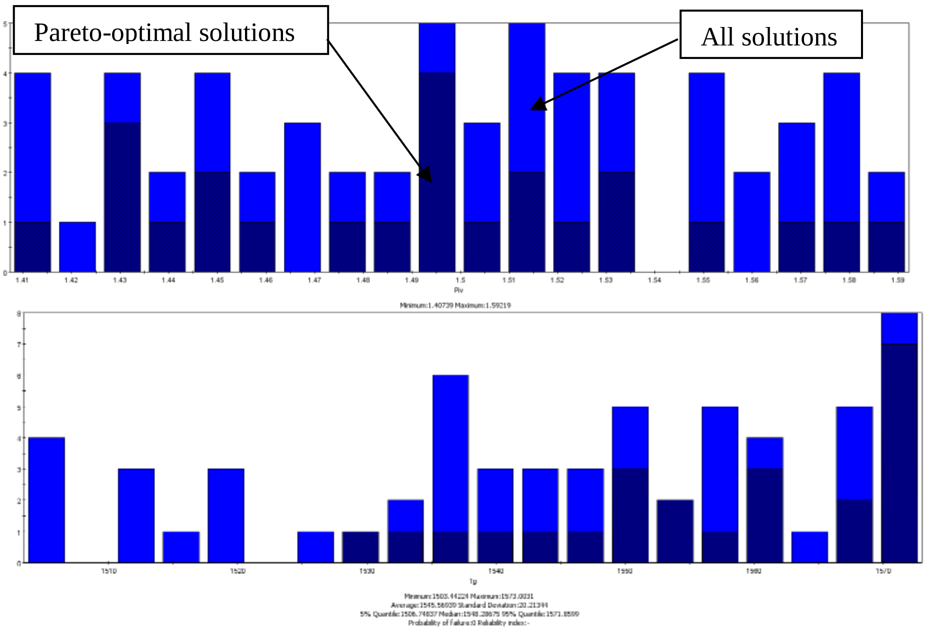
Fig. 11 - Correlation matrix of influences between design variables and objectives for LRWBJ

Based on the analysis of the data, presented on the Fig.12 it could be concluded about advisability of change of variation range of cruise gas temperature shifting it on higher values. Upper value for wing loading should be limited by value of ~ 700 kg/m^2.

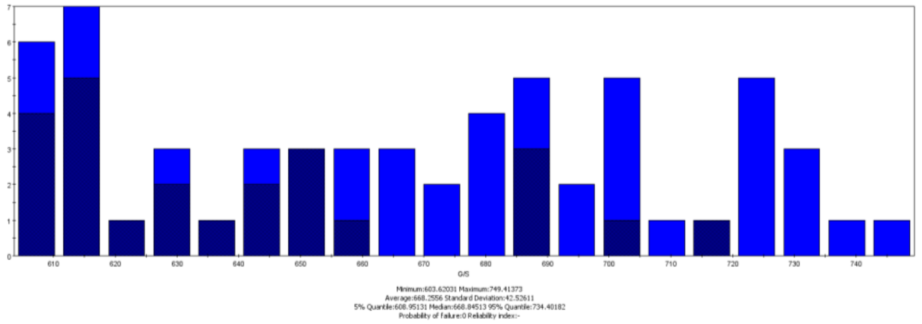
Choice of rational engine parameters at its optimization on aircraft level is inevitably connected with adoption of number of compromise decisions.

a) FPR_{CR}

b) $T4_{CR}$



c) G/S



d) R/G

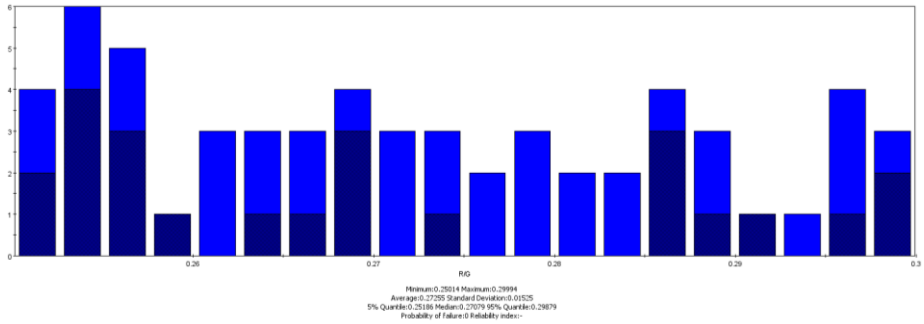


Fig.12 - Distribution bar chart for all calculated variants and Pareto-optimal solutions obtained during optimization

Pareto-optimal solutions obtained during the optimization are reasonable divide on 2 groups, first of which include aeroplanes with home base aerodromes of class A (runway length < 3250 m), and second one with runway length no more than 2800 m (class B). The options with max range and acceptable level of fuel efficiency (no 1 and 8) could be selected from them for more detail analysis.

Improvement of range for the selected variants of aircraft could be equal to ~1-3% relative to baseline case, and improvement of fuel efficiency could reach 2%.

6 Conclusions

Multiobjective study on optimal engine design with the thrust level in 30 tf class for large range widebody jet is carried out in the activity using the tools of distributed collaborative environment Optimus, which allow sufficiently easy to integrate all aircraft and PS model to implement optimization studies, to adjust set of optimization task, and which has wide set of optimization methods and tools for fore- and postoptimization analysis.

Procedure of optimization studies implementation including phases of input data preparation, parametric studies, postoptimization analysis, assessment of the risk to reach declared data due to impact of random factors and recommendation delivery are implemented by example of debug 4-parametric 3-criteria task, based on objective functions such as cruise flight range on optimal altitude, balanced field length and fuel efficiency.

It will be appropriate if further additional criteria of other disciplines (e.g. costs and environmental) will be considered and task of looking for optimal engine solutions will be solved in multidisciplinary problem statement.

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