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Evaluation of IPSEpro extended by MATLAB applied to Steam Turbine Cycle analysis

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Abstract

This paper investigates thermodynamic optimization of a supercritical coal fired power plant. The main goal of the study was to assess IPSEpro software combined with MATLAB environment, aimed at multiobjective optimization of the thermal cycle in a relatively short timeframe. To verify the methodology, calculations were carried out using the IPSEpro (standalone) approach and IPSEpro-MATLAB with fmincon function. The decision functions were: thermal efficiency, gross power efficiency and total power load. It was shown that the results obtained with the IPSEpro standalone approach are similar to those obtained with the IPSEpro-MATLAB package. This means that the IPSEpro-MATLAB approach can be successfully used in future calculations. The evident benefit of the newly developed methodology is a significant reduction in computational time compared to the referenced method. It was shown that the computational time depends on both the methodology and the chosen objective function. The results show that the detected optimal point also depends on the shape of the objective function distribution. Optimization of the thermodynamic parameters of the sample ultra-supercritical power plant enables an increase in output power from 900 MW to 909.44 MW.

Keywords: Steam Cycle, Thermal cycle, IPSEpro, MATLAB, Optimization

1. Introduction

Increasingly stringent environmental constraints are driving the development of new low-emission power generation technologies. In recent years this has led to the introduction of technologies such as desulfurization, particulate removal, and control of mercury and NOx emissions. Currently, work is underway on new zero emission power plants. Super critical steam plants are rapidly becoming the preferred solution for reductions in CO_2 emissions. The current status of technology achieves efficiencies of 45% (LHV basis) with live steam parameters limited at about 300 bar and 600°C. This limit is mainly imposed by materials used in the high-pressure turbine. However, future development aims at 700°C and higher pressures [1]. The transition to ultra-supercritical parameters is a clear qualitative change as it could deliver a rise in the net efficiency of electricity generation of the order of 7..8 percentage points [2]. To achieve this, new high-temperature steels are required and solutions found to overcome the problem of very high steam bleed temperatures and the exergy loss in HP and IP regenerative heaters [3]. The next great challenge is

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Table 1: Basic parameters of ultra-supercritical coal-fired power plant [7]

Parameters	Value
Thermal efficiency, %	53.79
Mass flux, kg/s	611.92
Gross power production efficiency, %	52.03
Live steam temperatures, °C	700
Reheated steam temperatures, °C	720
Live steam pressures, bar	350
Power, MW	900

the capture and storage of carbon dioxide (CCS) [4]. Installations performing such tasks have to be integrated with power plant infrastructure. This requires joined-up planning and design of the complete power plant system. For example, when considering post-combustion capture (PCC), additional space is need for an absorption [5] and stripping [6] installation.

The tools most often used in power plant modeling measure thermodynamic performance and analyze the economic costs of the plant. There is a broad range of heat and mass balance commercial software on the market. A concise comparative overview of selected programs is presented in the paper of Haggstahl and Dahlquist [8] and Kowalczyk at al. [9]. One of the required features of such programs is the possibility of multiobjective optimization of the whole thermal cycle. In this paper, the IPSEpro software package from SimTech [10] is used. Since the optimization tools available in IPSEpro software are very limited due to the number of test parameters and the efficiency of calculations, it was decided to extend it with MATLAB environment. Assessment and testing of two combined software environments are the main aim of the paper. As the test case an ultra-supercritical coal-fired power plant based on new technology AD700 [8] was selected. Table 1 contains the values of the most important parameters of that power plant.

2. Methodology

The IPSEpro package for optimization analysis uses a Toolbox included in the PSExcel module [2]. However, this tool has some limitations due to the number of possible test parameters and the efficiency of calculations. In fact, the optimization is based on calculations of the entire space of solutions (with specified accuracy), and then the selection of the optimum value (combinatorial approach). Where the decision variables matrix grows in dimension this method becomes too costly and should be replaced with a more rational optimization procedure. Hence the decision to use MATLAB environment, which provides algorithms for standard and large-scale optimization and is more flexible in terms of implementation of more complex optimization procedures [11]. The algorithms included in the Optimization Toolbox solve both constrained and unconstrained continuous and discrete problems. The basic functions enabling detection the optimal value are:

- fminbnd—finding minimum of single-variable function on fixed interval,
- fmincon—finding minimum of constrained multivariable function,
- fminunc—finding minimum of unconstrained multivariable function,
- fminsearch—finding minimum of unconstrained multivariable function using derivative-free method

Power plant optimization is a multivariable problem with constraints. Hence the fmincon functions seem to be the best suitable option for such a case. Since some of the non-linear terms are not required, the function takes the simplified form:

$$x = f\min con\,(fun, x0, lb, ub, options) \quad (1)$$

$$options = optimset\,(DMinC, DMaxC, TX) \quad (2)$$

where x is a solution found by the optimization function, fun is a function to be optimized, $x0$ is a starting point, lb/ub are respectively the lower and upper boundary of the matrix, options defines parameters used by the optimization functions. Options parameters are defined as: *optimset* is an internal function to set or change values in the structure options. DiffMinChange (DMinC) and DiffMaxChange (DMaxC) are respectively the minimum

Figure 1: Schematic connection between IPSEpro, PSExcel and MATLAB

and maximum change of variables for finite difference gradients. TolX (TX) is the termination tolerance of x [11].

Both software environments had to be combined before starting the calculations. The connection between IPSEpro and MATLAB was made using PSExcel and a special macro file, which enables fluent data exchange in both directions. The communication procedure between IPSEpro and MATLAB is as follows:

- determination of the point in the solution space in MATLAB,
- sending the point coordinates to IPSEpro via PSExcel and execution of the macro file by MATLAB,
- simulation procedure in IPSEpro,
- sending the results to PSExcel,
- sending the results to MATLAB.

This program configuration ensures low time consumption, freedom as regards the number of objective functions and full control of IPSEpro software [10]. A schematic representation of the connection between IPSEpro, PSExcel and MATLAB is shown in Fig. 1. The IPSEpro-Matlab approach can be described as follows: The user defines the boundary values of optimized parameters (lb, ub) and the starting point ($x0$). Optionally, it is possible to specify the $DMinC$, $DMaxC$ and TX parameters; otherwise they take a default value. When initial conditions are preset the standard Matlab fmincon function starts the loop calculations. For each loop the fmincon function solves equation (1) with respect to equation (2). Additionally, depending on the type of optimized function (thermal efficiency, gross power production efficiency and/or total power generation), equations 3, 4 or 5 are also computed in each loop. The algorithm stops whenever the TX parameter is reached.

3. Results

The basic structure of ultra-supercritical coal-fired power plant AD700 is shown in Fig. 2 (schematic view) and Fig. 3 (the results from IPSEpro), while Table 1 contains the values of the most important parameters of the thermal cycle.

The structure of the ultra-supercritical steam cycle consists of a boiler, three main turbine sections (HP, IP, LP), an additional Tuning Turbine (T-T), a condenser, five low-pressure regenerative preheaters, deaerator, three high-pressure regenerative preheaters and an external motor to supply the main pump. The live steam enters the HP turbine, where it is expanded to 79.74 bars. Part of the steam is extracted to two high pressure heat exchangers and T-T, which reduce the live steam mass flux to 392.6 kg/s. Next, the steam is reheated and enters the IP turbine, where it is expanded to 5 bar. The IP turbine has no extractions, so all the steam is directed to LP. The LP turbine has three extractions and the flow leaving this section is 5 kPa. The Tuning Turbine supplies two low pressure regenerative preheaters, deaerator and the first high pressure regenerative preheater.

The analysis was performed based on three objective parameters: thermal efficiency (η_{th}), gross power production efficiency (η_{gpp}) and total power generation (P_T) which is sum of power produced by a main generator (P_g) and power produced by the Tuning Turbine (P_{T-T}). Those three functions can by described as follows:

$$\eta_{th} = \frac{Q_{in}\eta_{boiler} - Q_{out}}{Q_{in}\eta_{boiler}} \tag{3}$$

$$\eta_{gpp} = \frac{P_T}{Q_{in}} \tag{4}$$

$$P_T = P_G + P_{T-T} \tag{5}$$

where: Q_{in}—heat input to the steam cycle; Q_{out}—heat output from the steam cycle; η_{boiler}—boiler efficiency; P_G—power production by main generator and P_{T-T}—power production by T-T turbine.

Since multiobjective optimization of the whole thermal cycle is a complex problem, in the current case it was decided to limit the analysis to only part of the thermal cycle, i.e., the high-pressure turbine and one chosen high-pressure feed water heater, marked

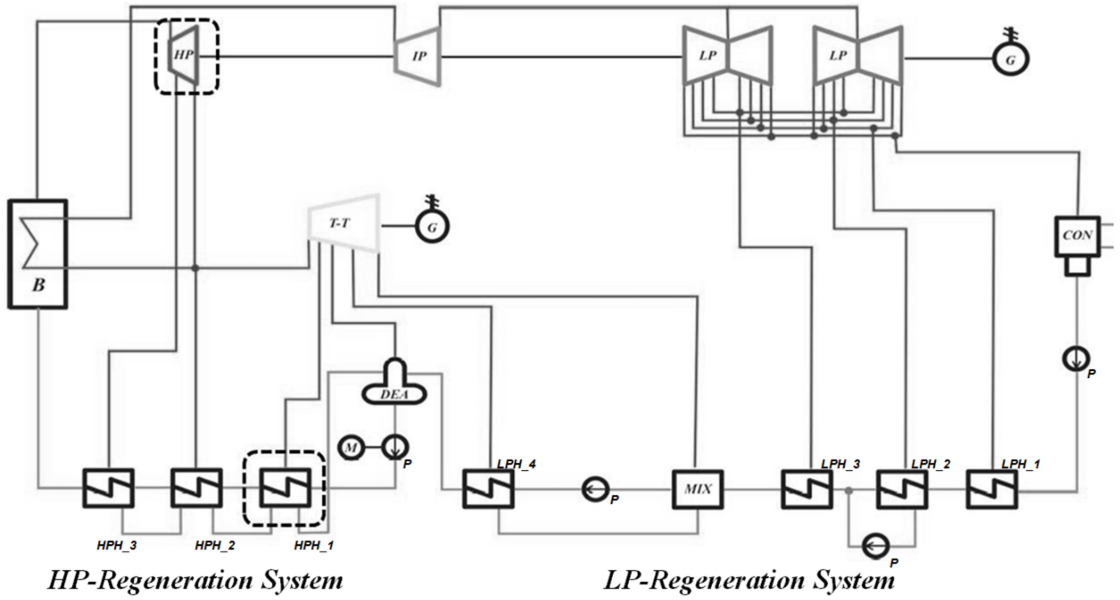

Figure 2: Structure of ultra-supercritical coal-fired power plant. B—Boiler, HP—High Pressure turbine; IP—Intermediate Pressure turbine; LP—Low Pressure turbine; T-T—Tuning Turbine; G—Generator; CON—Compensator; DEA—Deaerator; M—External Motor; P—Pump; HPH and LPH—Heaters

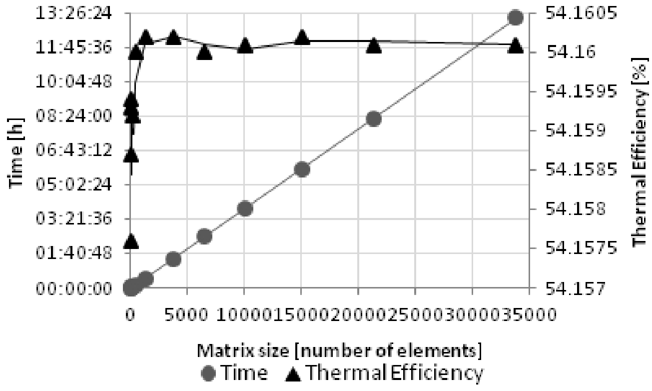

Figure 4: Matrix size and thermal efficiency as a function of time

by the dashed line in Fig. 2. The first task was to investigate the influence of matrix size on the computational time consumptions. The calculations for the high pressure steam turbine were performed with IPSEpro (standalone).

Two decision variables—bleed pressure (p1) and exit pressure (p2)—were chosen and the calculations were performed for bleed pressure 85<p1<220 bar and for exit pressure 50<p2<100 bar. The size of the matrix dimension was changed by altering the step size for both p1 and p2 parameters. The pressure range was constant for all cases. Fig. 4 shows the time calculation and thermal efficiency (to simplify in these cases the Q_{out} account, only the heat waste in the condenser) as a function of matrix size. The results show, as expected, that average computational time is a linear function of matrix size. Moreover, the value of thermal efficiency reaches a stable level for a matrix size of 375 elements, which corresponds to 9 minutes of calculation time.

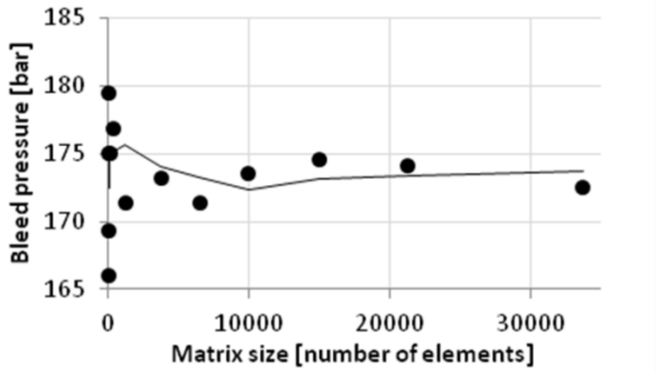

Figure 5: HP bleed pressure vs. matrix size

For thermal cycle optimization efficiency is not the only key parameter. Here knowledge is also required of the optimal value of decision variables (here p1 and p2). Fig. 5 and Fig. 6 show the evolution of bleed (p1) and exit (p2) pressure respectively as a function

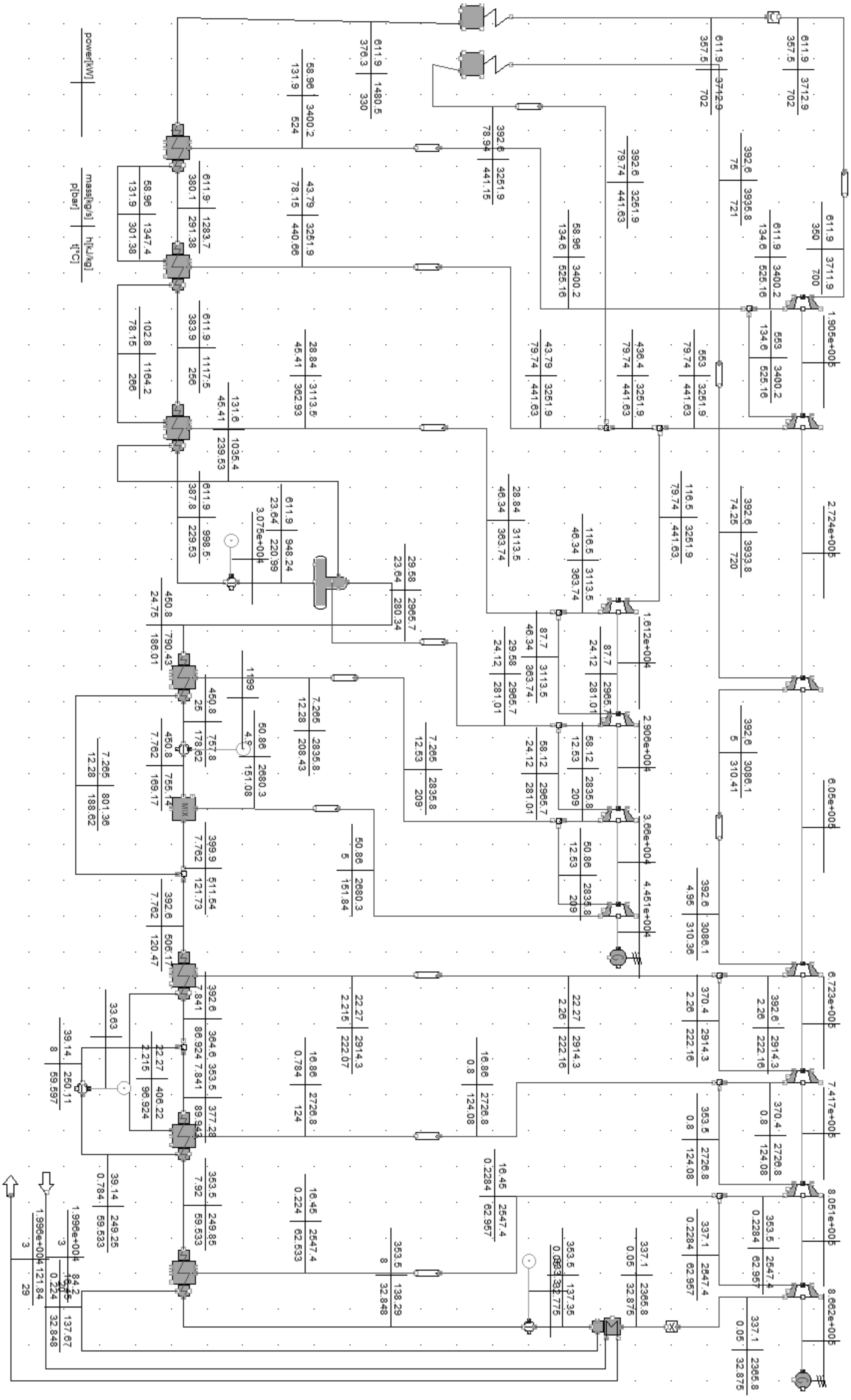

Figure 3: Sample thermodynamic cycle data of ultra-supercritical 900 MW power plant

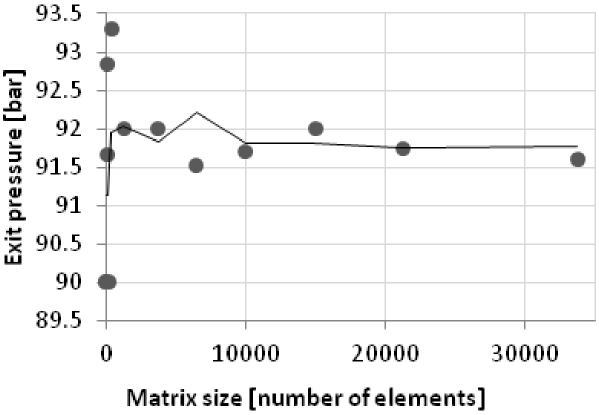

Figure 6: HP exit pressure vs. matrix size

of matrix size. In both cases, for small matrix dimensions, large pressure variations are observed. Pressure values stabilize only for matrix size consisting of 10000 elements, which corresponds to 4 hours' calculation time. This means that a relatively long computational time is required to optimize—and obtain a stable solution—in a simple case such as a high pressure steam turbine with only two decision variables.

In the next step the calculations were performed with IPSEpro (standalone) and with IPSEpro-MATLAB and fmincon function for a high-pressure turbine and for one chosen high-pressure feed water heater. The objective functions were thermal efficiency (η_{th}), maximum gross power production efficiency (η_{gpp}) and total power generation (P_T). The calculations were done for HP bleed pressure in the range 85<p1<220 bar and HP exit pressure in the range 50<p2<100 bar. In the case of the preheater two decision variables were chosen: dt_in (temperature differences at inlet to preheater) and dt_out (temperature differences at outlet from preheater). The range of parameters are 1<dt_in<40°C and 0.1<dt_out<5°C. For calculations performed with standalone IPSEpro (PSExcel) the matrix size was 10000 elements for HP pressures and 27000 elements for HP preheater. Using IPSEpro-MATLAB calculations with fmincon function the minimum change of the variables was 1.0e^{-3} and maximum change of the variables was 1.0. The termination tolerance of the optimization functions was 1.0e^{-10}. The starting points and the optimal points are given in Table 2.

In Fig. 7 the charts present the surface of thermal efficiency η_{th} (Fig. 7a), gross power production efficiency η_{gpp} (Fig. 7b) and total power P_T (Fig. 7c) obtained with IPSErpo (standalone). The white region on the graph shows the optimal values. For η_{th} the optimal value 53.82% was obtained for p1=157 bar and p2=81 bar, for η_{gpp} the optimal value 52.17% was obtained for p1=202 bar and p2=95 bar, while for total power generation the optimal value 909.44 MW was obtained for p1=112 bar and p2=100 bar. Table 2 shows that the optimal coordinates obtained for IPSErpo (state standalone) are slightly different than for IPSEpro-MATLAB calculations. These differences result from the flat distributions of objective functions close to the optimal point. The other reason for this discrepancy is the assumed step size. MATLAB allows the use of a very small step size for a wide range of optimization parameters. Such a small step size for IPSEpro (standalone) is also possible, but it is very time consuming.

The most important differences are seen in respect of computational time. For the IPSEpro MATLAB package the time is 16 times shorter for the first and almost 42 for the second case. For IPSErpo (standalone) the computational time is a linear function of the matrix dimension, while for IPSEpro-MATLAB the computational time is an exponential function of matrix size.

The last task was to analyze inlet temperature difference and temperature differences at the "hot" end of the first high pressure preheater (dashed line in Fig. 1). The optimizations were performed for thermal efficiency and htc_area. The htc_area parameter is a product of heat transfer coefficient "k" and heat transfer area "A". Assuming that "k" does not vary with temperature, the htc_area is a good estimation of the heat transfer area. Distributions of both parameters are presented in Fig. 8. It can be seen that thermal efficiency is growing for lower values of dt_in and dt_out (Fig. 8a). However, it causes an increase of the heat exchange area as a function of power (Fig. 8b). It must therefore be concluded that this approach produces an undesirable increase in heat exchanger cost, while delivering only a marginal gain in efficiency.

Table 2: Comparison of optimal result for IPSEpro and IPSEpro-MATLAB

			Optimal point						
	Parameters	Starting point	IPSEpro			IPSEpro-MATLAB fmincon			Unit
			for η_{th}	for η_{gpp}	for P_T	for η_{th}	for η_{gpp}	for P_T	
HP	p1	134.61	157	202	112	157.6	200.8	111.5	bar
Turbine	p2	79.74	81	95	100	81.9	94.7	100	bar
	Solution time		Around 4:00 hour			Around 5 minutes			
Preheater	dt_in	10	1			1			°C
	dt_out	2	0.1			0.1			°C
	Solution time		Around 10:30 hour			Around 15 minutes			

4. Conclusions

The aim of this paper was to develop an alternative optimization tool to the one available in the IPSEpro environment. It was assumed, that the tool should allow for multi-objective optimization of the whole thermal cycle within a relatively short timeframe. For this purpose it was decided to combine two environments, i.e., IPSEpro, which is very efficient as regards simulation of thermodynamic problems, and MATLAB, which provides algorithms for large-scale optimization and is flexible in terms of implementation of more complex optimization methods. The developed communication procedure allows for fluent data exchange between both programs and ensures low time consumption, freedom regarding the number of variables considered and full control of IPSEpro software.

To test and verify the new optimization package, selected elements of the ultra-supercritical power plant AD700 thermal cycle were analyzed. IPSEpro was used, as extended by MATLAB and the fmincon optimization function as well as a special macro file. Selected as objective functions were: thermal cycle efficiency (η_{th}), gross power production efficiency (η_{gpp}) and total power generation (P_T). It was shown that the results obtained with the IPSEpro standalone approach and with the IPSEpro-MATLAB package were similar to each other. The small differences result from flat objective functions distributions close to the optimal point. This means that the IPSEpro-MATLAB approach can be successfully used in future calculations. The most important advantage of the IPSEpro-MATLAB approach is the very short computation time, which depending on the task varies between 5 and 15 minutes. In contrast, when using IPSEpro (standalone) the computation time is of the order of hours.

Optimization of the thermodynamic parameters delivers an increase in thermal efficiency from 53.79% to 53.82%. For gross power production the efficiency gain was around 0.14% (from 52.03% to 52.17%). The optimization of total power generation allows one to increase overall power from 900 MW to 909.44 MW.

The results obtained for the heat exchanger show the same optimal point for both considered cases. However, this optimal point is unsatisfactory. From the economic point of view some additional constraint function is needed, but it cannot be introduced within a standard MATLAB fmincon function. Future work will seek to properly define the objective function and constraints, taking into account the economic criteria.

Acknowledgments

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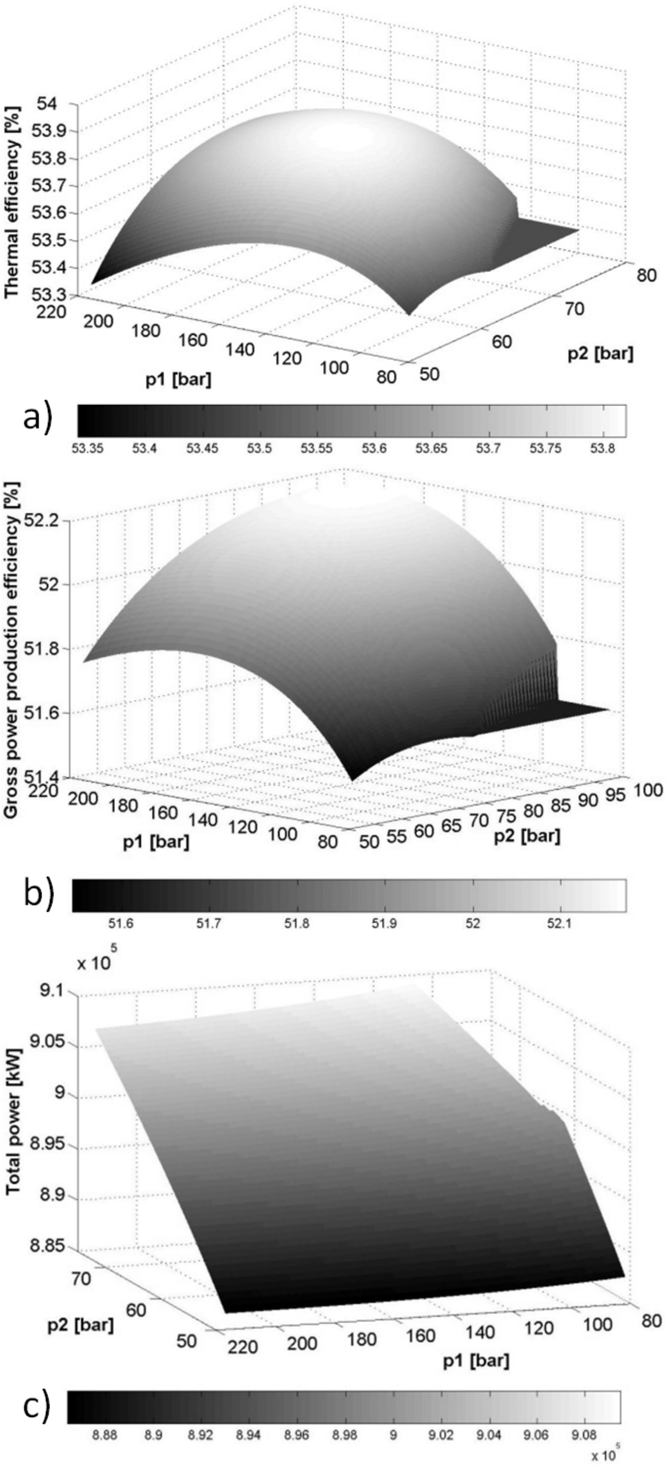

Figure 7: Distributions of thermal efficiency η_{th} (a), gross power production efficiency η_{gpp} (b) and total power production P_T (c)

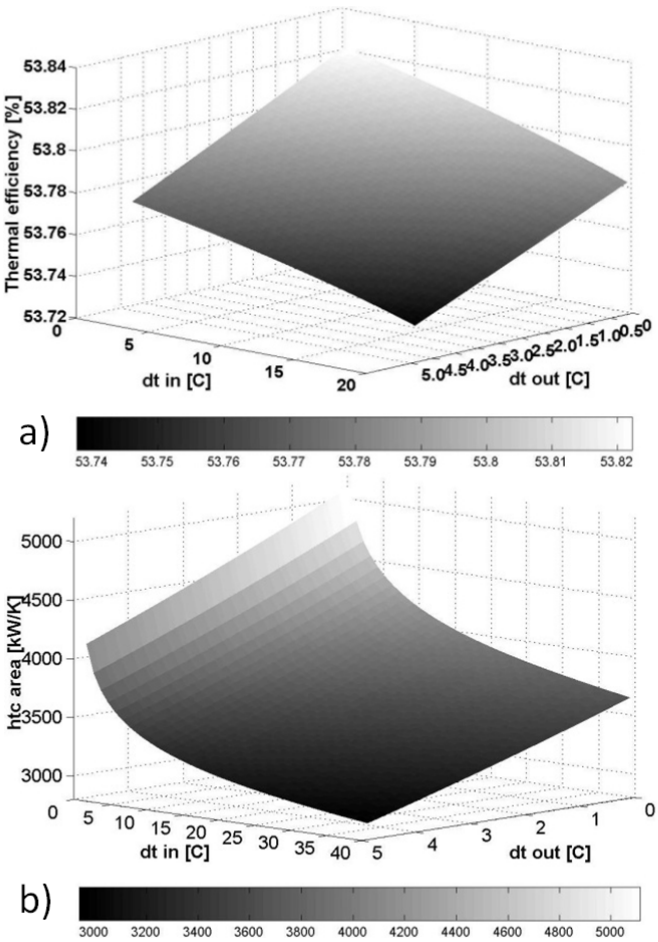

Figure 8: Distributions of thermal efficiency as a function of dt_in and dt_out (a) and heat exchanger geometry as a function of dt_in and dt_out (b)