# Optimization of a three spool axial compressor to increase the efficiency of a gas turbine engine

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**Abstract**. The paper provides a description of the algorithm, an example of a specific task, and the results of the optimization of a 15-stage three-spool compressor for a ground-based GTU by the efficiency criteria of the engine. It can be performed by using the proposed algorithm to find such a compressor configuration that will be not just the optimum compressor, but the best option for working as part of the engine under the specified operating conditions and with various types of required restrictions. Using the proposed algorithm, varying only the stagger angles of the profiles, the authors managed to find a way to increase the overall efficiency of the NK-36ST engine by 0.43%. Obviously, it is possible to achieve a more impressive result and at the same time to increase reliability, reduce the weight and cost of the engine by applying more complex models by changing the shape of the blade profiles.

## 1. Nomenclature

| | | |
|---|---|---|
| $G$ | = | mass flow rate of the working fluid, kg/s |
| $p^*$ | = | total pressure, Pa |
| $T^*$ | = | total temperature, K |
| n | = | rotor speed, %; |
| $\eta$ | = | efficiency |
| $y+$ | = | non-dimensional wall distance |
| $\alpha$ | = | flow angle, degree; |
| $\gamma$ | = | stagger angle, degree; |
| GTU | = | gas turbine unit; |
| IGV | = | intel guide vane; |
| LPC | = | low pressure compressor; |
| IPC | = | intermediate pressure compressor; |
| HPC | = | high pressure compressor; |
| RW | = | rotor wheel; |
| GV | = | guide vane; |

*Note.* The flow angles in this research are measured from the aerofoil cascade front.

## 2. Motivation

The Russian Public Joint Stock Company Gazprom is one of the largest energy companies in the world. Its main activities are geological exploration, production, transportation, storage and sale of gas, gas condensate and oil, as well as the production and sale of electricity and heat. PJSC Gazprom provides a continuous cycle of gas supply from the field to the consumer [1, 4].

The important feature of the gas industry of the Russian Federation is that its main gas fields are located to the east of the Urals, and gas consumers are in Europe and China. Such a geographical location determines the presence of a large and extensive gas transmission system, through which natural gas is supplied from the field to the consumer. For example, the length of the Druzhba gas pipeline (across the territory of the former USSR) is approximately 3,900 km, and of the Soyuz gas pipeline is 2,750 km [3] (Figure 1). In total, PJSC Gazprom owns 161.7 thousand km of trunk pipelines included in the unified gas supply system of Russia [4].


**Figure 1.** Diagram of the unified gas supply system of the Russian Federation [2].

The key elements of gas transportation system are gas pumping stations, which increase the pressure of natural gas in the gas pipeline and give an impulse necessary for its movement. Compressor stations are located evenly along the entire pipeline every 100...150 km. In 2013, PJSC Gazprom had 279 linear compressor stations, 6 gas processing complexes and 21 underground gas storage facilities, also using compressor stations. 87.2% of compressor stations have a gas turbine drive (about 3400 gas turbine engines (GTE) in total) [4].

Among the ground based GTUs of PJSC Gazprom, only 4% (for 2013) have a capacity of over 25 MW. This segment is constantly growing, drawing the attention of engine-building enterprises both from Russia and abroad. One of such enterprises is PJSC "Kuznetsov" [5]. In this segment, the company is promoting the NK-36ST engine with a capacity of 25 MW (Figure 2). It is made according to the scheme with a free turbine and has a three-spool core engine, developed based on an aviation bypass engine. Based on the same core engine, a gas turbine drive of the NK-37ST power station of similar capacity is produced, which differs from the NK-36ST in free turbine module.

In 2013, there were 5 such engines in PJSC Gazprom [4]. Another 4 related NK-37ST engines were used in power plants in Russia and Belarus. The company is taking active steps to improve the technical and operational qualities of the engines of the specified family in order to increase their fleet and their market share.

To increase the appeal of NK-36ST among customers, PJSC "Kuznetsov" together with the Samara National Research University [8] with the support of the Government of the Russian Federation (By the Order of the Government of the Russian Federation No. 218 dated 04/09/2010) have developed an modernized variant of NK-36ST, which provides an increase in the overall efficiency of the engine by at least 3% while maintaining the power of the basic variant and to the maximum use the structural elements of the base engine.

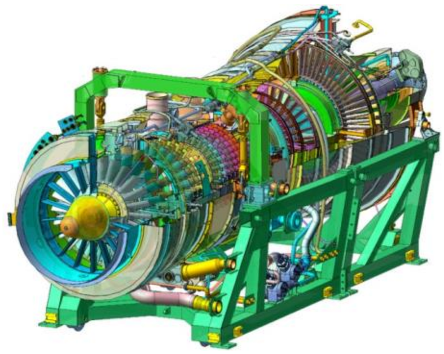

**Figure 2.** NK-36ST engine [7].

The authors of the paper were actively involved in this work they analysed the workflow of turbomachinery and optimized the shape of their blades. As a result, the variants were found that provide a low-pressure compressor efficiency increase by 1.3%, a low-pressure turbine (LPT) by 1%, a free turbine by 0.3% [9], a high-pressure compressor (HPC) by 0.5% [11].

In the course of work on the project for upgrading the LPC of the NK-36ST engine, the authors encountered the following phenomenon. Using the methods of computational gas dynamics in conjunction with mathematical optimization, a variant was found of changing the LPC, which improves its efficiency at the nominal mode of operation by only 0.3%. However, as shown by the analysis of the engine workflow, the upgrade changed the joint operation of the engine components and shifted the position of the line of joint operation to a favourable area. As a result, the efficiency r of the LPC at the mode of interest when operating as part of an engine increased by 1.1% (abs.) [10]. On the basis of the described results and the experience of other optimizations carried out by the authors, it was concluded that increasing the efficiency of a component when considered in isolation from the product to which it belongs may not lead to an increase in engine parameters as a whole, but, on the contrary, to their deterioration because of the violations of joint work of the components and the negative impact of the modernization on the neighbouring components. As a result, it was decided to initiate a simultaneous optimization of the 15-stage 3-spool compressor of the NK-36ST engine according to the criteria of engine efficiency, in order to find not only the most efficient configuration of the turbomachinery, but the best one for use on a specific engine modification.

## 3. Test object

The design scheme of the axial compressor under consideration is shown in Figure 3. It consists of three independent spools, each of which is rotated by a separate turbine with its own rotational speed. The first one from the inlet is a three-stage LPC with an inlet guide vane (IGV). Then, there is a five-stage intermediate pressure compressor (IPC) with an IGV and an air bypass valve. Its peculiarity is that the rotor blades of its last (5th) stage have an annular band in the flow part. HPC consists of seven stages with IGV. Annual frames with power fins are located between LPC and IPC, as well as between IPC and HPC. In total, there are 33 blade row and 2 annular frames in the flow section of the compressor.

The total pressure ratio in all stages at the nominal mode of operation (n = 100%) is - $\pi_c^*$=22. The air flow rate at the compressor inlet is G = 99.2 kg/s. Of these, 2% is extracted after the first stage to cool the engine body and purge its internal cavities.

## 4. Description of the computational model of the workflow in the three-spool compressor

The computational model of the compressor workflow was created in the NUMECA software [12] using computational models of compressor spools created by the authors earlier [9, 10, 11]. The choice of NUMECA is due to the presence of special modules for the qualitative modelling of the working processes of turbomachinery, as well as the rich successful experience of the authors using this product in turbomachinery optimization [9, 10, 16, 17].

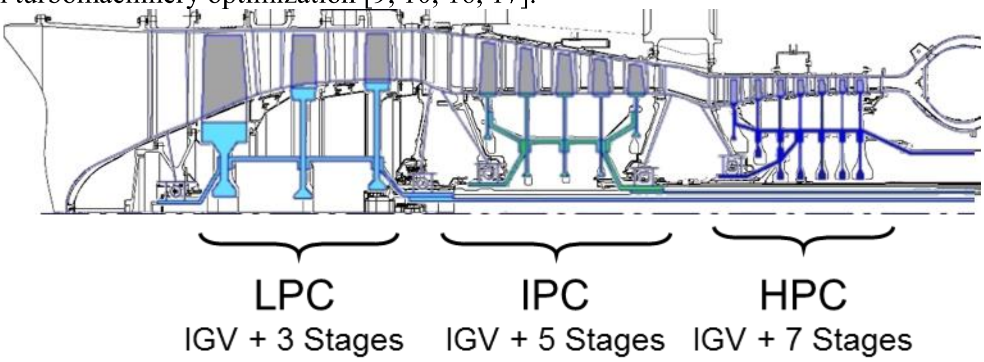


**Figure 3.** Design scheme of the three-shaft fifteen-stages compressor of NK-36ST.

The geometric model of the computational domain of the three-shaft compressor was built based on the design documentation of the compressors and engine annular frames of the NK-36ST engine provided by PJSC Kuznetsov. It contained the domains of the inlet and outlet areas, sector models of the LPC, IPC, HPC and flow parts of the annular frames between them (Figure 4).

The shape of blade aerofoils was transferred to NUMECA as text files in the *.geomTurbo* format, which were previously created in the Profiler program. This program was developed at Samara National Research University [8]. It allows you to convert a table of coordinates, which in the design drawing describes the shape of the blade into the text files of the initial data to build computational models of turbomachinery in the NUMECA and TurboGrid programs [13, 14].

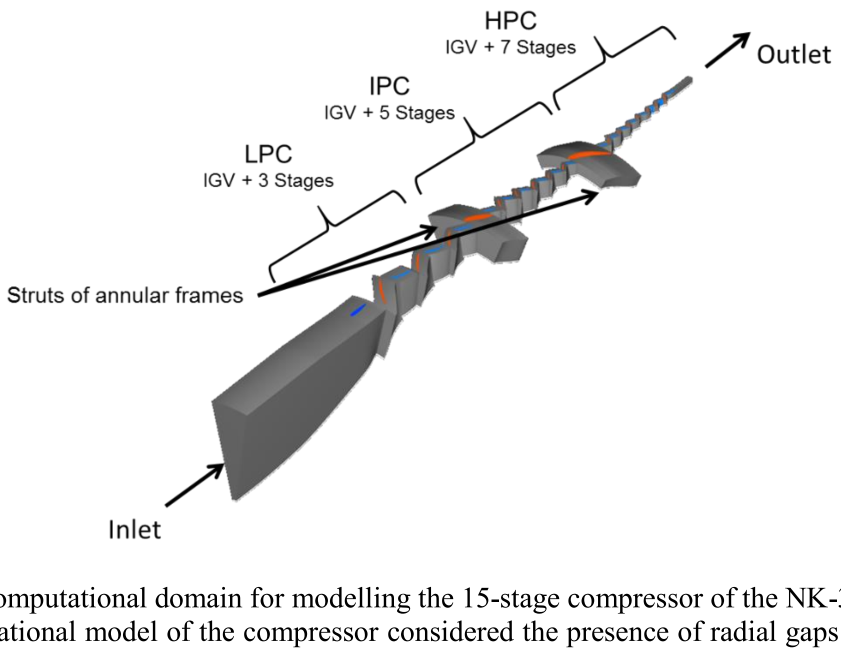


**Figure 4.** Computational domain for modelling the 15-stage compressor of the NK-36ST engine.

The computational model of the compressor considered the presence of radial gaps over the blades and the extraction of the working fluid behind the rotor of the first stage of the LPC for cooling the

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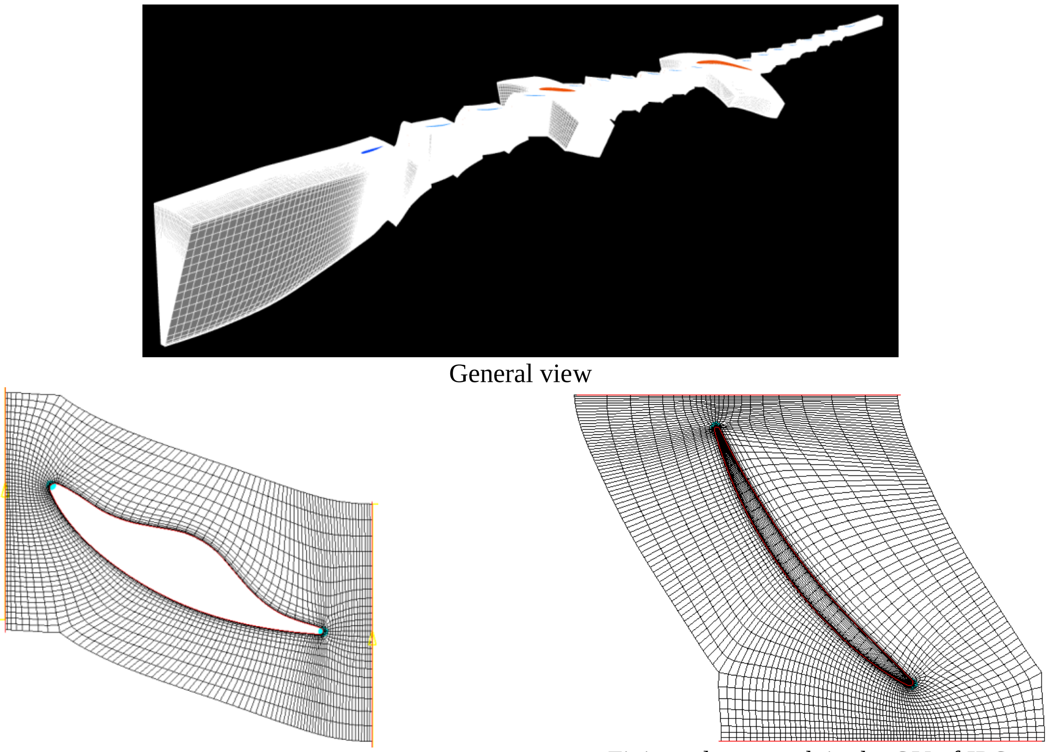
outer casing of the engine. The following assumptions were used when creating a numerical model of a workflow in the compressor:

- all models of blade rows and annular frames contained only one blade passage with periodic boundary conditions on the lateral surfaces;
- the calculation was carried out in a steady-state statement;
- an ideal gas with the properties of dry air was used as the working fluid; its viscosity and isobaric heat capacity varied depending on the temperature of the flow;
- k-ε (Low Re Yang-Shih) model was used to simulate turbulence. To improve the quality of the description of processes in the boundary layers, the Extended Wall Function option was used when describing turbulence;
- as the boundary conditions at the inlet to the LPC, the value of the total pressure p* = 101.325 kPa and the total temperature T* = 288.15 K was set, the flow direction at the inlet to the computational domain was set axially;
- in the considered computational domain, the areas of space around the rotor blades and guide vanes were distinguished. The area around GV was calculated in a fixed coordinate system. The region around the RW was calculated in a rotating coordinate system, the rotation speed of which coincides with the rotation frequency of the rotor;
- The *Full Non Matching Mixing Plane* interface was used to transfer data between the stator and RW areas. It averages the flow parameters in the circumferential direction in the region located upstream and transmits as a boundary condition to the region located downstream.

The created model was meshed with finite volumes of block-structured mesh using the internal tools of the NUMECA. The mesh model contained 11 million finite volumes. The average number of elements in each row is 350 thousand for the RW and 270 thousand for the GV (Figure 5). The minimum value of skewness is *21.6°*. The maximum value of the parameter y + for this grid was *1*, *Aspect Ratio - 2000*.



General view

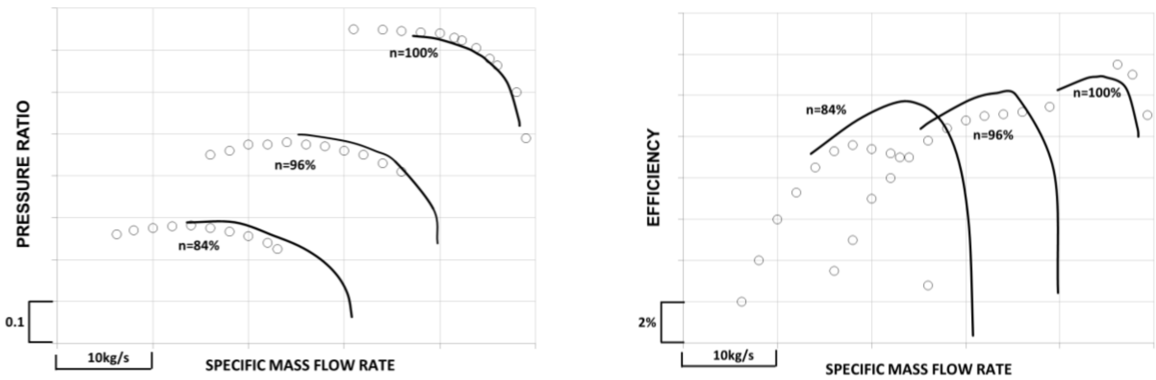
Finite volume mesh in the RW of the HPC first stage

Finite volume mesh in the GV of IPC

**Figure 5.** Mesh model of the compressor of NK-36ST.

The numerical models of each spool were separately validated by comparison with experimental data provided by Kuznetsov PJSC. Comparison for LPC is shown in Figure 6, for IPC - in Figure 7, for HPC - in Figure 8. Analysing the comparison results, it can be concluded that, despite some quantitative differences, the calculated and experimental dependencies are qualitatively little different. The numerical model does not allow to accurately determine the quantitative value of the maximum efficiency of the compressor. The reason can be in the insufficient information about compressor geometry or test conditions. The model does allow to find with great accuracy such a combination of its parameters at which this maximum will take place. Thus, it is suitable for finding the shape of an efficient compressor blades using optimization methods.

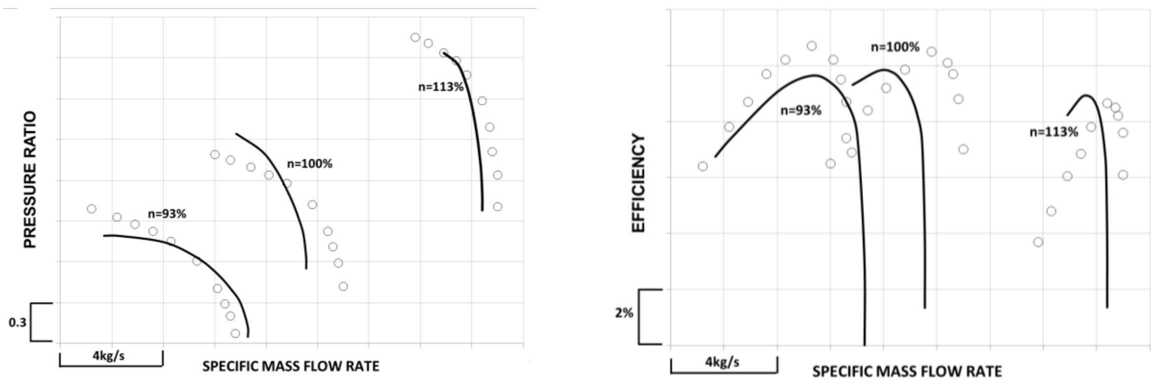
The contours of parameters in the flow section of the compressor at the nominal operating mode (n = 100%) obtained using the created computational model are shown in Figures 9 and 10.




Pressure characteristics Efficiency characteristics

° - test results of LPC at PJSC Kuznetsov; ▬ - results of CFD calculation

**Figure 6.** Comparison of the calculated and experimental characteristics of NK-36ST LPC.




Pressure characteristics Efficiency characteristics

° - test results of IPC at PJSC Kuznetsov; ▬ - Efficiency characteristics

**Figure 7.** Comparison of the calculated and experimental characteristics of NK-36ST IPC.

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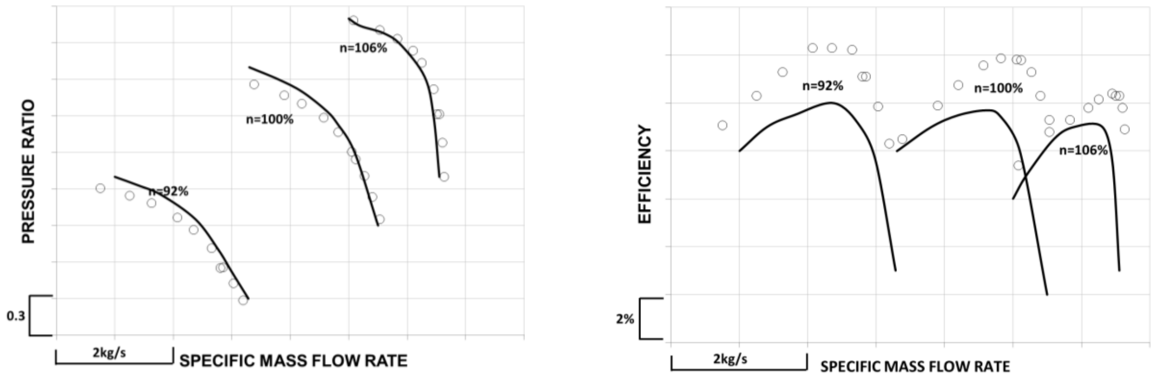


Pressure characteristics Efficiency characteristics

° - test results of HPC at PJSC Kuznetsov; ▬ - Efficiency characteristics

**Figure 8.** Comparison of the calculated and experimental characteristics of NK-36ST HPC.

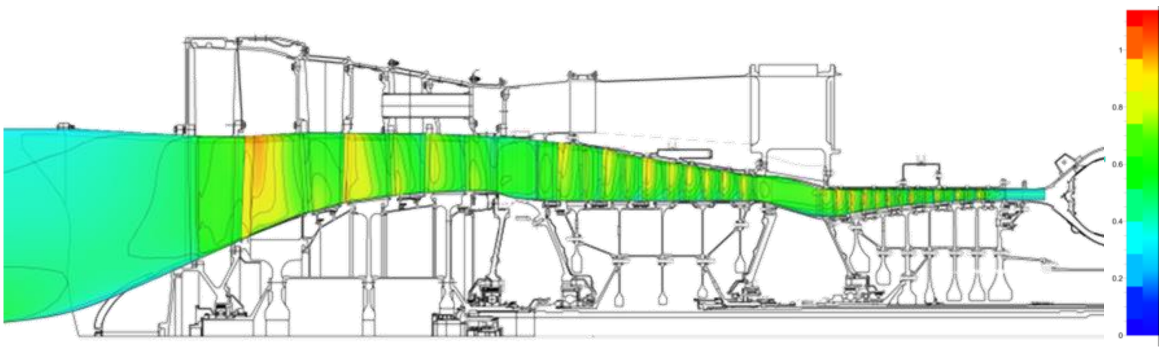

**Figure 9.** The contours of the averaged value of the Mach number in relative motion in the flow path of the NK-36ST compressor.

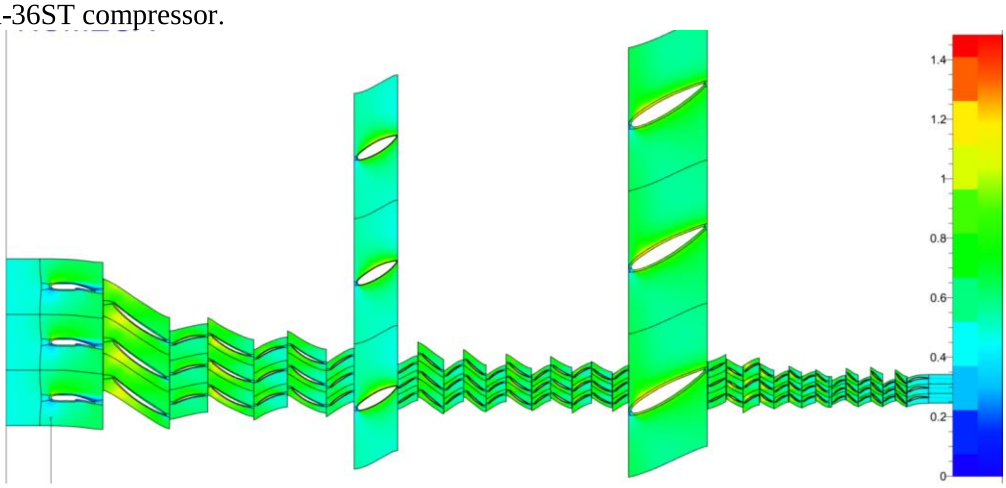


**Figure 10.** The contours of relative Mach number in the NK-36ST compressor in the cross section of 50% of relative height of the flow part.

## 5. Formulation of the optimization problem

To find the optimal shape of the blades of a three-spool compressor, the following algorithm was built, and an information circuit was implemented connecting the necessary software products. The algorithm is based on the use of the IOSO optimization program [15] (Figure 11). The core of the IOSO program is optimization method based on the construction of the response surface, which is refined and evolves with each iteration with the computational model. Each IOSO iteration contains two steps. At the first stage, based on previous iterations with the model with a different combination of variable parameters, the response function is constructed in the form of a multilevel graph. The next step is a search for the extremum of this function. This approach allows you to constantly adjust the response surface in the optimization process. As a result, an unusually small number of initial points are required to start the optimization process [15]. An important factor that influenced the choice of IOSO as an optimizer in solving the problem was the presence of many positive examples of its use in the area of improving the workflow of turbomachinery [9,10,16,17].

The IOSO forms a block of initial data, based on which the *Profiler* program creates a new blade geometry and transmits it as a text file to *NUMECA*. There, based on the information received, a calculation model is created and the flow in it is simulated, as a result of which the efficiency values and other compressor parameters are determined.

Based on the influence coefficients of efficiency of components on the engine efficiency (LPC - 0.08%, IPC - 0.142%, HPC - 0.167%) previously found using the thermodynamic model of the engine, the expected total engine efficiency is calculated by the formula [18]:

$$\Delta\eta_{\text{e}} = 0.08 \cdot \Delta\eta_{LPC} + 0.142 \cdot \Delta\eta_{IPC} + 0.167 \cdot \Delta\eta_{HPC}. \quad (1)$$

The found value found is transmitted to the IOSO program. There, based on the calculation data and data of previous iterations with the numerical model, a new combination of initial data is formed, and the cycle is repeated until the desired extremum is reached or the Pareto front is found (in the case of a multi-criteria setting) (Figure 11).

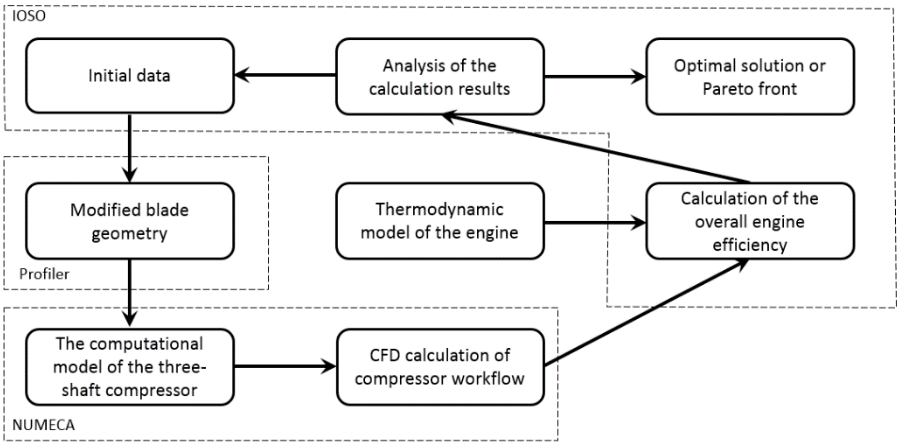


**Figure 11.** Flow chart of the optimization process.

The software packages used to solve the problem were implemented as completed commercial products. No changes were made to the algorithms of their work by the authors.

When solving the problem, the goal was to achieve maximum efficiency of the engine at the nominal mode of operation (n = 100%).

When searching for the optimal configuration of the compressor, the following parameters were varied (Figure 12):

- stagger angles of three characteristic sections (hub, middle and shroud) of all LPC blades;
- stagger angles of all the blades of the entire IPC and HPC.

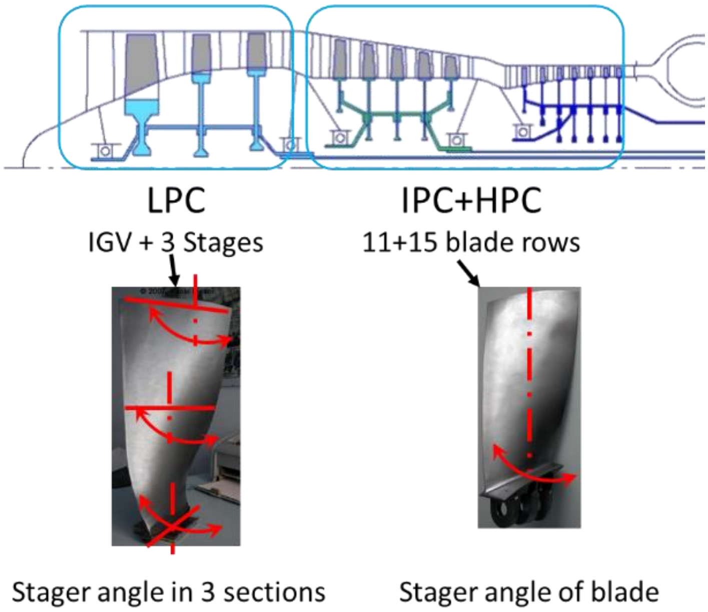


**Figure 12.** Variable parameters in the optimization problem.

Greater attention to the LPC blades is caused by their large relative height. All stagger angles were varied in range from ±5°. The total number of variable parameters is 46.

When solving the optimization problem, no restrictions were used except for the requirement that the total pressure ratio of the compressor was not less than the initial one.

## 6. Optimization results

The problem was solved using a cluster of 10 desktop computers. Calculation time was 150 hours. IOSO took 725 cycles (iterations with the numerical model) to find a solution.

As a result, a variant was found that provides an increase in the overall engine efficiency by 0.43% due to a limited change (only due to the stagger angles) of the blades of all three compressors of the three-shaft engine. At the same time, the efficiency of the LPC increased by 0.265%, the efficiency of the IPC increased by 1.618%, and the efficiency of the HPC increased by 1.096%. The magnitudes of changes in stagger angles $\gamma$ of the cross sections are given in Tables 1 and 2. In the tables, a positive change means a decrease in the stagger angle, and a negative one means an increase relative to the initial value.

**Table 1.** Changing the stagger angles of the profiles of the LP compressor blades, which provide an increase in the efficiency of the NK-36ST engine by 0.43%.

| **Spool** | **LPC** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Stage** | 1 | | | 2 | | 3 | |
| **Blade** | IGV | RW | GV | RW | GV | RW | GV |
| **Hub, deg** | -0,857 | 0.042 | -0.003 | -0.169 | -0.399 | -0.026 | -0.421 |
| **Middle, deg** | 0.654 | -0.069 | -0.471 | 0.532 | 0.208 | -0.127 | 0.001 |
| **Shroud, deg** | 0.083 | 0.167 | -0.432 | 0.002 | -0.523 | -0.010 | -0.087 |

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**Table 2.** Changing the stagger angles of the profiles of the IP and HP compressor blades, which provide an increase in the efficiency of the NK-36ST engine by 0.43%.

| **Spool** | | | | | | | **IPC** | | | | | | **HPC** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Stage** | | 1 | | 2 | | 3 | | 4 | | 5 | | | 1 | |
| **Blade** | IGV | RW | GV | RW | GV | RW | GV | RW | GV | RW | GV | IGV | RW | GV |
| **Δγ, deg** | 0.11 | -1.39 | -0.86 | -0.14 | -2.7 | -0.4 | -2.54 | 0.24 | -2.51 | -1.36 | 0.71 | -2.93 | -1.23 | -1.99 |
| | | | | | | | | **HPC** | | | | | | |
| **Spool** | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | | |
| **Stage** | RW | GV | RW | GV | RW | GV | RW | GV | RW | GV | RW | GV | | |
| **Blade** | -2.6 | -1.99 | -0.94 | -2.07 | 1.32 | -1.18 | -1.6 | -3.34 | -0.35 | -1.88 | -1.85 | 0 | | |

As the comparison of the contours of the main parameters (first of all Mach numbers) (Figure 13) of the initial compressor variant and the optimized is showing, the efficiency increase is mainly due to the decrease in the velocity level at RW inlet (a slight redistribution of work) and better matching of the rows in the incidence angle including the coordination of adjacent spools).

## Conclusion

As a result of this work, an algorithm for optimizing a 15-stage three-shaft compressor of a ground-based gas turbine unit by the engine efficiency criteria was developed and successfully implemented using the example of the NK-36ST engine. The created model provides optimization of turbomachines according to the criteria of a higher level than compressor efficiency, which reduces the number of optimization criteria and simplifies the analysis. On the other hand, in this way not only the optimal configuration of the compressor is searched for, but the one that is most effective for the product in specific conditions with current limitations. The result is not just an optimal compressor, but an engine (finished product) with the best parameters. Namely, the characteristics of the latter (and not the parameters of its components) are primarily of interest to customers.

An important advantage of the created optimization algorithm is the fact that it considers the operation of the compressor stages not isolated, but takes into account their joint influence and the joint operation of the components, which allows us to consider the factors that were not previously taken into account in optimization and achieve more significant results.

The price for the advantages of the optimization algorithm described above is that it is based on a complete numerical model of the workflow of a multi-stage compressor, which requires significant computer resources and calculation time. Also, a big problem is that the description of the geometry of such a model requires many independent variables, which is also a factor that increases the time to obtain the optimal solution.

Using the developed algorithm, authors can only increase the overall efficiency of GTU NK-36ST by 0.43% by changing the stagger angles of the profile of the compressor blades.

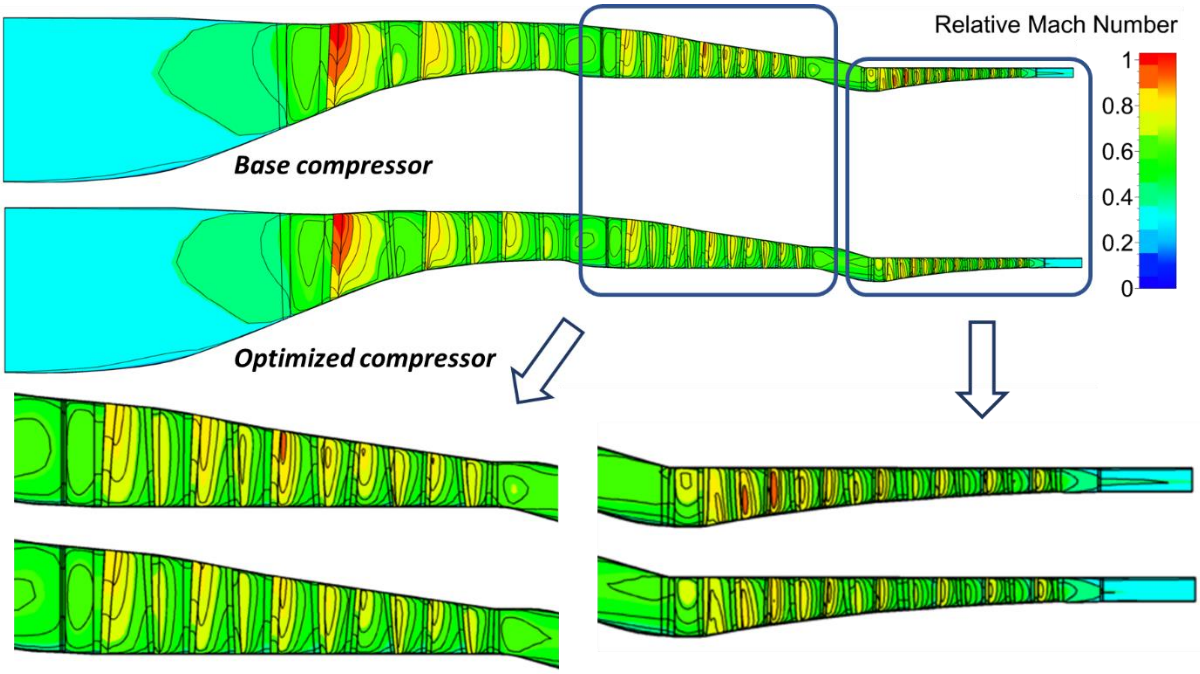


**Figure 13.** Comparison of the Mach number contours in the relative motion of the original and optimized compressor variants.

The authors plan to continue improving the optimization algorithm by including a detailed thermodynamic model, strength, mass, cost, and other models, as well as introducing more complex parametric models to change the profile shape. Planned upgrades will further increase the number of independent variables and the authors will have to find a way to reduce them and the time to obtain the optimum.

## Acknowledgments

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