# Simulation and optimisation of thermal power stations by use of Turabs


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**Abstract**

Elsam is focusing on the complex task of ensuring optimum operation of power stations producing both district heat and power by launching its Turabs optimisation project. The task is aimed at calculating a PQ diagram for Elsam's seven largest production units located on Funen and in Jutland, Denmark, thereby enabling pricing of the heat and power production at the individual power stations. The system is deeply rooted in a simulation programme by the name of Turabs developed by Elsam Engineering A/S over the last ten years. The system consists of two application programmes, run online, and one off-line module for "what-if" calculations. The system is implemented in a new internal priority network connecting the seven power station units to each other. Turabs performs online calculations of the seven power station units and returns data stamped with date and hour to a real-time database. Corresponding simulated PQ diagrams provide Elsam with a continuous picture of fuel amount and $C_v$-value within the operating areas of all seven power stations, which enable optimisation of the mutual operation of the power station units.



*Keywords*: Turabs, plant optimisation, numerical simulation, $C_v$-value, PQ diagram


**Nomenclature**

| | |
|---|---|
| $\varepsilon$ | Scalar - convergence criteria |
| $\overline{F}$ | Residual vector |
| $\overline{x}$ | Solution vector |
| $\overline{b}$ | Right side vector |
| $\overline{\overline{A}}$ | Symmetric matrix |
| $P_{kondens}$ | Power production at condensing mode with the same boiler load |
| $P_{actual}$ | Power production at actual load. |
| $Q_{district\,heating}$ | District heat production at actual load. |
| $C_v = \frac{P_{kondens} - P_{actual}}{Q_{district\,heating}}$ | A relation between loss in power production caused by district heat production and the actual district heat production. |


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**Abbreviations**

| | | | |
|---|---|---|---|
| SKVB3: | Skaerbaekvaerket, unit 3. | VHP: | Very High-pressure turbine. |
| NJVB3: | Nordjyllandsvaerket, unit 3. | HP1: | High Pressure turbine no. 1. |
| ESVB3: | Esbjergvaerket, unit 3. | HP2: | High Pressure turbine no. 2. |
| SSVB3: | Studstrupvaerket, unit 3. | LP1: | Low Pressure turbine no.1. |
| SSVB4: | Studstrupvaerket, unit 4. | LP2: | Low Pressure turbine no. 2. |
| ENVB3: | Enstedvaerket, unit 3. | TOL: | Turabs Online application. |
| FYVB7: | Fynsvaerket, unit 7. | TWI: | Turabs What If application. |
| HPPH: | High pressure pre-heater. | LPPH: | Low pressure pre-heater. |
| TPQ: | Turabs PQ application. | | |

PQ-diagram: A diagram showing a plant operation area with respect to district heat and power production.
SQL: An ANSI standard computer language for accessing and manipulating databases.
InSQL®: WonderWare® SQL database for online monitoring of data.

## 1. Introduction

Elsam has seven main production units, which are connected with each other and with the European continent through a high voltage system. The power system is further connected with both Norway and Sweden through AC sea cables. The production units are designed for fossil fuels (natural gas, coal and oil), they produce both heat and power, and the power stations have drawn up long-term contracts for supply of power and district heat through distribution companies. Elsam's portfolio also includes the world's largest offshore wind farm with an output of 160 MW at maximum production. It may thus be something of a jigsaw puzzle to organise the heat and power production also taking into account the production of green energy and the power reserves which may be supplied from the Norwegian market based on hydro power as well as power reserves from the remaining European market.

## 2. Mathematical modelling

The system of mathematical modelling is implemented in a Web-based IT environment under an internal priority network connecting the power station units mutually and with Elsam.

The modelling system comprises three different applications and applies Turabs as its fundamental element. Each application handles various functions with various target groups in the Elsam Group. An online application has been developed, Turabs Online (TOL), which comprises calculation models of Elsam's seven largest production units. For consequential calculations an analysis tool has been developed with Turabs What If (TWI). For mutual optimisation between the units, Turabs PQ application (TPQ) has been developed which is used for identification of the operating ranges of the unit and mapping of the fuel consumption and $C_v$-values for the total operating ranges of all units.

### *2.1 Background*

By the end of the 1990's Turabs was selected as Elsam's simulation tool to optimise the power plant process at the individual units. A prototype of the system was fully developed in year 2000 and was subsequently installed and tested at SKVB3. On basis of the satisfactory experience it was decided to expand the system to comprise all units.

## 3. Units

The seven units are specified in table 1 below. The units are all backpressure plants - with the exception of ENVB3. Two of the units are so-called convoy plants (SKVB3 and NJVB3), which have identical thermodynamic cycles. SKVB3 is natural gas-fired whereas the other units are coal-fired.

Table 1.
Characteristics of Elsam's seven largest units

| Unit name | Superheater temperature [°C] | Superheater pressure [bara] | Max. net power production [MW] | Max. district heat production [MJ/S] |
|---|---|---|---|---|
| SKVB3 | 582/580/580 | 290/77/19.5 | 391 | 435 |
| NJVB3 | 582/580/580 | 290/77/19.5 | 391 | 435 |
| ESVB3 | 560/560 | 251/56 | 378 | 460 |
| SSVB3 | 540/540 | 220/49 | 350 | 455 |
| SSVB4 | 540/540 | 220/49 | 350 | 455 |
| ENVB3 | 540/540 | 200/45 | 660 | 80 |
| FYVB7 | 538/540 | 240/60 | 371 | 480 |

In the following section the description of the individual units is limited to comprise only the turbine cycle at the convoy plants, ie. a description of SKVB3.

## 4. Skærbækværket unit 3

Over time Denmark has been dependent on foreign fuel resources and this has been an incentive to try to reach a continuously higher efficiency at power stations. It was therefore a natural consequence to build a unit with double reheat and supercritical steam data. The efficiency at SKVB3 is thus 48% in condensing mode with a fuel utilisation of up to 93% by combined heat and power production. The overall efficiency of the unit was increased to 49% by installation of an expansion turbine, which by reducing the pressure of the natural gas, supplies a net output to the power production of 4 MW. The boiler is built as a 75 m high tower boiler with a furnace volume of 59,000 $m^3$. The boiler efficiency is 95.7% by gas firing.

The unit is equipped with an Alstom® extraction unit, designed with maximum capacity for district heat production. The turbine plant comprises five turbine parts:

- A very high-pressure turbine with 14 steps.
- A compact module with a high pressure and intermediate pressure part (HP/IP0) with 6 and 9 steps, respectively.
- An asymmetric intermediate pressure part IP1 and IP2 with 5 and 7 steps respectively. Steam extraction for two serial connected district heat exchangers from the first (IP1) and the second (IP2) part, respectively.
- Two double-current low-pressure turbines (LP1 and LP2).

The steam is reheated to 580 °C both after the very high-pressure turbine (VHP) and after the high-pressure turbine (HP). The double reheat results in the efficiency of the plant being increased by approximately 1 percentage point compared to a plant with single reheat. The turbine plant is throttle-regulated and is normally run in slide pressure mode, which results in the best available efficiency. Due to the slide pressure mode, the up or down throttle of the plant takes place based on the boiler pressure while the control valves of the turbine are wide open. The live steam pressure varies from 285 bara at full load to 90 bar in circulation mode. The regulation capacity of the plant is according to Elsam's load gradient requirements. The outlet pressure is 78 bara. In the high pressure turbine the steam is expanded from 76 bara to 20.5 bara and in the first intermediate pressure turbine (IP0) it is expanded from 19 bara to 7 bara, after which the steam is led to the asymmetrical IP1/IP2 turbine. Here the steam is expanded to a pressure of 2.3 bara by outlet from IP1 and to approx. 1 bara by outlet from IP2. From here the steam is led either to the district heat exchangers or to LP1 and LP2, respectively, and further on to the condenser.

### *4.1 Main cooling-water system*

The plant is cooled using seawater and the main cooling-water system is optimised for an inlet temperature of 10 °C. The condenser at the cooling-water side is divided into two parts. Operation can thus be maintained while one part is cut off. The condenser pipes and the tube plates are made of titanium to avoid corrosion at the seawater side. Cooling water is taken in from Kolding fiord and led through two 50% main cooling pumps to the cooling-water intake structure with automatic cleaning grating and on through two mussel filters to the condenser. The total amount of cooling water for supply of the main cooling system is 14,000 kg/s at 100% load.

### *4.2 District heating*

District heating is supplied to the surrounding towns with a total population of approx. 250,000 inhabitants. At SKVB3, steam for the district heat production is extracted at two outlets of the asymmetrical double-current intermediate-pressure turbine and led to the two heat exchangers. These heat exchangers are serial connected by which is achieved the best possible reduction of the power production combined with heat production. Outlet pressure and temperature is 1.34 bar and 220 °C and 0.46 bara and 113 °C, respectively. The district heating water is heated to a forward temperature of 105 to 120 °C. The return temperature is normally 48 °C. The maximum district heat production is 435 MJ/s in backpressure mode only. The local area can at most take 330 MJ/s district heating. The remaining production capacity can be used for storage in a district heat storage tank balancing economy and energy in relation to heat and power production. The district heat production can be regulated from a minimum of 15 MJ/s to the required output, being subject to, however, the usual interdependence between power and heat production. The district heat storage tank holds 25,000 $m^3$ and can instantaneously release a power production capacity of approx. 60 MW.

### *4.3. Control system*

The control system performs all tasks of control, regulation, supervision and protection of boiler, turbine, generator, condensate system including auxiliary systems and district heating and own consumption. The operating situation and the development in the efficiency of the individual plant components are continuously supervised by means of calculations in the control system. Results of this supervision and measuring signals from several parts of the process make up around 6,000 tags per plant, which are transferred to a central InSql® database where data can be compared and analysed over time to obtain optimum operation both financially and technically. It is also possible to compare operational results from Elsam's other power stations as all control systems send data to the central InSql® database.

**5. The application Turabs**

Turabs is a simulation programme developed by Elsam Engineering for calculation of turbine and water/steam circuits in general. Turabs is the result of more than 10 years of continuous development and is tuned through the experience gained from energy projects worldwide. The system is a static calculation programme, which with a comprehensive component library and advanced water/steam and gas library can be used for design and consequence calculation of power station units. Turabs equips engineers to carry out accurate pressure, temperature and flow analyses from a position of knowledge, and rapidly achieve an optimised design. This cuts production costs and improves product quality. The system is run on a Windows platform and comprises a pre-processor, which can run in a design and in an off-design mode so that based on a design calculation, consequence calculations can quickly be established in the form of off-design calculation. With Turabs online, an off-design simulation is established based on online measuring data from the various power station units. Turabs includes an individual equation solver, which empirically is very robust. Turabs solves (minimises a functional **F**) a constrained nonlinear equation system by establishing a Jakobiant matrix which is solved iteratively by means of a modified Newton Rapson algorithm.

$$\overline{F} = \overline{\overline{A}}\,\overline{x} - \overline{b} \qquad (1)$$

A Cholesky decomposition [1] is used in connection with the iterative solution of the equation system (1) and at the same time a Cuthil McKey re-numeration of the equation system is used. The solution vector is accepted during an iteration process when the Euclidean norm is less than $\varepsilon$:

$$\frac{1}{2} \cdot \sum_i F_i^{\,2} \le \varepsilon \qquad (2)$$

where ε is the convergence criterion. The solution vector is supervised by a control routine, which ensures that the solution will always be within a predefined definition interval.

The following solver algorithms (search directions) are available:

- The Line search Method, [2] page 116
- The Double Dog Leg Step Method, [2] page 139
- The Locally Constrained Optimal Hook Step Method, [2] page 134
- The method of Bisection, [2] page 25

The various solvers are extensively described in [2]. The Turabs system includes an algorithm, which utilises a hierarchic priority of the above search directions dependent on the convergence speed of the equation solver at the actual operating point.

The hierarchy indicates how fast the line search and dogleg methods are compared to the method of bisection. The method of bisection is not used until it is absolutely necessary.

Moreover Turabs includes a comprehensive component library of turbines, generators, condensers, pre-heaters, pipes, valves and controllers which are all implemented in the Turabs code. In general the involved components are very detailed and fulfil the above descriptions of the actual plant. A comprehensive modified water/steam (IFC67) and gas library [3] is connected covering the pressure and temperature range from 0 to 1000 °C and 0 to 800 bara.

## 6. Functionality

The design models for Elsam's power station units are established based on guarantee heat balances and measurements of heat consumption at the individual units. The models operate within the normal load area, ie. from 15 % load to 100 % load varying from condensate mode only to backpressure mode. The models may also operate in the heat and power overload by bypassing the HP or LP pre-heaters. The design models are established based on no-loss line at 100 % load. Three applications each with Turabs as a common denominator have been developed for each unit. A process calculation based on TWI is shown in Fig. 1.

### *6.1 Turabs online*

By calculating the entire power station process a number of key figures showing the operating situation, eg. unit efficiency and $C_v$-value, can be obtained for each unit. It is also possible to get indications of suddenly arising problems at a unit if inconsistencies between the measured data and the corresponding calculated data of the unit are registered. It is thus possible to compare the entire data basis for the computer model and track down a defect component or track down long-term deviations on vital components. The system is able to optimise the unit by means of a number of operating parameters and thus increase the efficiency of the unit. One example is that Turabs online (TOL) calculates an optimum amount of cooling water to the condenser at the individual units, but many other parameters can be optimised. TOL receives data from the control system each 60 seconds and subsequently makes an off-design calculation. The calculation time varies from 0.5 to 2 seconds for a system with 1300 nonlinear equations. The calculations take place at a 3 GHz Pentium PC.

Calculation data are returned to the central InSql database so that a time serial analysis can be performed of the measured and calculated data.

### *6.2 Turabs PQ application*

The TPQ system is able to map the fuel consumption and the $C_v$-value within the entire load area of the power station unit under varying heat and power production and is thus able to supply data to Elsam's new operation optimisation programme, Octopus [4], which can optimise the production at the seven power station units. The diagram is based on 144 TWI calculations. For each calculation point in the PQ diagram is attached a $C_v$-value and a gross boiler input so that the fuel consumption can be estimated quickly. A PQ diagram for SKVB3 with all possible overload situations is illustrated in Fig. 2. The corresponding area with the $C_v$-values as a functional value is shown in Fig. 3. The entire PQ diagram with overload situations can be seen at the Web portal for the seven units. The PQ diagram gives the plant operators a precise overview of the actual mobility of plant operation.

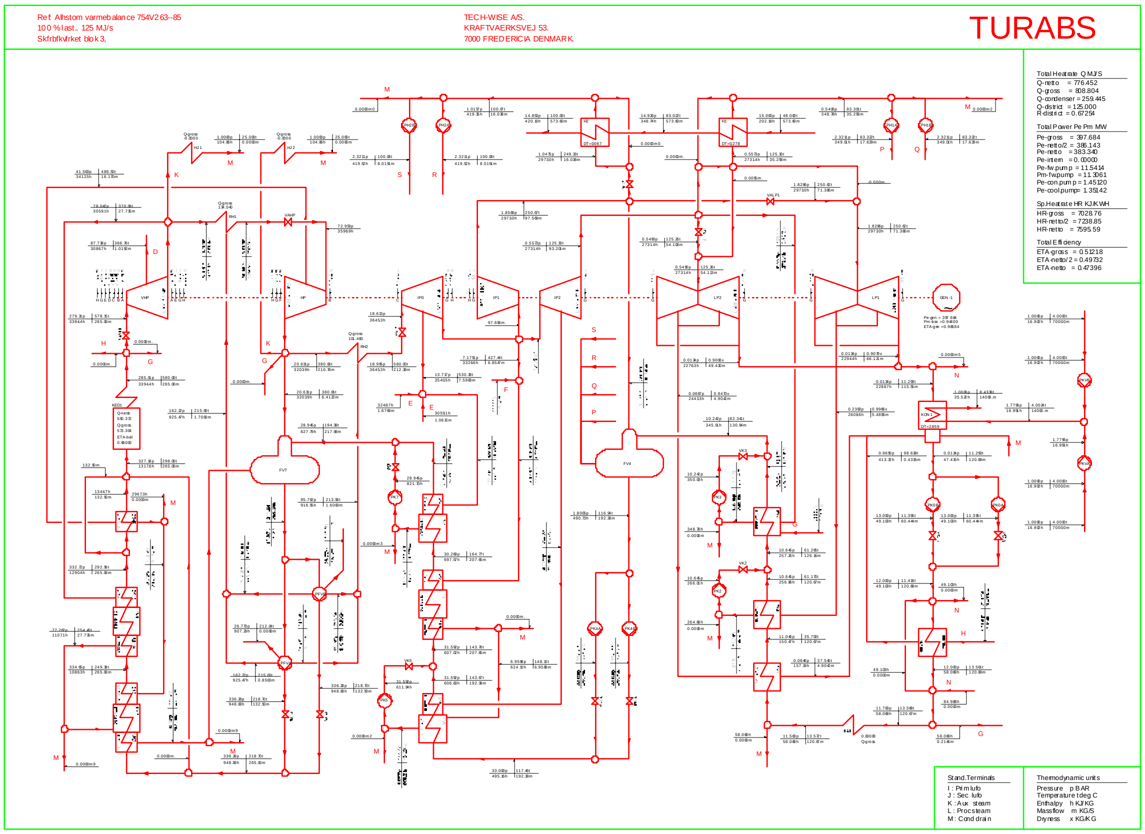


Fig. 1. Process calculation with Turabs What If

## *6.3 Turabs What If*

By means of Turabs What If (TWI) it is possible to calculate how a unit operates. One of the positive side effects of modelling the units is that it is possible to illuminate how a unit will react in other operating situations, a model can for example show how much power can be produced at the cost of heat production and thus enable pricing of the district heat production.

In the TWI application, control valves, pre-heaters, fouling factors and pumps can be activated and specified according to request. It is of course also possible to change the model boundary data and thus perform consequence calculations. Subsequently it is possible to print a report containing the main data of the power station unit, and a number of service tools have been developed which enable individual design of reports. Finally it is possible to generate a drawing of the unit as shown in Fig. 1. The drawing is based on AutoCad® 2004 and includes calculation data that are configured in a database.

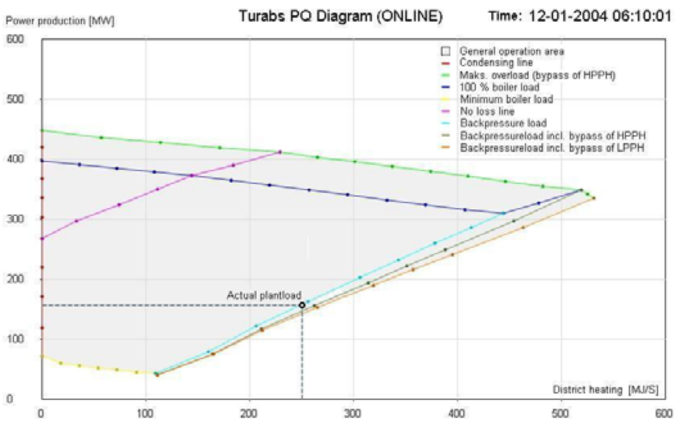


Fig. 2. PQ operation area

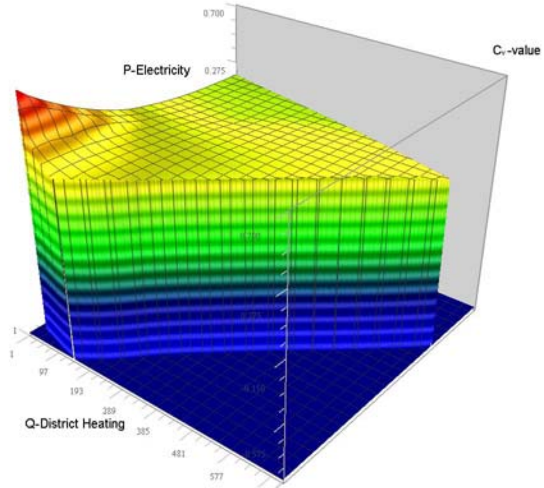


Fig. 3. $C_v$-values in plant operation area.

## 7. Architecture/design

The Turabs system is located at the internal priority network with the exception of the actual Web portal, which is placed in an administrative network to ensure easy access. The Web portal communicates through a firewall with a server centrally in the priority network. This server is called the "broker" as it sees to the distribution of tasks in the priority network. Both these central servers are doubled to ensure a high reliability. In addition an SQL server (InSQL® server) is used for storage of data. At the local power stations are servers, which typically run the local TOL application for the individual unit. The various Web services used to obtain or possibly store data at the unit are also located on these servers. The IT infrastructure is shown in Fig. 4.

### *7.1 Database structures*

The online applications applies a Microsoft® SQL Server 2000 to store information from the System. TOL stores input data and calculated data in the central InSQL® database as well as the corresponding measured data for validation. The visual configuration of the Web portal is also kept in the database. For TWI, input and output are stored, if required by the user. The TPQ application is running one time every day and the corresponding data are stored for each unit together with a set of default data.

### *7.2 Web portal*

The basis for the design of a user-friendly interface has been to develop a system which secures easy access to the system everywhere in the Elsam Group and with overall control of the user access to the system. With the choice of a Web solution implemented at Elsam's intranet only Elsam's employees have access to the system.

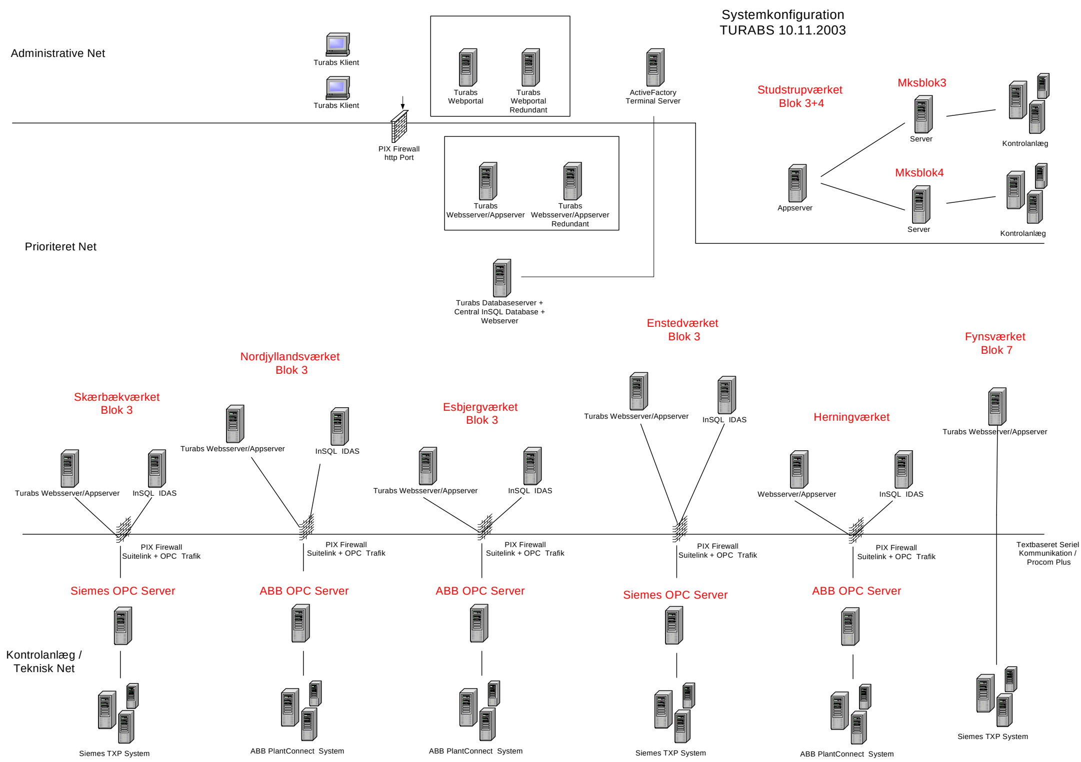


Fig. 4. IT-infrastructure

It is possible to navigate from the TOL, TWI and TPQ applications by means of a map with hotspots or it is possible to navigate via control bars to a TOL side where TOL can be reached for each unit. There are similar possibilities concerning TWI and TPQ where it is possible to navigate to the individual units. An online forum has been established where the users can communicate with advanced users of the system or they can express their approval/disapproval of the system or simply share their experience with the system.

Online data maintenance is a system that enables the advanced users to perform online adjustments of the off-design model without having to shut down the portal. The advanced users can also adjust the layout of the reports on basis of a TWI calculation. Data can be added or removed from the report as requested.

## 8. Future

The Turabs system was implemented by the end of 2003 with a satisfactory trial operation period in December 2003.

An online monitoring system gives great perspectives and a formalised cooperation has already been initiated with the involved units concerning a training programme which will ensure that the operating personnel is able to convert their knowledge of the system into improved operating results. A precondition for success is a well-founded cooperation with the operating personnel. The goal is to reach a payback time for the system of less than one year.

A number of new initiatives are in the foundry concerning modelling of boiler plants. The component library of Turabs is to be extended also to include complex boiler and furnace components to enable modelling of complete boiler plants including water/steam circuit and the actual combustion process by convective transport of flue gas in the flue gas ducts of the boiler. The aim is for Elsam Engineering to establish a pilot project focusing on expanding the online model of SSVB3 with a complex boiler model. With access to all measuring data relating to the boiler plant we have be best preconditions for modelling the boiler in a realistic way and optimising both the water injection and flue gas recirculation.

## 9. Conclusion

The Turabs project has in many ways been groundbreaking. First of all it has contributed to the accumulation in the Elsam Group of extensive and detailed process knowledge of Elsam's main units; knowledge that is further maintained in advanced mathematical models. At the same time a unique system has been established for Elsam from where online plant data can be retrieved from the units by means of open standardised protocols. Furthermore a database has been established in the project where historical data are stored for analyses and other advanced use such as data mining; and the project has laid the foundations for the creation of the priority network which is the cornerstone in the IT architecture over which Elsam's technical IT-systems will be built in the future. Turabs is a part of Elsam's strategic optimisation tool and will over time increase the efficiency of the power plant units and be a main supplier of data to Elsam's global plant optimization tool. Corresponding simulated PQ diagrams provide Elsam with a continuous picture of fuel amount and $C_v$-value within the operating areas of all seven power stations, which enable optimisation of the mutual operation of the power station units. The TWI applications are a decision tool for plant operators and the TOL applications optimise the cooling water flow and calculate online $C_v$-value for pricing the district heat production. Having in mind that the TOL application is a picture of an ideal trimmed power plant, with respect to fouling factors, pre-heaters and turbine blades, the application will be used for online performance analysis. Time series of measured and calculated parameters can be evaluated and if/when major deviations occur, there is time for action.

## Literature


[1] Numerical Recipes. The Art of Scientific Computing (Fortran Version), 2nd edition, Cambridge, University Press. ISBN 0 521 38330 7.

[2] Numerical Methods for Unconstrained Optimisation and Nonlinear Equations, J. E. Dennis Jr. and R. B. Schnabel, Prentice Hall Series in Computational Mathematics 1983. ISBN 0-13-627216-9.

[3] Baehr & Diederichsen, Berechnungsgleichungen fuer enthalpie und entropie der komponenten von luft und verbrennungsgasen, BWK bd 40 1988 nr 1/2 - januar/februar.

[4] Moelbak T. (2003). Integrated model based optimisation of a power production system. Proceedings of ECOS 2003 Copenhagen, Denmark.