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Process Plant Performance Monitoring and Analysis by Recon

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SUMMARY

1. Chapter 1 of this report formulates problem of PPMA (Process Performance Monitoring and Analysis). Five main performance states of process plants are defined and their comparison is discussed.
2. Chapter 2 discusses RECON's **Modes of calculation** and **Direction of calculations**. There are two basic Modes of calculation:
 - **Direct solution** of a set of equations suitable for plant's simulation
 - **Data reconciliation** based on statistical adjustment of redundant measured values suitable for identification of model parameters

It is possible to change a Mode of calculation and a Direction of calculation by changes of variables' type (M, N or F).

These two modes of calculation and switching among them are of key importance. They make possible to identify model parameters from process data and to use models in PPMA (to simulate plant's behavior under changed conditions).

3. Theory presented in Chapter 2 is illustrated in Chapters 3 and 4 containing two case studies – modeling a coal fired boiler and a Rankine steam cycle.
4. Chapter 5 deals with enhancing standard Recon models by inclusion of empirical models obtained from historical process data.
5. Appendix 1 analyses redundancy, observability and solvability of models in RECON.
6. Appendix 2 is a case study of the influence of coal quality on boiler' performance.
7. Appendix 3 describes details of using RECON models Variants
8. Appendix 4 is about details of configuring simulation mode of calculation (simulation files).

GLOSSARY AND ABBREVIATIONS

Base case. The state of a plant around which we predict plant's behavior.

Calculation Mode. There are 2 basic calculation modes in RECON: Data Reconciliation and Direct calculation.

DR - Data Reconciliation. (1) Statistical correction of redundant measured variables to obey model equations. (2) Calculation of unknown variables from the reconciled ones.

DRV – Data Reconciliation and Validation. DR combined with data Validation

Degree of Redundancy (DoR). Difference “No of equations – No of unknowns”.

Direct Calculation. Solving model equations to calculate values of unknown variables. Number of independent equations equals number of unknowns (DoR = 0)

Direction of Calculation – Classification of model variables as Inputs and Outputs of calculation.

HHV – Higher Heating Value (sometimes called GCV – Gross combustion Value)

HR – Heat Rate – ratio of consumed energy and the electricity produced. In this report are used HRSC and HRPP

HRPP – HR of a whole power plant

HRSC – HR of a steam cycle

HTC – Heat Transfer Coefficient

IEE – Isentropic Efficiency of a steam turbine

Just determined system. System of equations which is nonredundant and observable. All its unknowns can be uniquely calculated by solving model equations by **Direct Calculation**.

KPI – Key Performance Indicator

LHV – Lower Heating Value

Model. Model in RECON is a system of generally nonlinear algebraic equations in the implicit form. Model describes relations among model parameters and model operational variables.

Model parameters describe properties of plant equipment (heat transfer areas, heat transfer coefficients, isentropic turbine efficiencies, etc).

Model operational variables describe a state of a system (process flowrates, temperatures, pressures, etc.). **Synonym: Process Variables**

Observability. System is Observable if all unmeasured variables can be **uniquely** calculated by solving model equations.

PPMA – Plant Performance Monitoring and Analysis

PTC – Performance Test Code

Redundant system. System containing at least one redundant variable (which must be reconciled to fulfill model equations).

Solvability. System of equations is Solvable if all model equations can be zeroed by proper values of unmeasured and reconciled measured variables.

Types of variables in RECON

- Type **F**. Fixed value. A known constant which is not changed during calculation (data reconciliation)
- Type **M**. Measured, estimated or otherwise set value with some uncertainty. Type M variable can be reconciled if it is redundant.
- Type **N**. Unmeasured variable which should be calculated. Some initial guess is required to start calculation. **Synonyms: Nonmeasured, Unknown**
- Type **Z**. Type used in task Variants, similar to F type. Its value during calculation is zero, irrespective of value imported from data sources. Type Z serves mostly for elimination of unused equipment and plant's subsystems when they are out of operation, bypassed, etc.
- **Note:** The **F** type variable can be viewed as the **M** type variable with zero uncertainty.

UDE – User Defined Equation. Equations created manually by RECON's users.

WiQ – What if Query

1 INTRODUCTION

Plant Performance Monitoring and Analysis (PPMA) is a continuous comparison of a present state of a plant with some **reference state**. In this way it is possible to **quantify possible degradation** of a plant performance due to equipment wear off, fouling, etc. Plant's performance is usually characterized by several KPIs (Heat Rate, electric power produced, gross margin, etc.).

The reference state can be for example

- Design (vendor guarantees)
- Results of acceptance tests (as built)
- Plant state at the time the PPMA started.

It is important to realize that a design state may be a state which has never existed in practice. Once a plant is accepted it is too late to worry about plant guarantees. On the other hand side the other possibilities has the advantage of being evaluated by the same or very similar methods like the PPMA proper (biases can cancel).

PPMA means **regular** evaluation of a plant behavior on the basis of existing plant instrumentation. This differs from ad hoc **performance tests** which can use special instruments and measuring methods. The main target of PPMA is to inform plant operators about a real state of a plant, to help in plant's efficiency monitoring, equipment diagnosis, instrumentation functionality, process optimization, maintenance planning, etc.

PPMA is not a trivial task. A plant's efficiency is influenced by many external impacts. Some of them can be forecasted or controlled (for example a plant load), the others are completely out of our power (for example the ambient temperature). It has no sense to compare simply production at a reference state with a real production at a (variable) different state (for example at different load and ambient temperature).

Performance of a plant is defined by **two groups of variables**:

- (1) **state of plant's equipment** (heat transfer areas, heat transfer coefficients, catalyzer activity, efficiencies, tightness, fouling, ...)
- (2) **external operating conditions** (load, temperatures, pressures, environmental variables, ...). Important are the **Reference operating conditions**.

There are **three major groups** of external operating variables in classical power plants:

- power plant load expressed as electric power export and heat export (in the case of cogeneration plants)
- environment parameters which are different for individual power plants. Generally important are ambient air temperature and humidity. In the case of

power plants cooled by sea water also the sea water temperature.

Atmospheric pressure is important mainly for combined cycle systems with gas turbines.

- fuel quality defined by its composition and heating value. PPMA can be complicated also by blending of different fuels.

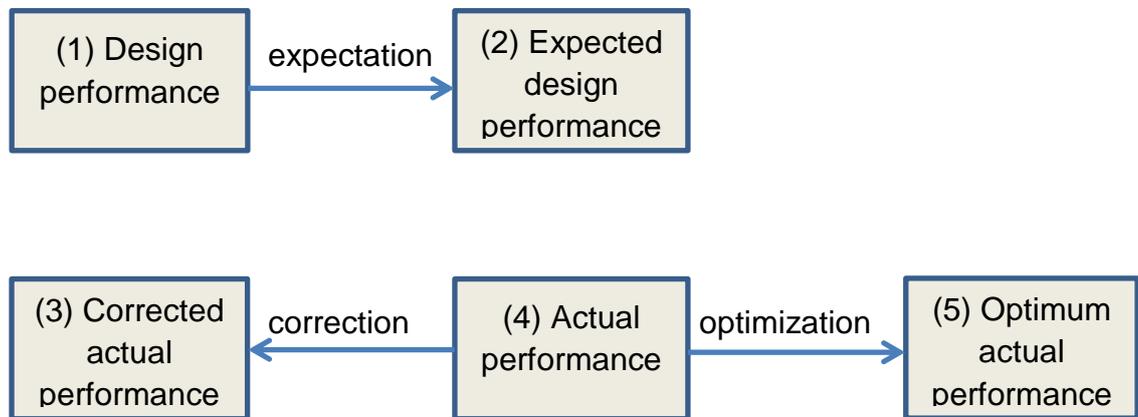
Typical states of a plant operation are shown in the next Table 1.1 (here we suppose that the **reference state is the design state**).

		Operating condition (variables)		
		Design	Actual	Optimum
Equipment state	Design	Design (rated) performance (1)	Expected design performance (2)	
	Actual	Corrected actual performance (3)	Actual performance (4)	Optimum actual performance (5)

Table 1.1: Performance states of a plant

- (1) **Design (rated) performance** is usually defined in design flowsheets or flowsheets of a plant after a revamp (mass and energy balance sheets). From this information it is also possible to deduce equipment parameters like mass and heat transfer coefficients, turbine isentropic efficiencies, etc. In practice a design can consist of several design flowsheets (different modes of operation, raw materials, some equipment out of operation, plant's load, etc.).
- (2) **Expected design performance** means theoretical behavior of a plant under a **design equipment state and changed operating conditions**. Typical examples of operating conditions are plant load, ambient temperature, temperature of cooling water, etc.
- (3) **Corrected actual performance** is the actual performance corrected for differences between actual and design operating conditions. In Performance test manuals this problem is frequently solved via correction coefficients, graphs and the like. A more sophisticated solution of this problem is using simulation models.
- (4) **Actual performance** is based on a real plant measurement. Measured values can be modified during a data validation process by data reconciliation. The Actual performance state has thus two versions: (a) as measured and (b) as reconciled and validated.
- (5) **Optimum actual performance** is a state which can be achieved by maintaining control variables at optimum values. Ways to this performance state can be of different complexity – from rules of thumb to advanced online process optimizers.

The situation can be depicted in the next figure:



There are two possibilities how to use performance states described above in PPMA:

- The first possibility is to compare states (1) and (3), i.e. the Design performance and the Corrected actual performance. The difference of these two states quantifies a **degradation** of a plant in time [8]. The advantage of this method is that we compare the existing state with a constant state (design) which makes the comparison easier. The difference of these two states defines the plant's degradation by one set of KPIs. Degradation can be characterized by simple technical parameters of equipment (for example by Heat Transfer Coefficient of an heat exchanger) or by a complex KPI like Heat Rate of a plant which requires detailed evaluation of the whole plant. Comparison of states (1) and (3) is also the essence of acceptance tests of new or revamped plants.
- The second possibility is to compare states (2) and (4), i.e. the Expected design performance with the Actual performance. Here we compare two dynamic states. The advantage of this approach stems from the fact, that in this way we can see continuously a real impact of plant's degradation on plant's economy. It is clear that in this case a plant's degradation is not a single set of numbers but trends depending on operating conditions. A difference between the Actual Performance and the Expected Design Performance is a basis of **Plant Performance Monitoring** [8].

In both cases one performance state must be calculated from another performance state. In Recon this can be achieved either by **Parametric Sensitivity calculations** or more exactly by **Simulation**.

The main target of this report is to show how RECON can be used in the whole complex of activities connected with PPMA.

The PPMA is usually implemented in two steps:

- (1) In the beginning there is the identification of model parameters (HTCs, IEEs, etc.). In the case of a new plant this can be done on the basis of design flowsheets. For already running plants we can use data reconciliation of redundant historical data collected during standard plant's operation. In both cases RECON is used in the **DRV Calculation mode**.
- (2) The next step is a simulation of a plant behavior under changed conditions. The model parameters (HTCs, IEEs, etc.) now serve as inputs for simulation. Here RECON is used in the **Direct Calculation mode** (simulation).

2 MODES OF CALCULATION IN RECON

Any model in RECON can be symbolically written as

$$F(x,y,c) = 0 \quad (2-1)$$

where $F(x,y,c)$ is a vector of generally nonlinear algebraic functions

x	vector of measured variables (M type)
y	vector of unmeasured variables (N type)
c	vector of constants (F type)

System of equations is **Solvable** if all model equations can be zeroed by proper values of unmeasured variables, reconciled measured variables and constants (if there exist such vectors x and y with which the system of equations (2-1) is exactly fulfilled). In the opposite case the system of equations (2-1) is **Unsolvable**. Solvability is a property of model's equations and of the classification of variables as M, N and F type.

Another important notion is the **Observability**. System (2-1) is **Observable** if y can be **uniquely** calculated by solution of (2-1). For example, it is well known that if we have one linear equation with two unknowns, such system is solvable (with indefinite number of solutions) but it is not observable. See also Examples in Appendix 1.

Next in this report we will work with solvable and observable models.

2.1 Direction of Calculation

What follows now is not a scientific problem analysis but a common sense view on calculations in practice. Calculation **variants** are characterized by "direction" of calculation or, in other words, by selection of inputs and outputs of a calculation. In this sense variables belong to one of two groups:

- Known variables, which can serve as **calculation inputs**. In Recon they belong to types M (Measured) or F (Fixed). In practice they are measured or otherwise set (qualified estimates, literature data, etc.). Fixed variables can be viewed as Measured ones with zero uncertainty.
- Unknown variables, which are supposed to be calculated when solving model equations (**calculation outputs**). In Recon they belong to the type N (uNmeasured)

Examples of calculation variants are shown in the next figure. Here it is supposed that process inputs (raw materials, fuel, etc.) enter in a flowsheet from left and products step out on the right.

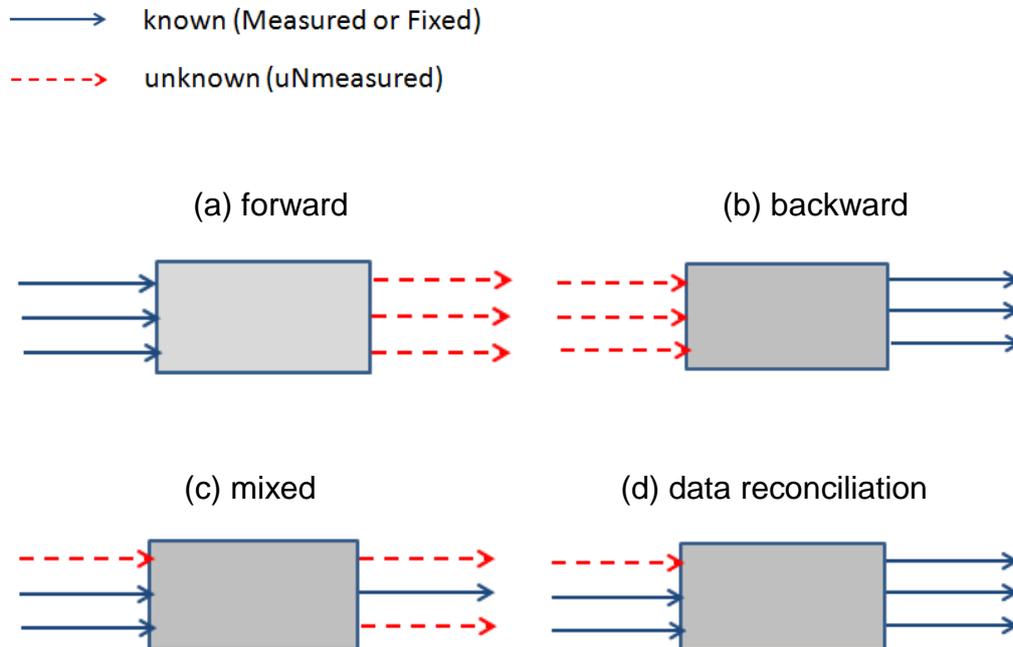


Fig. 2.1: Calculation direction

Sometimes it is required to calculate production from feeds (forward calculation), in another situation we need to calculate inputs for required production (backward calculation) or to start calculation with some combination of inputs and outputs in a general case. In the first 3 cases it is supposed that we just solve a system of equations for a given selection of unknown variables (direct calculation). In this case the number of unknowns equals the number of (independent) equations.

$$N_{eq} = N_{nv} \quad (2-2)$$

where N_{eq} = No of equations

N_{uv} = No of unknown variables.

The “direct calculation” variant is frequently used for “simulation” calculations. This case is sometimes called a **Nonredundant or Just determined model**.

Note: During direct calculation measured variables (M type) are not changed. They behave like constants (F type).

The case of “data reconciliation” means a different situation when the number of unknowns is lesser than the number of equations. Here (some or all) measured

variables are redundant and must be reconciled to enable the final solution (a **Redundant model**). The Equation (2-1) then has a form

$$F(x', y', c) = 0 \quad (2-3)$$

where x' vector of reconciled measured variables
 y' vector of calculated unmeasured variables

The vector of adjustments $x' - x^+$ (where x^+ are measured values) is minimized by the Least squares method. For details see [2,7].

The classification of variables in a general case is shown in the next figure:

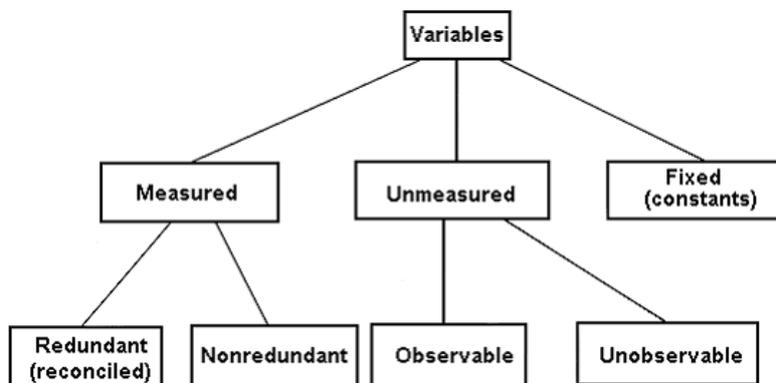


Fig. 2.2: Classification of variables

Here *Measured* variables mean *known variables* or *inputs* of calculation. *Unmeasured* variables mean *outputs* of calculations. *Fixed* variables are those measured or otherwise known variables which must not be reconciled (must remain constant).

2.2 Variables' interchange rules

A change of calculation direction or a change of calculation between Direct Calculation and Data Reconciliation is based on a change of variables' types. In practice we need to change for example

- Unsolvability model to a Solvable one
- Redundant model to a Nonredundant one
- Interchange variables among M, N and F types while the solvability and redundancy remains the same.

During this process we use the following **Variables' interchange rules**. It is important to realize that:

1. Putting one redundant variable among unmeasured decreases degree of redundancy by one. This variable is then observable but can be either redundant or nonredundant.
2. Putting one nonredundant variable among unmeasured ones changes this variable to unobservable
3. Putting one unobservable variable among measured ones makes this variable measured nonredundant
4. Putting one unmeasured observable variable among measured ones makes this variable measured redundant.

Note: These rules hold exactly for linear models and uncorrelated errors of measured variables. In most cases they also hold for nonlinear models (some exceptions are shown in Appendix 1).

The rules above are useful for creating different calculation variants. In general, it is recommended to modify variables' type one by one and to look at classification of variables after every change.

In this way it is possible to modify the direction of calculation. Important is the requirement of system *solvability* and *observability* (all unknown variables are *observable*). Further in this report it is supposed that the final **solution is fully solvable** and **observable**.

To summarize this Section:

- There are two basic modes of calculations: **Direct solution** of a set of equations and **Data reconciliation** based on statistical adjustment of redundant measured values (nonlinear optimization)
- There exist many directions of calculation characterized by inputs and outputs of calculation
- It is possible to alter a mode and a direction of calculation by changes of variables' classification by their type (M, N or F).

Note: It is good to note that the notion "calculation direction" has its clear meaning in sequential calculations typical for some simulation programs. Here the calculation usually starts from known inputs and ends at calculated outputs. On the contrary, Recon is based on implicit sets of equations which are solved **simultaneously**. This is a reason why the "calculation direction" in RECON does not mean a real sequence of calculations but only a placement of known and unknown variables on a flowsheet.

A full understanding of this Section needs some examples. A reader can find them in the Appendix 1.

2.3 Calculation Variants in RECON

In general, there are two methods of maintaining a system of variants in RECON:

1. It is possible to create a set of RECON tasks differing in tasks' names. For example tasks' names can be Model1, Model2, etc.

2. The second possibility is to create many model Variants under one model.

The second possibility has several advantages. Here is a brief description of RECON's variants:

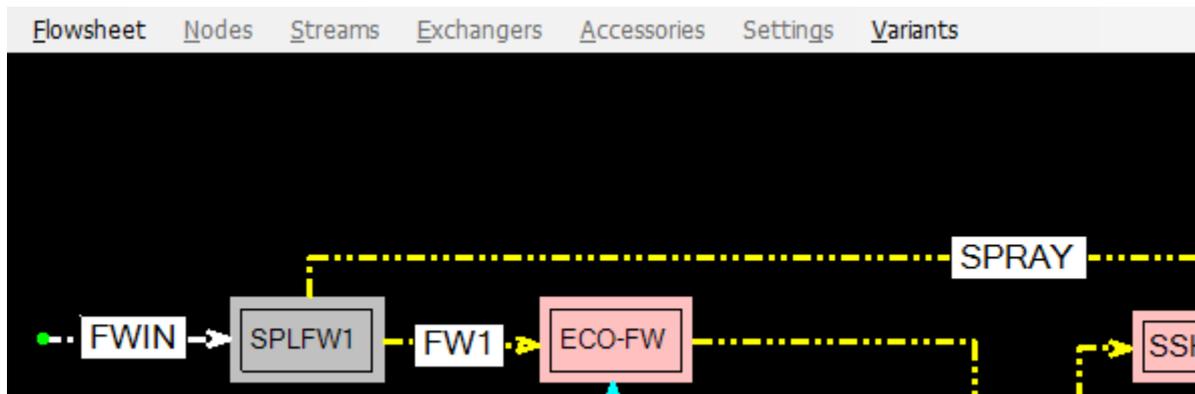
Variants of a task have always the same balance schema as the base-case (mother) task. There are only two things which distinguish a variant from its mother task.

- Individual variants can differ in variables' types (M,N,F). Besides that it is possible to use the type Z (fixed zero flow-rate). When the Z is applied, the stream has exactly zero flow-rate regardless the initial value set in the mother task. The Z type can be useful when some plant's equipment is out of operation.
- In individual variants the individual User Defined Equations can be made active/inactive.

The variants defined are stored in a special database in MS Access format (.MDB file). This database is located in the same directory as the task itself (i.e. its BDT-file). The database holds the name of the task with "@V" appended. For example a model EXAMPLE with the EXAMPLE.BDT file has the database of variants EXAMPLE@V.MDB.

RECON's model variants simplify the maintenance of the whole set of models (adding or deleting streams and nodes, configuration of imports and exports, etc.).

The Calculation variants in RECON are available from menu Calculation/Variants (available after calculating a task). The following screen appears:



The screen is with a black background showing that this is not a normal RECON mode. Details of the management of Variants are described in Appendix 3.

2.4 Simulation

Simulation means prediction of a plant behavior under some defined conditions. It can be used as a part of optimization, *What if?* studies, etc. In PPMA the simulation is used mostly in two situations:

- Calculation of plant's behavior under some changed condition, for example to compare the Actual performance with the Expected design performance (see Table 1.1.).
- Calculating plant's operation curves which are trends of important process characteristics as functions of input variables (for example a trend of the coal consumption versus the power plant electricity production).

It should be noted here that RECON is not a real process simulator. It is not designed to simulate a plant on the basis of detailed construction of plant's equipment (for example, it can't calculate a condenser's heat transfer coefficient (HTC) from its material, dimension of tubes, etc. or to calculate a temperature profile in a coal fired boiler firebox). Instead of this, RECON is capable to calculate performance of a condenser on the basis of HTC provided by RECON's user. In such situation RECON can be used for extrapolation of condenser's behavior in some vicinity of the base case. Moreover, it is possible to complement a RECON model by User defined equations (UDE) to make the simulation more realistic (for example to model some HTC as a function of accompanying variables). Such UDEs can be based either on a statistical analysis of historical data or on other sources like technical literature or equipment vendor's information (for details see Chapter 5).

In RECON simulation calculations are conditioned by the existence of two text files. Both files must be located in the same directory as the simulated task. The extensions of these files are

- CFG – the configuration file containing variables important for simulation
- DAT – the data file containing values of input variable for which this simulation should be done.

For details of simulation files see Appendix 4. Simulation proper is used throughout next two Chapters and in Appendix 2.

2.5 Parametric sensitivity

Another possibility of exploring plant's behavior in the vicinity of a base case is the use of **parametric sensitivity**. This method can be applied to just determined and observable models used in the previous section. It is supposed that the Eq. (2-1) is transformed to the explicit form (this is not easy but it is a problem of RECON itself).

$$\mathbf{y} = \mathbf{f}(\mathbf{x}) \quad (2-4)$$

where \mathbf{x} is a vector of calculation inputs and \mathbf{y} is a vector of calculation outputs (the transformation of Eq. (2-1) to Eq. (2-4) is done inside RECON). The parametric sensitivity p_{ij} is defined as the partial derivation of y_i according to x_j :

$$p_{ij} = \frac{\partial y_i}{\partial x_j} \quad (2-5)$$

Approximately it holds that the parametric sensitivity equals the increase of variable y_i when the variable x_j is increased by 1. It is clear that for one output variable y_i parametric sensitivities form a vector and for the vector \mathbf{y} parametric sensitivities form a matrix (Jacobian).

With some caution parametric sensitivities can be used also in PPMA. It approximately holds

$$\Delta y_i \cong p_{ij} \Delta x_j \quad (2-6)$$

where Δy_i is the increment of y_i caused by increasing x_j by Δx_j .

The equation (2-6) holds exactly only in the infinitesimal neighborhood of the model solution. For greater distances the applicability of parametric sensitivities depends on the distance from the base case solution and also on nonlinearity of the model (which is different for different variables).

Note: In RECON the input variables (x_j) for a parametric sensitivity study can be of M type only and of course the output (y_i) must be of the N type. If we need to study the sensitivity of an output to an F type variable, this one must be changed to the M type.

2.6 Comparison of simulation and parametric sensitivity

There are two kinds of errors connected with predicting plant's behavior in the vicinity of the base case:

1. Errors of the mathematical model proper as no model is completely exact in practice (with exception of simple mass balance models). Such errors are intrinsic for both methods (simulation and parametric sensitivity)
2. errors caused by linearization of the model. Such errors are typical for the parametric sensitivity method.

Both methods can be used for predicting plant's behavior in the vicinity of the base case. The base case can be for example the design state (off design calculations) or a real plant's state at some time (What If Queries).

The main advantage of using parametric sensitivity is its simplicity. Parametric sensitivities are available in RECON's results and can be used in automatically generated RECON Excel reports to predict plant's behavior outside the base case. The functions (2-6) can be thus easily configured in Excel reports' templates. The use of parametric sensitivities in an on-line mode is very simple and straightforward:

- after every DRV run an Excel report with parametric sensitivity model can be created and saved on the server
- such report can be either distributed directly to individual users or they can download reports manually
- What if Queries can be answered easily by manual manipulating of influencing variables in Excel sheets. Such solution is very fast (instant) and does not require connectivity with RECON and process data database.

There are also limitations of the parametric sensitivity method:

- there is the linearization error which should be taken in the account. There should be defined the vicinity of the base case where the linearization is justified (the linearization error can be neglected). Such vicinity of the base case can be found by comparison of parametric sensitivity results with simulation.
- this method can be used only for changes in model input variables. It can't be used for changes in model structure (for example when some apparatus or subsystem of a plant is out of operation).

The simulation is therefore more rigorous and general. Its major drawbacks are:

- the simulation proper takes some time (results are not instantaneous)
- even for well tuned models divergence of solution can occur.

Even if simulation does not suffer the linearization error problem, also here the allowed distance from the base case must be set to guarantee the validity of the model proper.

The selection of method used for prediction thus depends on more factors. RECON is capable of using both methods, simulation and parametric sensitivity.

2.7 What if Queries

Individual tasks where plant's behavior prediction plays role (performance monitoring, degradation monitoring, Performance Test Codes etc., see Chapter 1 of this report) belongs to a general problem of **What if Queries (WiQ)**. Here are some examples:

Query for PTC:

What is the Actual performance corrected for design operating conditions (states 4 and 3 in Table 1.1)?

Query for predicting equipment maintenance:

What will be Heat Rate of a plant after cleaning the main steam condenser? (return of the HTC to the original value)

Query about changing equipment properties:

What will be heat Rate of a plant after 10 % of a feed water heater's pipes will be blinded?

Query about plant economy:

What will be Heat Rate and Gross Margin of a plant with cheaper coal containing more moisture?

In all cases there are two states of a plant:

1. The original **Base state** with which changes are compared
2. The **New state** after changes defined in a WiQ.

In general, there are two groups of variables – *Influencing variables* (simulation *Inputs*) and *influenced variables* (simulation *Outputs*).

WiQs are important parts of Decision Support Systems using common sense and natural intelligence of operators (which can easily compete with Artificial Intelligence methods). Such queries can be also a prelude to process optimization in open control loop.

A typical WiQ interface between operators and plant data is the following table:

What-If? Queries

Inputs

Input (influencing) variable	Input value	Unit	Input changed	Diff.
Power		MW		
Gross Power		MW		
Net Power		MW		
Main steam temperature		DEG C		
Main steam pressure		kg/cm2		
HP steam spray		t/h		
O2 ex ECO		vol.% dry		
HPC efficiency		%		
IPC efficiency		%		
LPC efficiency		%		

Edit



Outputs

Output (influenced) variable	Output value	Unit	Output changed	Diff.
Heat rate				
Efficiency				
Gross Margin				

Steps in using such WiQ table are:

1. User selects data (timestamp) from a history database. **Reconciled data** of the Base state are automatically filled into the WiQ table (columns *Input value*, *Input changed* and *Output value*).
2. User makes manual changes of influencing variables (column *Input changed*)
3. After pressing the *Calculate* button program makes simulation with new values of influencing variables
4. Program fills the *Output changed* column by outputs of simulation

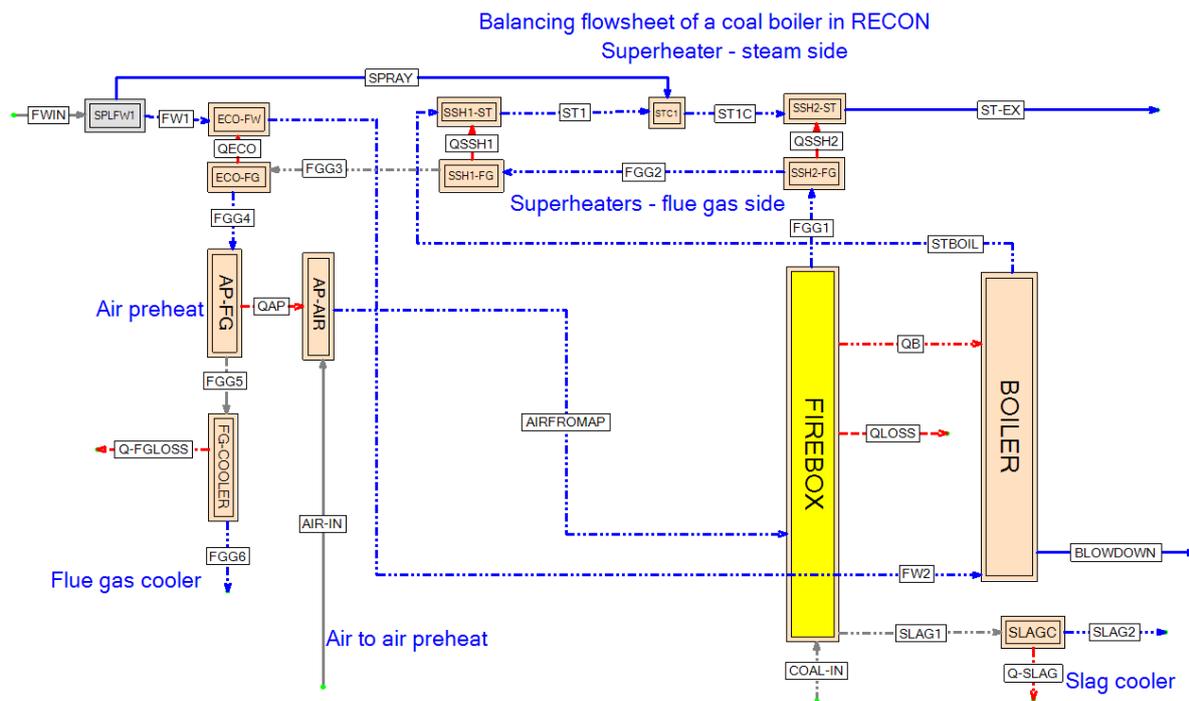
The complexity of such solution depends on selection of the modeling method (see the discussion in Subsection 2.6 of this report).

It is clear that WiQs can solve all basic tasks needed for PPMA defined in Chapter 1. Theory presented in this chapter will be now illustrated by two Case studies in Chapters 3 and 4. For the first fast reading of this report a reader can skip the next two chapters and continue by Chapter 5.

3 A COAL FIRED BOILER

3.1 Boiler description

The PPMA of a coal fired boiler will be illustrated on the case of the following flowsheet:



This is a little bit simplified model of a real coal fired boiler which contains the following main parts (for the original, more complex model, look at [4] where is also a detailed description of the boiler including problems connected with its monitoring):

- FIREBOX and BOILER (production of the saturated steam)
- two steam superheaters (SSHx) consisting of steam and flue gas parts
- one steam cooler (spray) SPR1
- economizer ECOx
- air preheater APx
- two hypothetical parts serving for calculating losses: (1) a flue gas cooler FG-COOLER and (2) a slag cooler SLAGC.

A rigorous modelling of a boiler requires a multicomponent model with a chemical reactor (FIREBOX). A basic information about such model follows:

G L O B A L D A T A

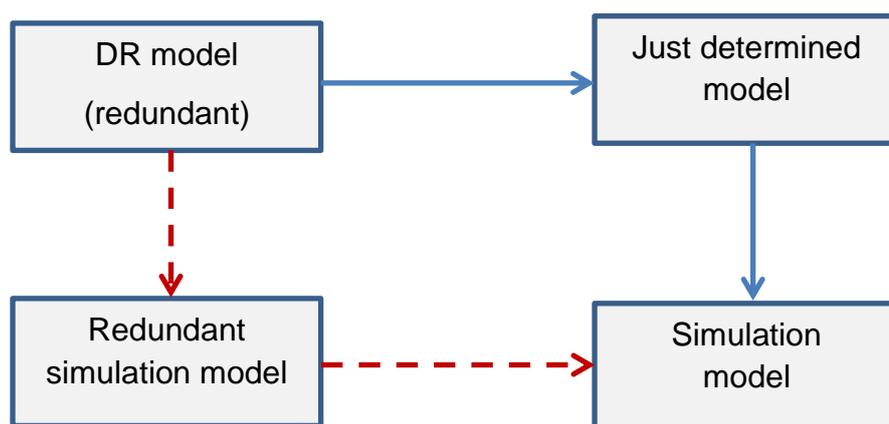
Number of nodes	14
Number of heat nodes	13
Number of streams	28
Number of energy streams	8
Number of components	9
Number of heat functions	4
Number of temperatures	15
Number of pressures	4
Number of auxiliaries	9
Number of react. nodes	1
Number of measured variables	18
Number of adjusted variables	16
Number of non-measured variables	44
Number of observed variables	44
Number of non-observed variables	0
Number of free variables	0
Number of equations (incl. UDE)	48
Number of independent equations	48
Number of user-defined equations (UDE)	8
Degree of redundancy (DoR)	4

3.2 Basic considerations

The starting point of modeling is the DR model with $DoR = 4$. This model serves for data validation and for identification of 5 Heat Transfer Coefficients (boiler, 2 superheaters, economizer and air preheater).

Our target is to **transfer the DR model to a Just determined model** suitable for simulation.

A simulation model should enable one to calculate required important output variables on the basis of inputs. All this process is more an art based on a common sense than a science. There are many ways how to do it. In the next figure:



There are two basic ways:

1. to remove redundancy ($DoR = 0$) while preserving the observability and then to interchange variables among inputs and outputs (for example to

use HTCs of heat exchangers as inputs in exchange for some temperatures) (full lines above)

2. to make a redundant simulation models in the first and then remove redundancy (dashed lines above).

3.3 Model modification

We will now use the first way described above. The DoR of this task is 4 and the same number of variables must be changed from measured to unmeasured. Let's look at the list of redundant variables.

REDUNDANT MEASUREMENTS

Type	Variable	Adjustability
MF	AIR-IN	0.435115
MF	BLOWDOWN	0.000028
MF	FWIN	0.319750
MF	ST-EX	0.350169
MF	SPRAY	0.021866
P	FW-IN	0.000000
P	ST-DRUM	0.000006
P	ST-EX	0.000002
T	AIREXAP	0.194607
T	FGEXAP	0.022923
T	FWFROMECO	0.000000
T	FWTOECO	0.008736
T	STEAMFROMSPRAY	0.603150
T	STFROMSSH1	0.057697
T	STFROMSSH2	0.014421
T	TFLUEGASEXECO	0.371228
V	[C<FGG5:O2>]	0.351490

There are several **rules of thumb** for selection of candidates for changing to unmeasured ones to decrease redundancy:

1. Don't use variables with low adjustability. Imagine for example a pressure of water which can be hardly calculated from a mass or enthalpy balance (even if this is theoretically possible).
2. Try to reduce the redundancy caused the mass balance.
3. Don't use variables which you will need later as inputs for simulations.

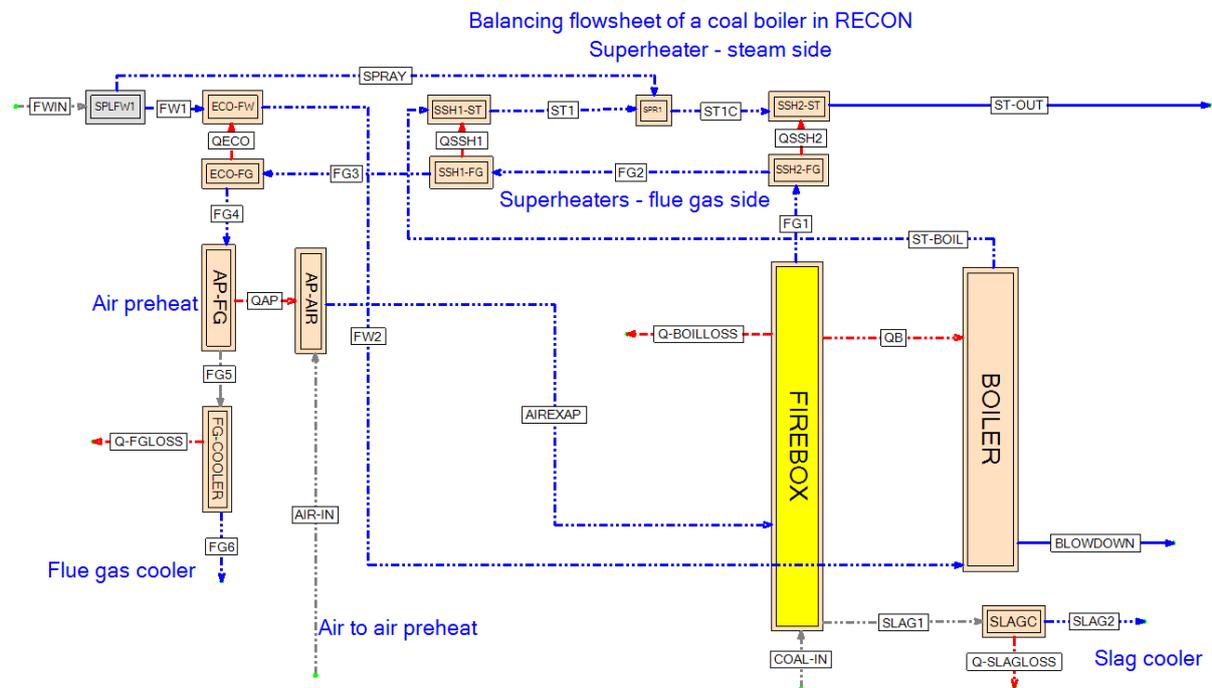
The first candidates for inclusion among unmeasured variables are mass flows of feed water (FWIN), air (AIR-IN) and spray water (SPRAY). After putting these 3 variables among unmeasured ones (DoR = 1) the list of redundant variables looks like this:

REDUNDANT MEASUREMENTS

Type	Variable	Adjustability
P	FW-IN	0.000000
P	ST-DRUM	0.000000
T	AIREXAP	0.192566
T	FGEXAP	0.022701
T	TFLUEGASEXECO	0.364857
V	[C<FGG5:O2>]	0.005249

Redundancy is now very weak. We can select temperature TFLUEGASEXECO which has the highest adjustability. By this selection the model is just determined (DoR = 0).

There remains to complete the variables' interchange. There are 5 model parameters (HTCs of heat exchangers) which must be changed to measured variables and 5 other variables must be changed from measured to unmeasured ones. Here is the flowsheet after transfer to the just determined model.



Note that flows of air and coal to the boiler are both unmeasured (they are given by the amount of produced steam and by the concentration of oxygen in flue gases).

The selection of variables which will be interchanged should be based on our intentions (the following simulation):

1. We want to study the influence of the boiler load and of the oxygen concentration on the flue gases boiler efficiency
2. We want to maintain the steam quality at the boiler exit (pressure and temperature).
3. The remaining measured variables (inputs) should be controllable (achievable by the existing control system).

4. It is clear that the new unmeasured (calculated) variables will be temperatures. This is natural as the exit temperatures of streams leaving heat exchangers are determined by HTC of heat exchangers.

The final list of 5 calculated temperatures is

- FW from of economizer
- Steam from SSH1
- Steam from steam cooler
- Flue gas from air preheat
- Air from air preheat.

3.4 Simulation

In this section we will show 3 examples of creating operational characteristics of the boiler (trends of important boiler output variables in dependence on selected input variables). The input variables will be

- The boiler load represented by the steam flow ST-OUT
- The mole concentration of O₂ in flue gases
- The HTC of the steam superheater SSH2.

The outputs will be

- **V<EFFICIENCY>** - boiler efficiency
- **S<Q-FGLOSS>** - energy loss in flue gases
- **S<COAL-IN>** - coal consumption
- **S<AIR-IN>** - air flowrate
- **S<SPRAY>** - flowrate of water to the steam cooler
- **T<FG1>** - temperature of the flue gas from the firebox
- **T<STEXSSH1>** - temperature of steam out of the superheater SSH1
- **T<STEXSPRAY>** - temperature of steam out of the steam cooler
- **T<STEXSSH2>** - temperature of steam out of the superheater SSH2
- **T<FGEXAP>** - temperature of the flue gas from the air preheater
- **T<AIREXAP>** - temperature of air from the air preheater.

Selected results of simulation are shown in 3 following tables:

Table 3.1 contains results of simulation with changing steam production (the base case steam flowrate is 120 t/h). The boiler's efficiency falls significantly with increased steam production. This is caused by a significant increase of the flue gas temperature at the boiler's exit. Interesting is also behavior of steam superheaters and of the spray.

Table 3.2 shows the influence of oxygen concentration in flue gases. The increase of O₂ concentration means the increase of air input, increase of flue gases flowrate, increase of the flue gas temperature at the boiler's exit and thus the fall of efficiency.

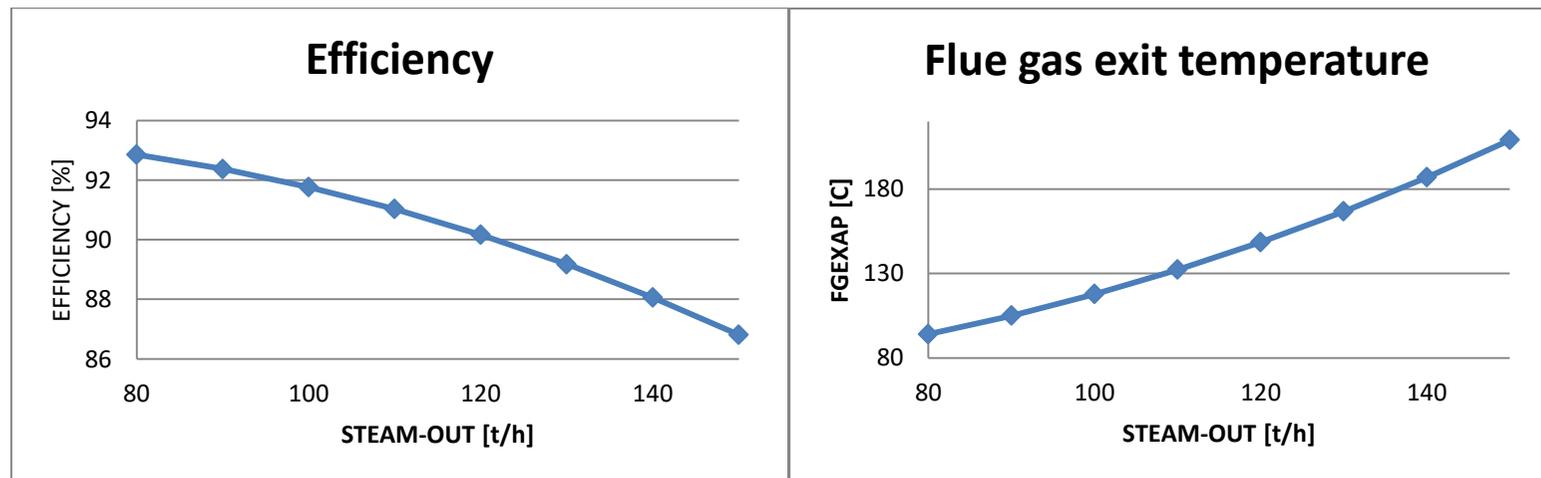
Table 3.3 concerns the influence of the steam superheater No 2 HTC (a fall of this HTC can be caused for example by soot fouling of this heat exchanger). This effect is partially compensated by increased function of the SSH1 in combination with the following steam cooler.

Tab 3.1. Simulation for different steam production (ST-OUT)

Task: COAL_BOILER_SMALL8 (simulation - HTC fixed, const STEAMEX temperature)

Simulation #1 [input is STEAM-OUT]

Series	S<ST-OUT>	V<EFFICIENCY>	S<Q-FGLOSS>	S<COAL-IN>	S<AIR-IN>	S<SPRAY>	T<FG1>	T<STEXSSH1>	T<STEXSPRAY>	T<STEXSSH2>	T<FGEXAP>	T<AIREXAP>
	[T/HR]	[1]	[GJ/HR]	[T/HR]	[T/HR]	[T/HR]	[C]	[C]	[C]	[C]	[C]	[C]
	Input	Output	Output	Output	Output	Output	Output	Output	Output	Output	Output	Output
1	80	92,85292914	8,50188459	19,19111575	102,5731568	9,690217867	956,2247659	454,3123822	363,1765612	535	94,05378144	309,4100118
2	90	92,37542329	11,15795074	21,701608	115,9912987	12,94929497	1007,251909	474,2887568	361,4245109	535	105,0266712	332,326049
3	100	91,76588338	14,4877293	24,27306376	129,7352799	16,26068888	1055,951631	492,9261084	360,5783343	535	117,7422993	357,4469795
4	110	91,02922149	18,61236385	26,91644521	143,8636914	19,60796161	1102,770289	510,1644703	360,2968701	535	132,2338369	384,2980119
5	120	90,16710622	23,66883071	29,64414717	158,4427812	22,97963902	1148,043121	526,040976	360,3798667	535	148,541765	412,4712872
6	130	89,17879634	29,81435233	32,47039654	173,5485897	26,36802184	1192,025261	540,637653	360,7007567	535	166,7164302	441,6134412
7	140	88,06137379	37,2328315	35,41183449	189,2700611	29,76785976	1234,915385	554,0533625	361,1760945	535	186,8235531	471,4164662
8	150	86,80974768	46,14339512	38,48828959	205,7131754	33,17492361	1276,880437	566,3844537	361,7491516	535	208,949556	501,604256

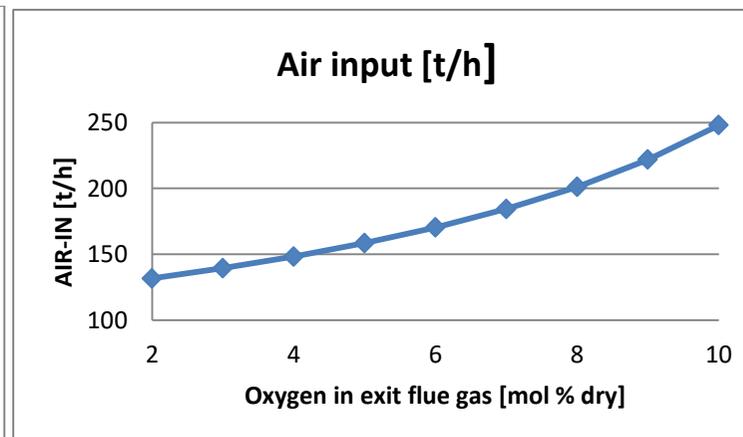
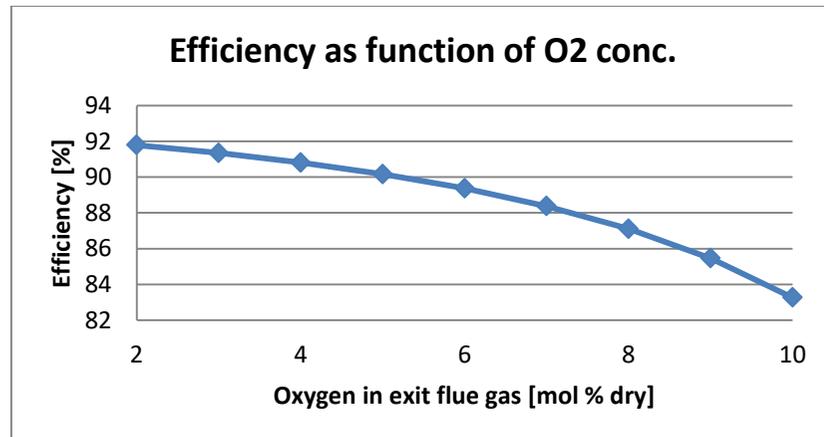


Tab 3.2: Simulation for different exit oxygen concentration

Task: COAL_BOILER_SMALL8 simulation - HTC fixed, const STEAMEX temperature)

Simulation #2 [input is O2 in FG5]

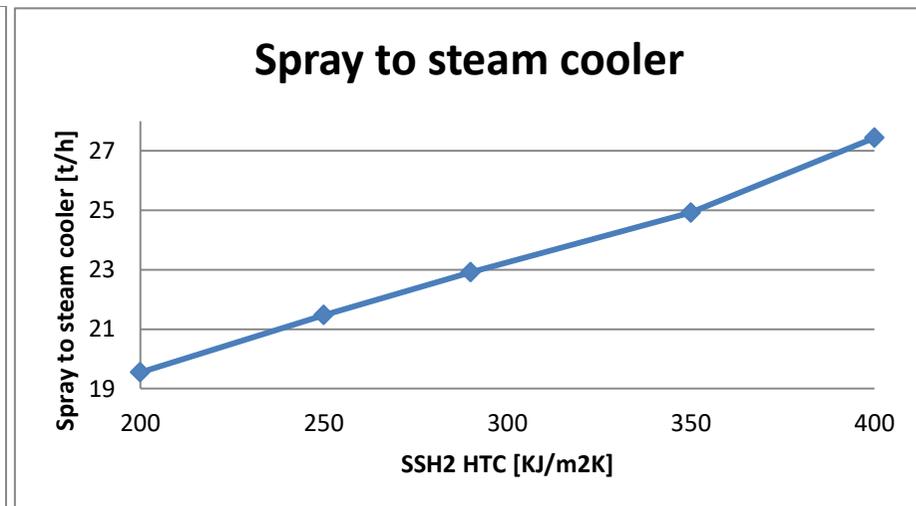
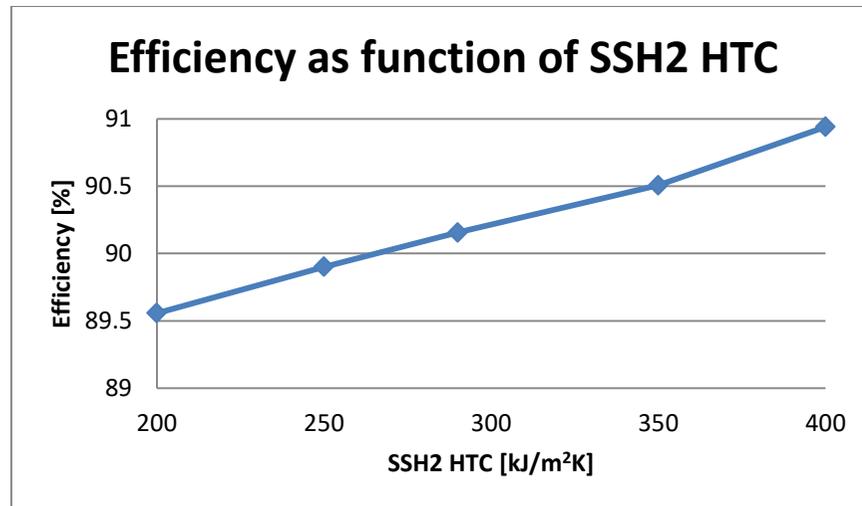
Series	C<FG5:O2>	V<EFFICIENCY>	S<Q-FGLOSS>	S<COAL-IN>	S<AIR-IN>	S<SPRAY>	T<FG1>	T<STEXSSH1>	T<STEXSPRAY>	T<STEXSSH2>	T<FGEXAP>	T<AIREXAP>
	[%]	[1]	[GJ/HR]	[T/HR]	[T/HR]	[T/HR]	[C]	[C]	[C]	[C]	[C]	[C]
	Input	Output	Output	Output	Output	Output	Output	Output	Output	Output	Output	Output
1	2	91,79111839	17,87258338	29,12060297	131,531893	21,55774916	1186,168563	505,856696	356,9522113	535	134,3097178	386,5042934
2	3	91,34785057	19,43420182	29,26163331	139,348056	22,0365408	1174,024574	512,354177	357,985397	535	138,2285376	394,7169709
3	4	90,81489792	21,33195511	29,43304427	148,2350335	22,51120562	1161,330491	519,0823568	359,1238071	535	142,9163355	403,3782399
4	5	90,16710622	23,66883071	29,64414717	158,4427812	22,97963902	1148,043121	526,040976	360,3798667	535	148,541765	412,4712872
5	6	89,36975552	26,59173786	29,90822509	170,3102717	23,43943546	1134,110427	533,2291972	361,7684038	535	155,3270386	421,954844
6	7	88,37371503	30,31708352	30,24484588	184,3112352	23,88783954	1119,467529	540,6462453	363,3075273	535	163,5724606	431,7490139
7	8	87,10735587	35,17646689	30,68399482	201,1328316	24,32167807	1104,030054	548,2926891	365,0200405	535	173,6967332	441,7115247
8	9	85,46233721	41,70389951	31,27396296	221,8200835	24,73726676	1087,682369	556,1730891	366,9358762	535	186,3071967	451,5955267
9	10	83,26687012	50,81729167	32,09776176	248,0645451	25,13019994	1070,255434	564,3006653	369,0965666	535	202,3324043	460,9691826



Tab 3.3: Simulation for different HTC of the Steam Superheater 2

Task: COAL_BOILER_SMALL8 simulation - HTC fixed, const STEAMEX temperature
Simulation #3 [input is HTC SSH2]

Series	V<HTC-SSH2>	V<EFFICIENCY>	S<Q-FGLOSS>	S<COAL-IN>	S<AIR-IN>	S<SPRAY>	T<FG1>	T<STEXSSH1>	T<STEXSPRAY>	T<STEXSSH2>	T<FGEXAP>	T<AIREXAP>
	[1]	[1]	[GJ/HR]	[T/HR]	[T/HR]	[T/HR]	[C]	[C]	[C]	[C]	[C]	[C]
	Input	Output	Output	Output	Output	Output	Output	Output	Output	Output	Output	Output
1	200	89,5567537	25,90150747	29,84617972	159,5226099	19,54836165	1161,431487	559,0182813	402,603363	535	159,0846291	440,3026183
2	250	89,90062154	24,63990624	29,73201876	158,9124395	21,47198575	1153,914137	540,7957076	377,9856341	535	153,148729	424,708767
3	290	90,15586507	23,70967771	29,64784337	158,4625368	22,91574216	1148,291593	526,6747705	361,0926449	535	148,7362223	412,9902363
4	350	90,5063322	22,44095728	29,5330382	157,8489232	24,9203263	1140,510595	506,4348325	340,2711552	535	142,6685614	396,6958064
5	400	90,94036945	20,88326053	29,39208387	157,095547	27,43888146	1130,773154	479,9756094	231,9632401	535	135,1396028	376,1791614



3.5 Parametric sensitivity

The parametric sensitivity in RECON is calculated in menu *Calculate/Parametric sensitivity*. For the coal consumption COAL-IN the vector of parametric sensitivities is

REPORT ON PARAMETRIC SENSITIVITY

MF COAL-IN

GIVEN VARIABLE IS SENSITIVE TO:

Type	Variable	Sensitivity	Unit
C	O2<FG5>	23.520	[T/HR] / [1]
MF	BLOWDOWN	0.049	[T/HR] / [T/HR]
MF	ST-OUT	0.277	[T/HR] / [T/HR]
P	BOILER	0.017	[T/HR] / [MPAG]
P	FW	-3.65E-3	[T/HR] / [MPAG]
P	ST-OUT	-0.142	[T/HR] / [MPAG]
T	FWTOECO	-0.059	[T/HR] / [C]
T	STEXSSH2	0.034	[T/HR] / [C]
V	HTC-AP	-1.46E-3	[T/HR] / [1]
V	HTC-BOILER	-3.81E-3	[T/HR] / [1]
V	HTC-ECO	-2.63E-3	[T/HR] / [1]
V	HTC-SSH1	-2.57E-3	[T/HR] / [1]
V	HTC-SSH2	-2.02E-3	[T/HR] / [1]

For example, the parametric sensitivity of coal consumption to steam production ST-OUT is 0.277 t/t. The parametric sensitivity to oxygen concentration in flue gases (O2<FG5>) is 0.2352 t/mol % (results above are given in RECON's intrinsic units where composition is in mole fractions).

Results obtained by Parametric sensitivities [see Eq. (2-6)] can be easily compared with results obtained by Simulations presented in Section 3.4. Very illustrative are curvatures in figures presented in Section 3.4.

4 A RANKINE STEAM CYCLE

4.1 Cycle description

The PPMA of a steam cycle will be illustrated on the case of the following flowsheet:

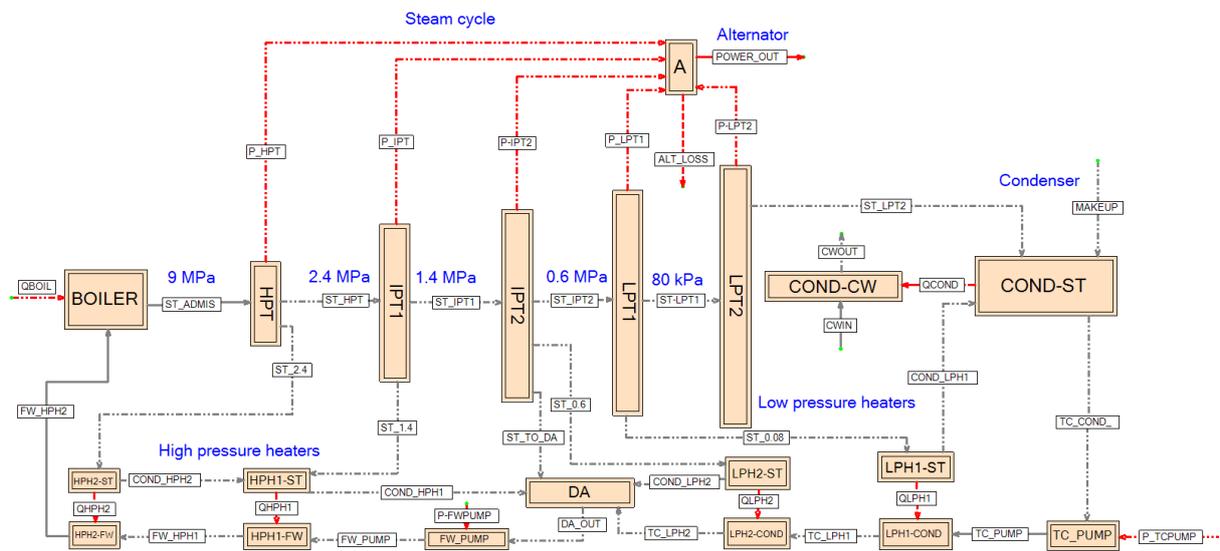


Fig. 4.1: Steam cycle flowsheet for Data Reconciliation

This is a little bit simplified model of a steam cycle which contains the following main parts (for the original, more complex model, look at [5] where is also a detailed description of the condenser including problems connected with its monitoring):

- steam is generated in the BOILER node (heat flux QBOIL represents the heat power of the boiler)
- the turbine consists of high pressure (HPT), intermediate pressure (IPT) and low pressure (LPT) sections. IPT and LPT turbines have two segments (IPT1, IPT2, LPT1 and LPT2). Steam is extracted at pressures 2.4 MPa, 1.4 MPa, 0.6 MPa and 80 kPa.
- there are 2 low pressure heaters of condensate (LPH1 and LPH2) and 2 high pressure heaters of feed water (HPH1 and HPH2).
- There is one condensate pump TC_PUMP and one feed water pump FW_PUMP.
- Naming convention for streams is
 - COND – steam condensate from heaters
 - FW – feed water
 - P – power
 - Q – heat flux
 - ST – steam

- TC – turbine condensate (train from the condenser)

As in the previous Chapter we will start with a redundant model used for DRV and for identification of model parameters from measured data. Basic information about such model follows:

G L O B A L D A T A

Number of nodes	20
Number of heat nodes	20
Number of streams	41
Number of energy streams	15
Number of components	1
Number of heat functions	1
Number of temperatures	21
Number of pressures	11
Number of wetnesses	4
Number of auxiliaries	17
Number of measured variables	25
Number of adjusted variables	23
Number of non-measured variables	61
Number of observed variables	61
Number of non-observed variables	0
Number of free variables	0
Number of equations (incl. UDE)	65
Number of independent equations	64
Number of user-defined equations (UDE)	26
Degree of redundancy	3

Note the difference between number of all equations and number of independent equations caused by a cyclic character of the flowsheet.

4.2 Model modification

The starting point of modeling is the DR model with DoR = 3. Again we can see a report about model redundancy (variables with very small adjustability were omitted):

R E D U N D A N T M E A S U R E M E N T S

Type	Variable	Adjustability
HF	POWER_OUT	0.025607
MF	CWIN	0.000003
MF	FW_HPH2	0.438529
MF	ST_ADMIS	0.436934
MF	TC_PUMP	0.451941
P	STEAM_0.08	0.000133
P	STEAM_1.4	0.000022
P	STEAM_2.4	0.000749
P	STEAM_ADMIS	0.000341
T	CWIN	0.000043
T	LPT_OUT	0.000616
T	STEAM_0.6	0.000023
T	STEAM_ADMIS	0.054444
X	XTOCOND	0.522666

The redundancy is caused mainly by 4 measured streams: generated electricity POWER_OUT, admission steam ST_ADMIS, turbine condensate TC_PUMP and feed water FW_HPH2. The last three were therefore set as unmeasured and after that the system is just determined (DoR = 0). The detailed mass and energy balance is completely defined by the measured generated electricity and by the state of streams (temperature, pressure and wetness). The just determined flowsheet is shown in the next figure:

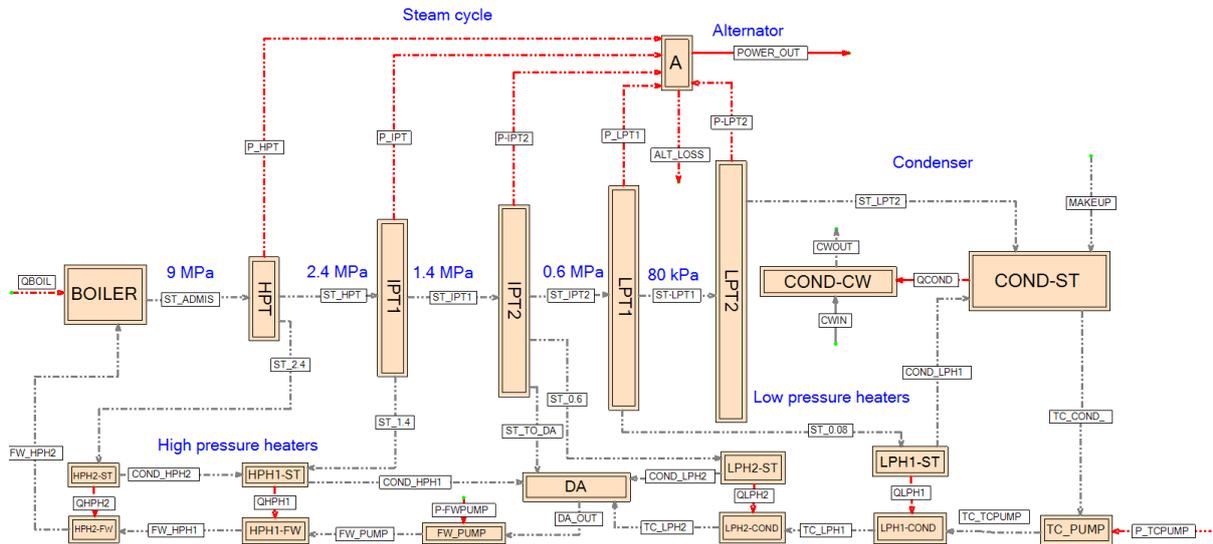


Fig. 4.2: Steam cycle flowsheet for simulation

The next step is the interchange of process variables among input and output subsets. There are 10 model parameters which are outputs in the DR mode of calculations. They are:

- isentropic efficiencies (IEE) of 5 turbine segments
- heat transfer coefficients (HTC) of 2 turbine condensate heaters, 2 feed water heaters and one condenser.

These unmeasured variables will be replaced by measured ones, mostly temperatures. In heaters they are the output temperatures of heated streams and in turbine segments they are temperatures of output steam. In the case of the two last turbine segment those variables are the output steam wetnesses.

4.3 Simulation

In this section we will show 4 examples of creating operational characteristics of the steam cycle (trends of important cycle output variables in dependence on selected input variables). The input variables will be

- The electricity produced **POWER_OUT**
- HTC of the HPH1 **HTC_HPH1**
- HTC of the HPH2 **HTC_HPH2**
- HTC of the condenser **HTC_COND**.

The outputs will be

- **V<HEATRATE>** - heat rate of the steam cycle HRSC (see the Note below)
- **V<EFF_CYCLE>** - efficiency of the cycle
- **S<QBOIL>** - heat input to boiler
- **S<ST_ADMIS>** - admission steam flowrate
- **S<QCOND**
- **S<QHPH1>**- heat flux in HPH1
- **T<FW_HPH1>** - temperature of FW from HPH1
- **S<QHPH2>**- heat flux in HPH2
- **T<FW_HPH2>** - temperature of FW from HPH2
- **P<COND_VAC>** - vacuum in the condenser
- **T<COND_SAT>** - temperature of steam out of the steam cooler

In all following examples the temperature of the cooling water is 15 °C (input) and 25 °C (output). The cooling water flowrate is calculated to match a heat balance of the condenser.

Note: The heat rate of the steam cycle HRSC is defined here as

$$\text{HRSC} = (\text{energy accepted in the boiler and in pumps})/(\text{electricity produced}) \text{ [MW/MW]} \quad (4-1)$$

The common definition of the overall Power Plant Heat Rate (HRPP) is

$$\text{HRPP} = \text{energy input}/\text{electricity output} \quad [\text{GJ/MWh}] \quad (4-2)$$

The relation between HRPP and the HRSC defined above is thus

$$\text{HRPP} = 3.6 \text{ HRSC}/\text{BEFF} \quad (4-3)$$

where BEFF is the boiler efficiency (see the Chapter 3). It should be noted that the calculation of HRPP in practice is much more complicated than is shown in this report due to complexity of real power plants (electric energy needed for pumps, fans, steam needed for soot blowing, etc.).

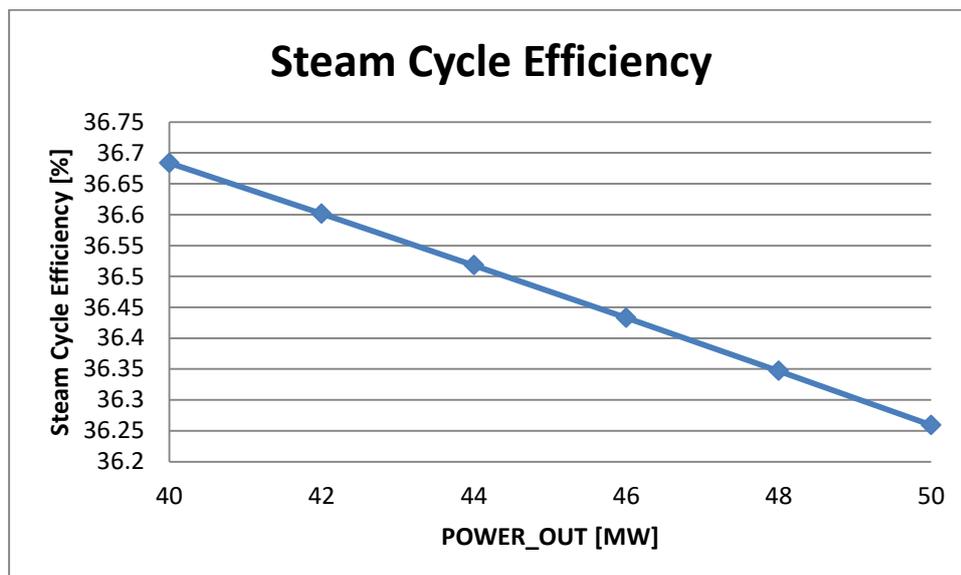
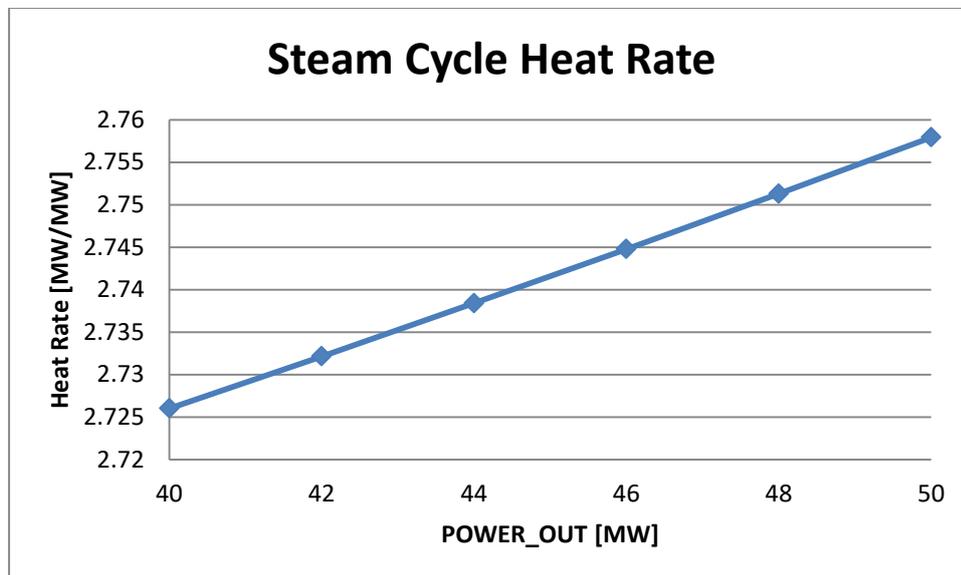
Selected results of simulation are shown in 4 following tables.

Tab 4.1: Simulation for different electricity production (POWER_OUT)

Task: STEAM_CYCLE_SMALL_7FINAL (calculates heaters' temperatures, cond. pressure, steam temp.)

Simulation #1 [input is power-out].

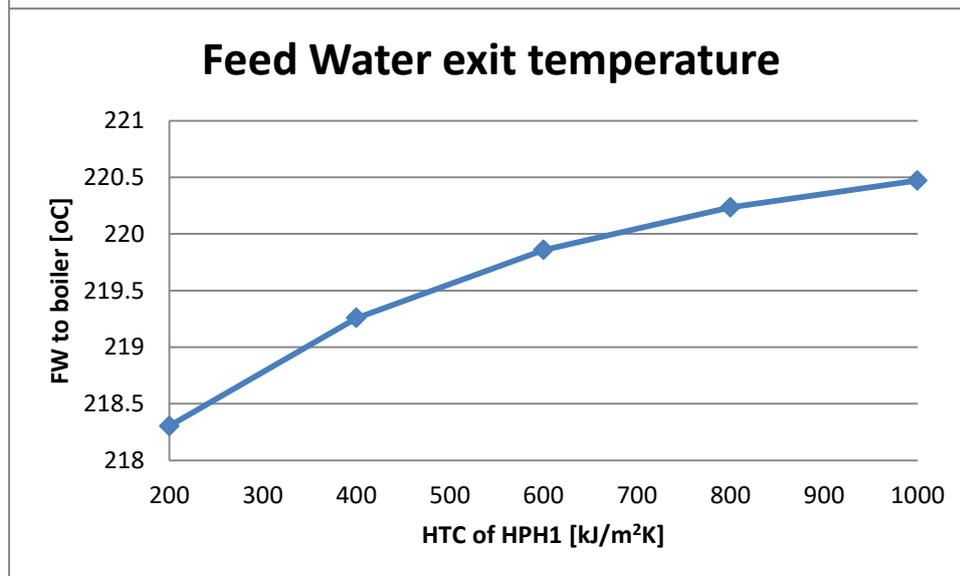
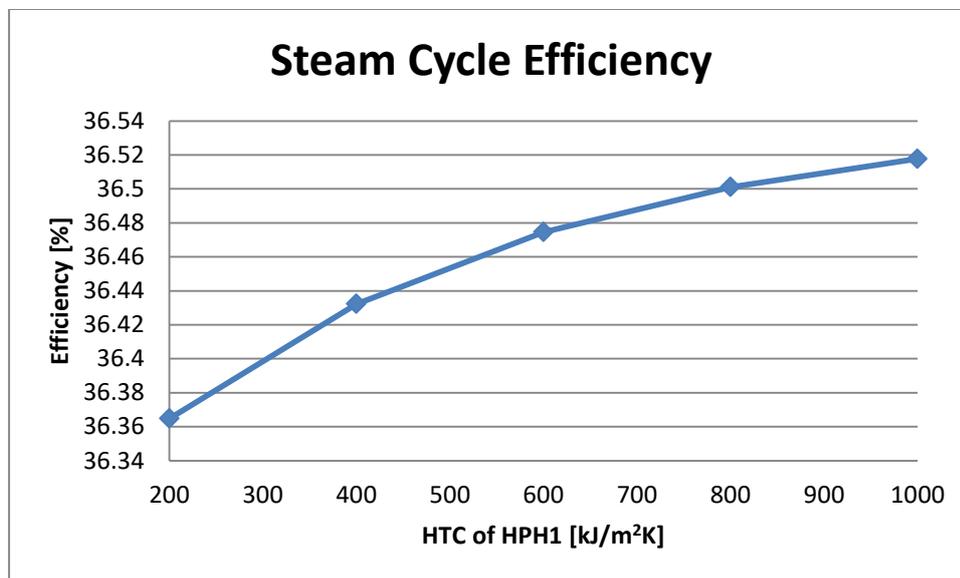
Series	S<POWER_OUT>	V<HEATRATE>	V<EFF_CYCLE>	S<QBOIL>	S<ST_ADMIS>	S<QCOND>
	[MWH/H]	[1]	[1]	[MWH/H]	[T/H]	[MWH/H]
	Input	Output	Output	Output	Output	Output
1	40	2,726013767	36,6836005	108,7586322	156,8635231	68,80055069
2	42	2,732133085	36,6014381	114,453185	164,9597099	72,49758958
3	44	2,738389968	36,51780834	120,1782251	173,08339	76,22515859
4	46	2,744777482	36,43282585	125,9342578	181,2351326	79,98376419
5	48	2,751289669	36,34659089	131,7217796	189,4155565	83,77390409
6	50	2,757921452	36,25919075	137,5412835	197,6253292	87,5960726



Tab 4.2: Simulation for different HTC of the High Pressure Heater 1 (HTC_HPH1)

Task: STEAM_CYCLE_SMALL_7FINAL (calculates heaters' temperatures, cond. pressure, steam temp.)
Simulation #2 [input is HPH1 HTC]

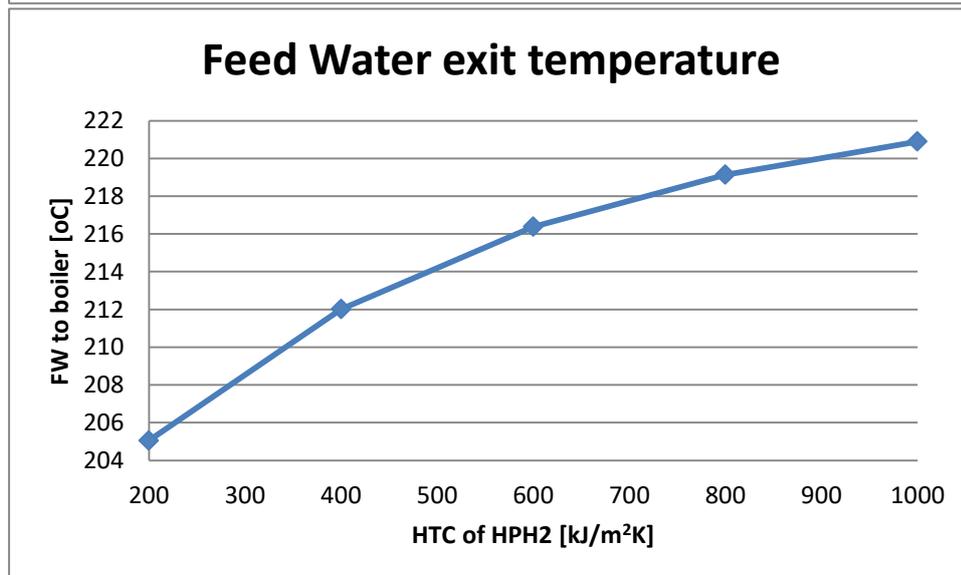
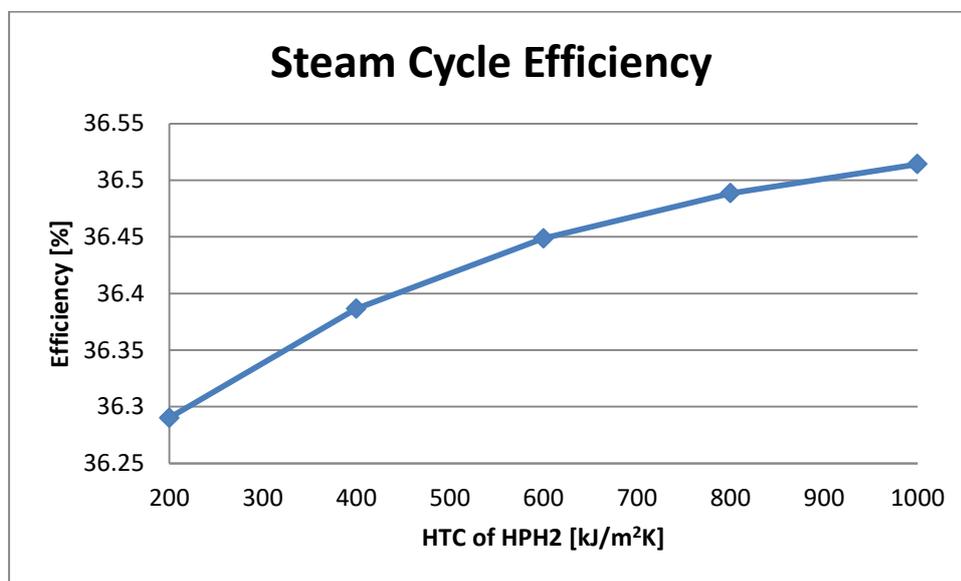
Series	V<HTC_HPH1>	V<HEATRATE>	V<EFF_CYCLE>	S<QHPH1>	T<FW_HPH1>	S<QHPH2>	T<FW_HPH2>
	[1]	[1]	[1]	[MWH/H]	[C]	[MWH/H]	[C]
	Input	Output	Output	Output	Output	Output	Output
1	200	2,749911719	36,36480376	2,887727118	175,7589588	9,140041966	218,3027684
2	400	2,744820106	36,43226009	4,68577396	184,2670498	7,550313786	219,2567309
3	600	2,741636242	36,47456889	5,808594852	189,5507017	6,558787872	219,8570157
4	800	2,739644166	36,50109063	6,510468223	192,8412159	5,939493913	220,2341745
5	1000	2,738398148	36,51769925	6,949211944	194,8931181	5,552578341	220,4707246



Tab 4.3: Simulation for different HTC of the High Pressure Heater 2 (HTC_HPH2)

Task: STEAM_CYCLE_SMALL_7FINAL (calculates heaters' temperatures, cond. pressure, steam temp.)
 Simulation #3 [input is HPH2 HTC]

Series	V<HTC_HPH2>	V<HEATRATE>	V<EFF_CYCLE>	S<QHPH1>	T<FW_HPH1>	S<QHPH2>	T<FW_HPH2>
	[1]	[1]	[1]	[MWH/H]	[C]	[MWH/H]	[C]
	Input	Output	Output	Output	Output	Output	Output
1	200	2,755570796	36,29012187	6,526504586	193,568757	2,419069808	205,0569315
2	400	2,748269007	36,38653994	6,569676018	193,4766131	3,956362114	212,017866
3	600	2,743592343	36,4485636	6,597153175	193,4175434	4,94178105	216,3803586
4	800	2,74059046	36,48848723	6,614719383	193,379608	5,574640152	219,1414667
5	1000	2,738665384	36,51413589	6,625955297	193,3552731	5,980623001	220,8961275



Tab 4.4: Simulation for different HTC of the Condenser (HTC_COND)

Task: STEAM_CYCLE_SMALL_7FINAL (calculates heaters' temperatures, cond. pressure, steam temp.)

Simulation #4 [input is condenser HTC]

Series	V<HTC_COND>	V<HEATRATE>	V<EFF_CYCLE>	P<COND_VAC>	T<COND_SAT>
	[1]	[1]	[1]	[MPA]	[C]
	Input	Output	Output	Output	Output
1	400	3,07355279	32,53563769	0,026152409	65,97398607
2	600	2,875244922	34,77964581	0,011120989	47,90129174
3	800	2,80128146	35,69794804	0,007502697	40,29834738
4	1000	2,762502522	36,19906198	0,005977931	36,09307349
5	1200	2,738750888	36,51299592	0,005159974	33,4372123
6	1400	2,722822797	36,72659128	0,004658053	31,62049031
7	1600	2,711487812	36,88012152	0,004322765	30,30968066
8	1800	2,703077927	36,99486389	0,004085426	29,32727856

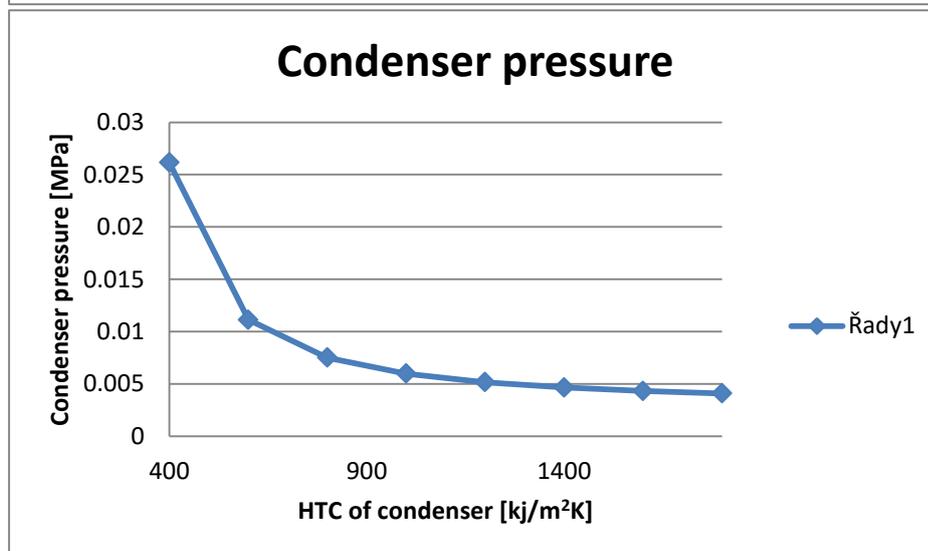
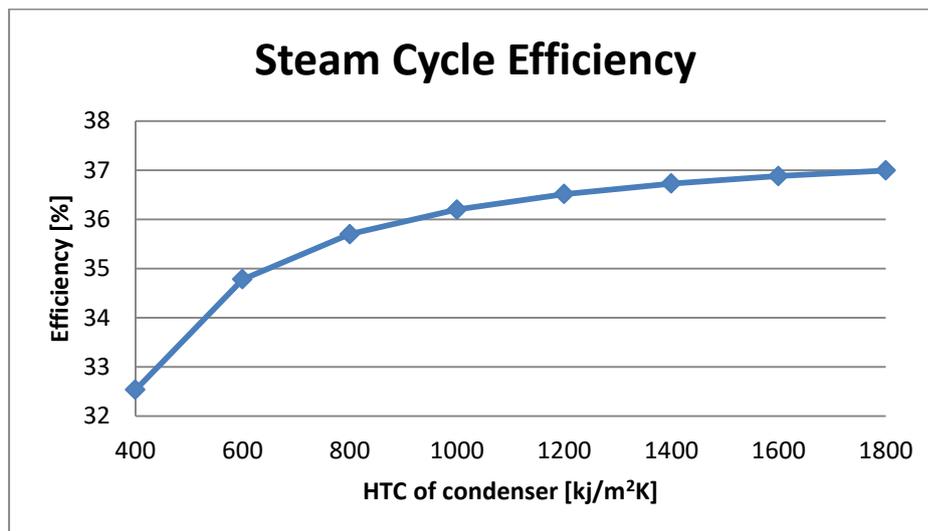


Table 4.1 shows the influence of the steam cycle load (electricity production) on the cycle's efficiency. The small fall of the efficiency is caused by the relative decrease of heat transfer from turbine to condensate and feed water heaters (lower Carnotization of the cycle).

Table 4.2 concerns the influence of the High Pressure Heater No 1 HTC on the cycle functioning. The influence on the cycle's efficiency and on the FW temperature on the Boiler's inlet is small. This can be explained by the fact that the HPH1 function is partially taken over by increased function of HPH2.

Table 4.3 concerns the influence of the High Pressure Heater No 2 HTC on the cycle functioning. The influence on this HPH is much more significant than in the preceding case of HPH1.

Table 4.4 studies the influence of very important part of the steam cycle – the condenser. There are several important variables influencing condenser's function. Here the HTC was selected as its degradation is frequently caused by fouling. Trends show how HTC's decrease influences significantly condenser's vacuum and thus the efficiency of the whole cycle.

4.4 Parametric sensitivity

The parametric sensitivity in RECON is calculated in menu *Calculate/Parametric sensitivity*. For the steam cycle efficiency EFF_CYCLE the vector of parametric sensitivities is

REPORT ON PARAMETRIC SENSITIVITY

Type Variable

V EFF_CYCLE

GIVEN VARIABLE IS SENSITIVE TO:

Type Variable	Sensitivity	Unit

HF POWER_OUT	-0.042	[1] / [MWH/H]
P STEAM_0.08	-3.191	[1] / [MPA]
P STEAM_0.6	-1.106	[1] / [MPA]
P STEAM_1.4	-0.104	[1] / [MPA]
P STEAM_2.4	0.237	[1] / [MPA]
P STEAM_ADMIS	0.451	[1] / [MPA]
T CWIN	-0.047	[1] / [C]
T CWOUT	-0.079	[1] / [C]
T LPT_OUT	0.00E+0	[1] / [C]
T STEAM_ADMIS	0.017	[1] / [C]
V EFF_HPT	0.098	[1] / [1]
V EFF_IPT1	0.035	[1] / [1]
V EFF_IPT2	0.049	[1] / [1]
V EFF_LPT1	0.119	[1] / [1]
V EFF_LPT2	0.117	[1] / [1]
V HTC_COND	1.29E-3	[1] / [1]
V HTC_HPH1	9.37E-5	[1] / [1]
V HTC_HPH2	1.21E-4	[1] / [1]
V HTC_LPH1	1.74E-4	[1] / [1]
V HTC_LPH2	0.00E+0	[1] / [1]

For example, the parametric sensitivity of the efficiency to the electricity generated POWER_OUT is -0.042 [1/MW]. This means that increasing the electricity generation by 1 MW the efficiency decreases by 0.042 %.

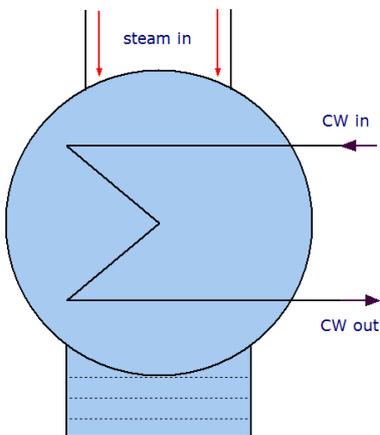
Parametric sensitivities can be compared also with simulations presented in the preceding Section (Table 4.1). The base case electricity generation was 44 MW. The difference of efficiencies between 44 and 46 MW is -0.085 % which means ca 0.042 %/MW.

5 INCLUSION OF EMPIRICAL MODELS IN RECON

Model parameters (HTC, IEE, ...) so far were supposed to be constants independent on other model variables. It is well known that this simplification is not justified in many situations. Neglecting parameters' variability frequently limits the application of modeling to a close vicinity of a solution point where parameters can be supposed constant. Problem with inadequacy of models in a broader range of variables can be solved by inclusion of further model equations describing relations of model parameters with other model variables. Such equations in RECON (User Defined Equations) can be of two kinds: (1) Detailed design/simulation models published in literature or based on proprietary information from equipment vendors. (2) empirical (regression) models based on statistical analysis of historical process data obtained in a DRV process. The second approach is called **Data driven modeling** and such models are sometimes called "**hybrid models**".

5.1 Modeling a steam condenser

Recall the Rankine cycle presented in the previous Chapter. Important part of it is a condenser:



HTC of such condenser is influenced mostly by

- cooling water flowrate (increases heat transfer in tubes)
- cooling water temperatures (increases heat transfer in tubes)
- condenser's heat power (influences the amount of condensed steam in the shell space)
- pressure/temperature in the shell side
- fouling on the tube side.

Some of these variables are not independent. For example the cooling water flow rate is strongly correlated with condenser's power. Correlated are also temperatures CW_{in} and CW_{out} (condensers are usually performed with constant cooling water temperature difference $CW_{out} - CW_{in}$).

By a detailed correlation and regression analysis of 9 months process data [9] was found that the condenser's HTC can be modelled by a linear model

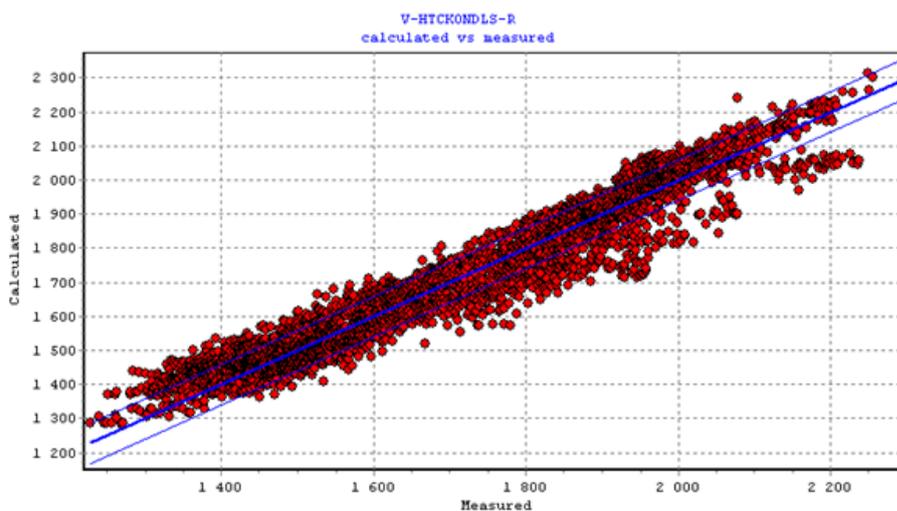
$$HTC = a + b \cdot F_{CW_{IN}} + c \cdot T_{CW_{OUT}} \quad (5-1)$$

where $F_{CW_{IN}}$ is flow of the cooling water

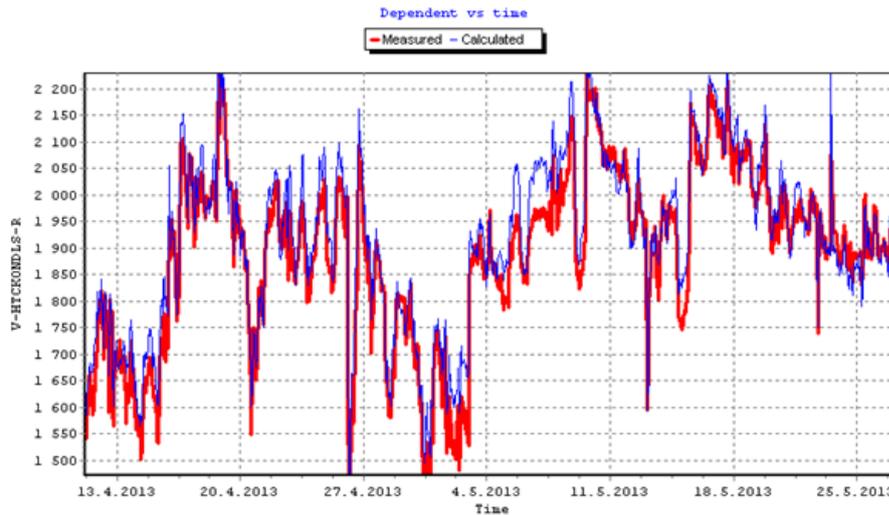
$T_{CW_{OUT}}$ is temperature of cooling water leaving condenser

a , b and c are regression coefficients.

The coefficient of determination of this model $R^2 = 0.933$. In the next figure is comparison of measured and calculated HTC:



The next figure shows how the model predicts the real HTC:



Note: Recon has a built in correlation and regression module which speeds up creation and comparison of statistical models on the basis of RECON's historical database. Quite complex multivariate linear or nonlinear models can be created and tested by several key strokes. This module has a full graphical functionality and can efficiently deal with outliers.

Our long term experience is that such empirical models provide usually better results than other sources of information and can be useful in PPMA.

Note: Developing empirical models requires long term historical data and some experience with statistical methods. Process variables are frequently correlated (for example due to process control) and models of similar quality can be based on different sets of variables. For example, in the condenser example above, the cooling water flowrate is strongly correlated with the condenser's heat load which can be used instead of the the CW flowrate in the model.

5.2 Inclusion of empirical models in RECON

UDEs can be used in both calculation modes – DR and Direct calculation. In the first case such models can help with the observability of the whole system. Any use of UDEs to increase the redundancy during DR is disputable and depends on quality of models included (DR should be applied to exact models only). In the Direct calculation mode UDEs helps to increase a region in which simulation can predict plant performance.

A Direct calculation is based on just determined models. The inclusion of UDEs in the overall RECON model therefore requires maintaining both the non-redundancy and the observability. The solution of this requirement is usually simple and straightforward.

For example in the case of the condenser model (5-1) there is one equation defining HTC added and at the same time the HTC is changed from measured to unmeasured. Therefore, in the sense of Eq. (2-2), the observability and redundancy is not changed.

6 DISCUSSION AND CONCLUSIONS

The Plant Performance Monitoring and Analysis (PPMA) is based on comparison of actual plant states with a reference plant state. This was thoroughly discussed in Chapter 1. There are two basic possibilities:

- To compare a *Corrected actual state* with the *Reference state* (most frequently a *Design state*). This is a way of the **Plant Degradation Monitoring**.
- To compare an *Actual plant state* with the *Expected plant state*. This means the **Plant Performance Monitoring**.

Both variants need calculations transforming a plant from one state to another with the aid of a plant model. There are at least three possibilities how to do it:

1. To use parametric sensitivities for the approximate corrections
2. To use operational curves created by simulation
3. To use simulation for predicting plant's behavior under a changed state.

It was shown in this report that any of these ways can be done with the aid of RECON. The first two methods are only approximate as changes caused by individual variables are not additive for nonlinear models. The third, simulation method, is clearly superior to the two previous ones. In this way it is possible to calculate

- *Corrected state* used for degradation monitoring
- *Expected state* used for performance monitoring
- state defined *ad hoc* by user (general WiQ, off line optimization).

See the next table:

Table 6.1: Use of the simulation by RECON in PPMA

Input parameters	Input variables	Result	Compare with	Target
Actual equipment parameters	Design process variables values	Corrected state	Reference state	Degradation monitoring
Design equipment parameters	Actual process variables variables	Expected state	Actual state	Performance monitoring
Actual equipment parameters	Modified process variables	State defined by user (WiQ)	Actual state	General WiQ, off line optimization

It was described in Chapter 2 how to change a model from one calculation mode to another one (see also Appendix 1). Especially, the way of changing a data reconciliation model (serving for model's parameters identification) to a just determined model serving for simulation is of a key importance.

This approach requires to create and to maintain several models of one plant. To manage this problem RECON enables one to create so called *Variants of Tasks* which are stored in one database.

A main critical point of these efforts is usually the quality of models. Throughout this report it was supposed that the main model parameters (heat transfer coefficients, turbine isentropic efficiencies) are constants. This can be a serious problem of this approach. In general, there are two methods how to improve the quality of models used in PPMA:

- To use detailed design/simulation models published in literature or based on proprietary information from equipment vendors
- To use empirical models based on statistical analysis of historical process data.

It is our long term experience that it is not easy to come to an acceptable agreement between process data and theoretical models (the only exceptions are mass and energy balances). On the other hand side the empirical models sometimes give surprisingly good results. This subject is discussed in Chapter 5.

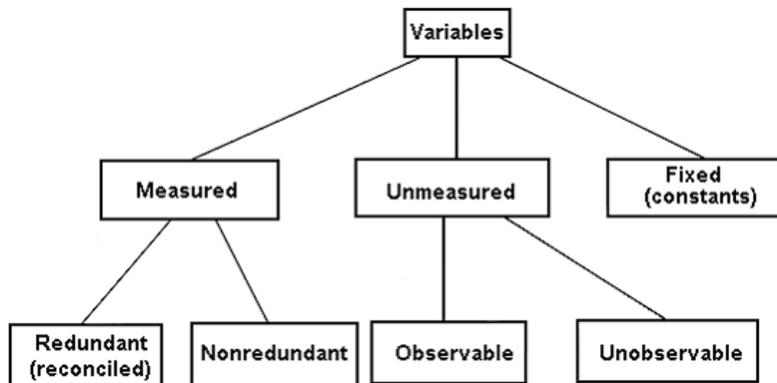
LITERATURE

- [1] V.V.Veverka and F. Madron: *Material and Energy Balancing in the Process industries*. Elsevier, Amsterdam 1997
- [2] F. Madron, Process Plant Performance. *Measurement and data processing for optimization and retrofits*. Ellis Horwood New York, 1992
- [3] V.V. Veverka: *Balancing and Data Reconciliation Minibook*,
www.chemplant.cz
- [4] *Balancing and Data Reconciliation of a coal fired boiler. Monitoring boiler efficiency*. Report CPT 321-13. Usti nad Labem 2013
- [5] *Balancing and Data Reconciliation of a steam turbine with auxiliaries*. Report CPT 322-13. Usti nad Labem 2013
- [6] *Modeling a 3-zone Feedwater Heater*. Report CPT 325-13. Usti nad Labem 2013
- [7] *Process data validation in practice. Applications from chemical, oil, mineral and power industries*. Report CPT 229-07. Usti nad Labem 2007
- [8] R.R.Gay, C.A.Palmer and M.R Erbes: *Power Plant Performance Monitoring*. Tech Books International, New Delhi 2006
- [9] V. Madron: *Condenser of a Steam Turbine* (in Czech). BC Thesis. . J.E.Purkyně University in Ústí nad Labem, Faculty of Production Technology and Management, Department of Energetics and Electrotechnics, Ústí nad Labem, 2015, 51 pages

APPENDIX 1: SOLVABILITY AND OBSERVABILITY IN RECON

A1.1: Basic situations for linear models

Please recall Fig. 2.2.



A1.1.1 Just determined observable system

Let's start with a simple mass balance flowsheet shown in the next flowsheet (full lines are measured, dash-dotted lines are unmeasured). This system generates 4 mass balance equations and has 4 unknown flowrates. This is just determined system (no redundancy, all unmeasured variables are observable).

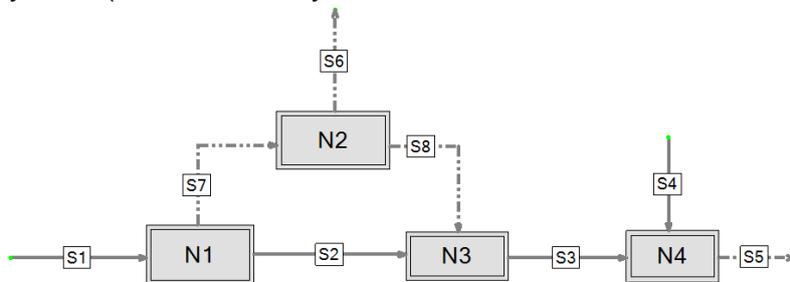


Fig. A.1: A fully observable system, zero redundancy

See also the excerpt from results:

Number of measured variables	4
Number of non-measured variables	4
Number of observed variables	4
Number of equations	4
Degree of redundancy	0

In this case 4 unmeasured flows can be calculated.

A1.1.2 Redundant observable system

The next Fig. A.2 shows an example of a system with data reconciliation:

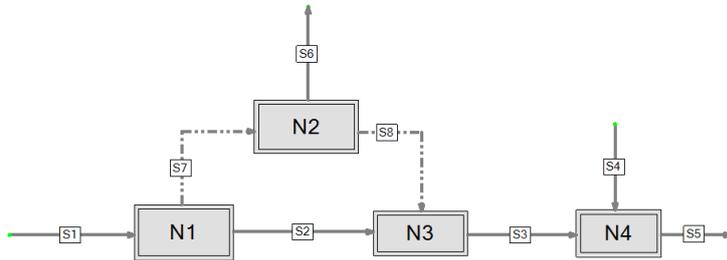


Fig. A.2: A fully observable system, 2 degrees of redundancy

See also the excerpt from results:

Number of measured variables	6
Number of non-measured variables	2
Number of observed variables	2
Number of equations	4
Number of non-observed variables	0
Number of independent equations	4
Degree of redundancy	2

We can look which flows are redundant (menu Calculate/Classification)

REDUNDANT MEASUREMENTS			
Type	Variable	Adjustability	
MF	S1	0.350775	KG/S
MF	S3	0.216093	KG/S
MF	S4	0.172182	KG/S
MF	S5	0.392338	KG/S
MF	S6	0.046343	KG/S

Question: How to change this system to a just determined system (nonredundant and observable)? See also the variables' interchange rules in Section 1.3.

Note that the flow S2 is nonredundant and therefore it can't be changed to unmeasured.

We suppose that the number of measured variables changed to unmeasured must be 2, but this selection is not arbitrary. RECON does not make possible to select these 2 variables directly. The only way is to change variables' type one by one. If we need to decrease the degree of redundancy by one, we must put one redundant variable as unmeasured.

By putting S1 among unmeasured, we get the following list of redundant measurements:

REDUNDANT MEASUREMENTS

Type	Variable	Adjustability
MF	S3	0.041622
MF	S4	0.166776
MF	S5	0.377706

MF	S3	0.041622
MF	S4	0.166776
MF	S5	0.377706

The next measured variable changed to unmeasured can be S3, S4 or S5.

A1.1.3 Unobservable system

The next case contains some unobservable variables:

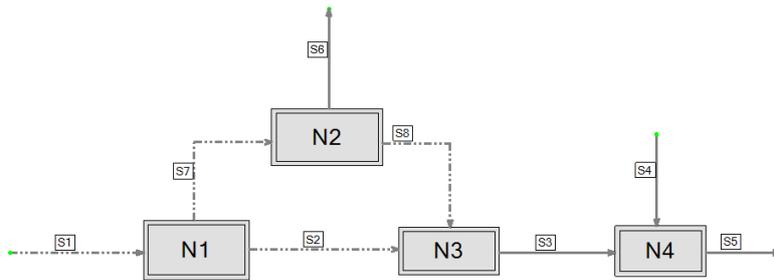


Fig. A.3: An unobservable system, 1 degree of redundancy

See also the excerpt from results:

Number of measured variables	4
Number of non-measured variables	4
Number of observed variables	1
Number of non-observed variables	3
Number of free variables	1
Number of equations	4
Degree of redundancy	1

WARNINGS

1. Some non-observable variables found (3):
Please use menu command 'Calculate>Classification'

The Classification gives the following message:

NON-OBSERVABLE VARIABLES

Type	Variable
MF	S2
MF	S7
MF	S8

MF	S2
MF	S7
MF	S8

Non-observable variables: 3
(must be measured or fixed)

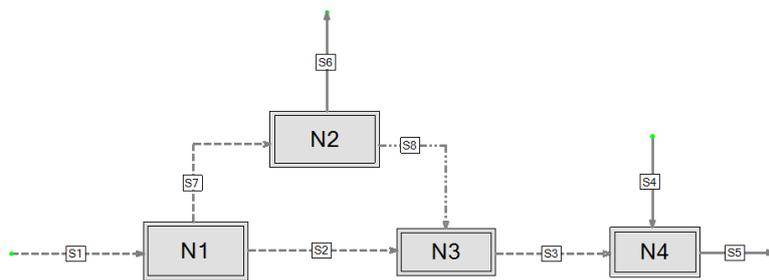
Important here is the **Number of Free Variables (NFV)** in the message above. This notion means the Number of unobservable variables which must be transferred to measured ones to make the task fully observable (in our task NFV = 1). This means

that it is sufficient to put just one variable from the list (S2, S7, S8) among measured (or fixed) ones to achieve the full observability.

The examples above show how to increase or decrease observability or redundancy of the task. In this way it is possible to modify the direction of calculation, e.g. to transfer a redundant system used for DR into a just determined system suitable for simulation needed for a plant performance analysis.

A1.1.4 Unsolvable system

The next example illustrates a problem of an unsolvable system which is mostly caused by too many fixed variables:



The dashed streams (S1, S2, S3 and S7) are of the F type. Here are main results of DR applied on this system:

Task: MC-5 (One-component balance overspecified)

ITERATIONS

Iter	Qeq	Qx	Qy	Qmin
START	9.9258E+00			
1	2.5000E-01	3.3809E-01	2.7900E+01	7.8199E-01
2	2.5000E-01	4.2509E-15	0.0000E+00	7.8199E-01
3	2.5000E-01	4.2509E-15	0.0000E+00	7.8199E-01
4	2.5000E-01	4.2509E-15	0.0000E+00	7.8199E-01
5	2.5000E-01	4.2509E-15	0.0000E+00	7.8199E-01

Task not converged !!!

GLOBAL DATA

Number of measured variables	3
Number of adjusted variables	3
Number of non-measured variables	1
Number of observed variables	1
Number of non-observed variables	0
Number of free variables	0
Number of equations	4
Number of independent equations	3
Number of user-defined equations	0
Degree of redundancy	2

WARNINGS

1. Significant residuals of dependent equations. Task not solvable. Please use menu command 'Calculate>Solvability'

There is also a message

ERRORS/WARNINGS

F I X E D M A S S S T R E A M S

Node

[N1]

has all incident streams fixed:

Stream	From node	To node	Value
S1	ENVIRON	N1	100.1 KG/S
S2	N1	N3	41.1 KG/S
S7	N1	N2	58 KG/S

Imbalance: 1

In this simple case RECON has analyzed the problem directly. In a general case we should use menu *Calculate/Solvability*. Here the previous message is completed by:

The following fixed variables are inconsistent:

Type Variable

MF S1
MF S2
MF S7

Remark

From the above variables
1 must be reclassified as 'M' (measured) or 'N' (unmeasured)

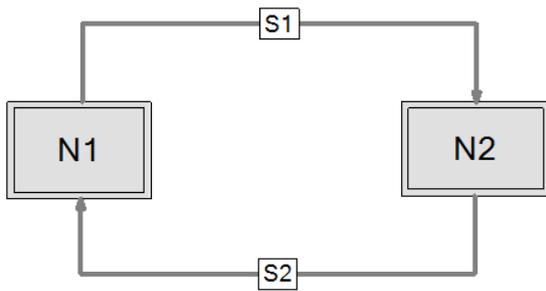
Please correct your task

The examples above have shown how to move between solvable/unsolvable, observable/unobservable and redundant/nonredundant models.

A1.2: Dependency of equations

Most of equations in RECON are generated automatically from a model built in the RECON's GUI. It is the intention of RECON's authors to generate only independent equations. Even if the existence of dependent equations in RECON is not fatal for successful task's solving, it is worth mentioning some situations where dependent equations can arise. Every dependent equation means a decrease of observability.

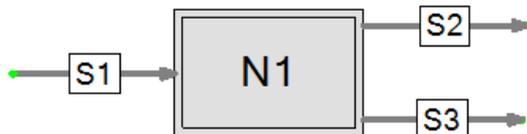
One of reasons for equations' dependency can be a cyclic flowsheet. A most simple example of this kind is the following schema:



For such system RECON generates 2 mass balance equations which are evidently dependent. A more realistic cyclic process is analyzed in Chapter 4 (a steam Rankine cycle).

Note: This is the reason why flowsheets in RECON don't contain explicitly the Environment node (which closes the cycle). The balance of the Environment node is automatically fulfilled if all other nodes are balanced.

Another problem can be caused by splitters.

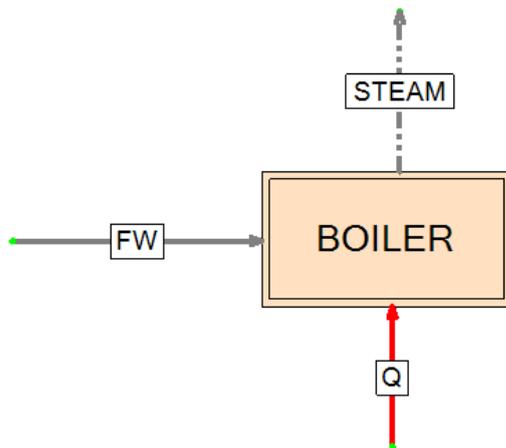


Splitters are nodes with one input stream and several output streams. All properties of all incident streams are identical (composition, temperature, pressure). The composition of all streams should be in RECON defined via master and slave streams. In such case RECON automatically generates around such node just one equation (mass or mole balance) because component balances are dependent on the overall mass or mole balances. If a RECON user tries to setup also the enthalpy balance around a splitter, this equation is already dependent on the mass or mole balance (an enthalpy balance around a splitter has no sense).

More complex cases of equations' dependency can be created by User Defined Equations. It is therefore recommended to monitor the difference between No of all equations and No of independent equations after adding a new UDE and try to explain what happened.

A1.3: Uniqueness of solution for nonlinear models

Let's imagine the next simple example of an enthalpy balance:



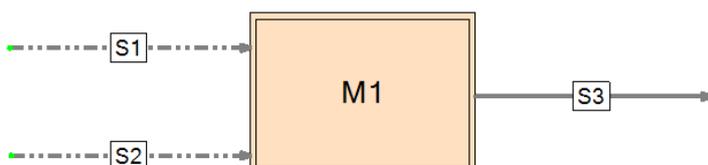
The feed water stream FW is heated by the heat flux Q to produce the superheated steam STEAM. This system generates two equations (mass and enthalpy balance) and it is supposed that two unknown variables can be calculated from the model. Such couple of unknowns can be for example the steam flowrate and the steam temperature (a fully observable system).

Number of measured variables	5
Number of non-measured variables	2
Number of observed variables	2
Number of non-observed variables	0
Number of free variables	0
Number of equations	2
Number of independent equations	2
Degree of redundancy	0

If we exchange the unmeasured flowrate of STEAM for the steam pressure (hence both T and P of the STEAM stream are unknown), they are now unobservable:

The task in RECON does not converge and T and P are thus not observable. Such behavior is caused by the fact that the STEAM enthalpy needed for closing the enthalpy balance corresponds to many couples of T and P. In other words, the system is solvable but the solution in terms of T and P is not unique. This kind of unobservability is called **structural unobservability**. The system is unobservable for any real couple of T and P, this is the property of this selection of measured and unmeasured variables.

The next example of an unobservable system is different. Let's imagine the mixer of two streams of different temperatures:



All three streams' temperatures are measured and also the stream S3 flowrate is measured. The enthalpy of all streams is defined by their temperatures. Such system

generates two equations and the flowrates S1 and S2 can be uniquely calculated (the system is fully observable), see the next RECON's output:

Number of measured variables	4
Number of non-measured variables	2
Number of observed variables	2
Number of non-observed variables	0
Number of equations	2
Number of independent equations	2
Degree of redundancy	0

Now let's suppose that the temperatures T_{S1} and T_{S2} are the same. In this case the task in RECON does not converge and flowrates of S1 and S2 are not observable. The reason for this calculation is the following: The mass balance reads

$$S1 + S2 = S3 \quad (A-1)$$

and the enthalpy balance

$$S1 \cdot H(T_{S1}) + S2 \cdot H(T_{S2}) = S3 \cdot H(T_{S3}) \quad (A-2)$$

In the case that $T_{S1} = T_{S2} = T_{S3}$, the Eq. (A-2) shrinks to the Eq. (A-1) and equations are therefore dependent. In comparison with the previous case of the structural unobservability, this phenomenon occurs only for specific values of some variables. This is called the **local unobservability**.

APPENDIX 2: COAL COMPOSITION AND THE BOILER PERFORMANCE

It is supposed that a coal is composed of 3 components:

- Liquid water (moisture)
- Ash (mineral part of a coal)
- Flammable part composed of 5 chemical elements: C, H, N, O and S

Energy content of a coal is expressed as the Lower Heating Value (LHV) or the Higher Heating Value. In RECON the dimension of LHV or HHV is kJ/kg of the flammable part of a coal. In practice, the information about coal composition and LHV or HHV is not available on-line. Typically the moisture, ash and LHV are results of lab analyses. The elemental composition of the flammable part is usually supposed to be constant (with exception of S).

In the next two examples will be shown how RECON deals with influence of coal moisture and LHV on boiler's performance.

A 2.1: Influence of the coal moisture

Liquid water present in a coal has negative impact on the boiler's efficiency mainly due the following reasons:

- Evaporated water increases mass flow of flue gases
- Water must be evaporated in the firebox while this evaporation heat is not recovered later.

In the next example will be supposed that the coal contains ash and the flammable part in the same ratio while the moisture is changed in the range 20 – 30 mass %. The base line composition is H₂O (26 %), Ah (30 %) and flammable part (44 %).

This problem will be studied by simulation. In the beginning some variables' types must be changed. Originally all 3 concentrations were of the F type.

Now, there will be 2 input variables in the simulation – concentrations of water and ash in the coal (variables of the M type). The flammable part concentration closes 100 % (N type variable).

The .CFG file needed for simulation is

input is coal moisture and Ash (%)

```
C<COAL-IN:H2OL>,C<COAL-IN:AH>
```

```
V<EFFICIENCY>,S<Q-FGLOSS>,S<COAL-IN>,S<AIR-IN>,T<FGEXAP>
```

The .DAT file with input data is

Coal composition

20,32.43

22,31.62

24,30.81

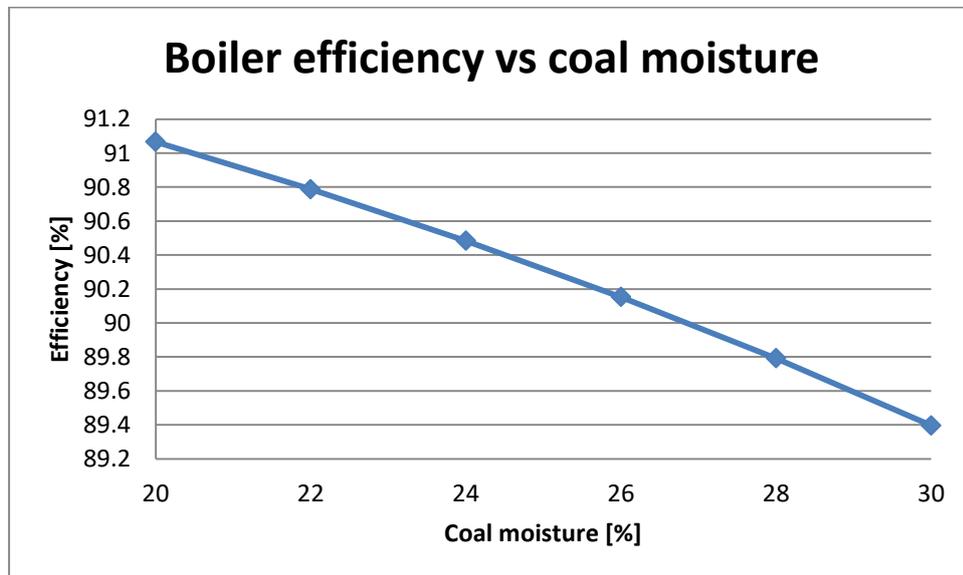
26,30.00

28,29.19

30,28.38

Results of the simulation follows:

C<COAL-IN:H2OL>	C<COAL-IN:AH>	V<EFFICIENCY>	S<Q-FGLOSS>	S<COAL-IN>	T<FGEXAP>
[%]	[%]	[1]	[GJ/HR]	[T/HR]	[C]
Input	Input	Output	Output	Output	Output
20	32.43	91.06644097	20.68850092	26.66413605	154.4996625
22	31.62	90.786959	21.65651508	27.57491095	155.7800109
24	30.81	90.48341073	22.71535592	28.55205982	157.1616766
26	30	90.15280227	23.87747496	29.60330661	158.6571931
28	29.19	89.79164632	25.15761608	30.73764845	160.2812549
30	28.38	89.39585931	26.57335715	31.96563402	162.0512054

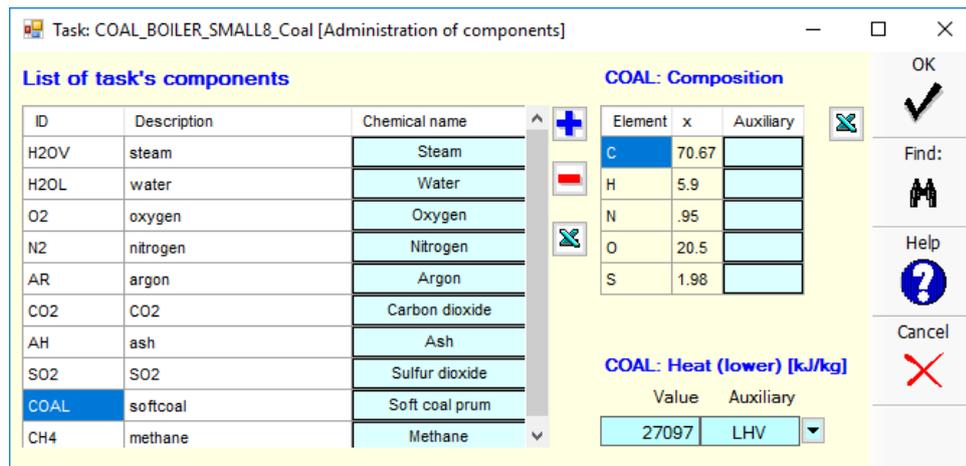


Note: The operational curve above has no simple relation with parametric sensitivity of the Efficiency versus Coal moisture as two input variables in simulation (moisture and Ash) are changed at the same time.

A2.2: Influence of LHV (Lower Heat Value)

LHV influences boiler's heat rate mostly via the amount of a coal and the amount of flue gases needed for calculating a required boiler's heat power. LHV is not a classical RECON variable. It can be only of the F type and therefore it can't be used in parametric sensitivity studies. The only way how to study the influence of LHV on the boiler's performance is the simulation.

LHV values can be imported from outside via an auxiliary variable which is linked with LHV. Such linking is configured in the panel invoked by menu *Accessories / Components*:



The component *Coal* accepts the LHV value from the auxiliary variable LHV (see the right bottom corner). The LHV variable is of the M type.

Note: The LHV value must be in basic SI units. Thus the LHV value 27 097 kJ/kg must be entered as 27 097 000 J/kg.

The .CFG file needed for simulation is

Input is LHV

V<LHV>

V<EFFICIENCY>,S<Q-FGLOSS>,S<COAL-IN>,S<AIR-IN>,T<FGEXAP>

The .DAT file with input data is

LHV

25000000

26000000

27000000

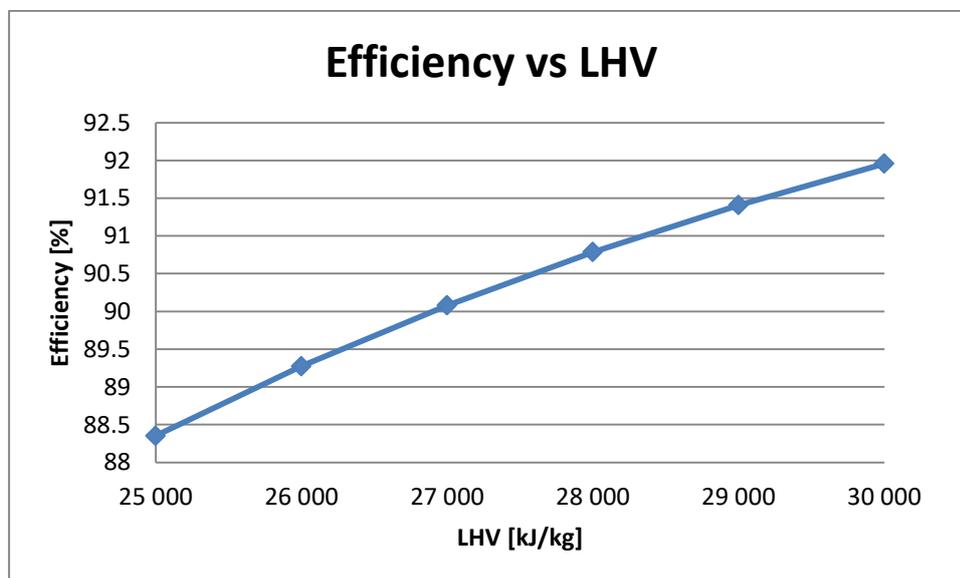
28000000

29000000

30000000

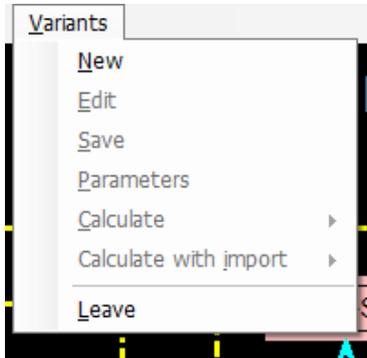
Results of the simulation follows:

V<LHV>	V<EFFICIENCY>	S<Q-FGLOSS>	S<COAL-IN>	S<AIR-IN>	T<FGEXAP>
[1]	[1]	[GJ/HR]	[T/HR]	[T/HR]	[C]
Input	Output	Output	Output	Output	Output
25 000 000	88.35145563	30.0041548	32.89776881	176.3136709	165.1949627
26 000 000	89.27523329	26.82328251	31.23065425	167.3788678	157.1696721
27 000 000	90.08027383	24.11812716	29.73966449	159.3879953	149.9233248
28 000 000	90.78596406	21.79823232	28.39664593	152.1901657	143.3540674
29 000 000	91.40782456	19.79416062	27.17936985	145.6662456	137.3783726
30 000 000	91.95842475	18.05174011	26.07001117	139.7207026	131.9267776



APPENDIX 3: MANAGING RECON VARIANTS

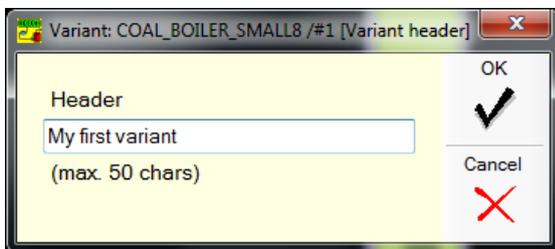
Variants are managed via the menu *Calculate/Variants* available after calculating a task.



While both the first and the last menu items are always enabled, the others depend on what work was done before.

New

This menu item enables you to set up a new variant. This operation is very simple and requires only defining a variant's header (description):



Variants are automatically numbered. This number corresponds with the order in which the variant was created. Total number of variants has no limit.

Note: *At the beginning the new variant agrees exactly with the mother task.*

When you have a variant defined, then you can start modifying its parameters (which moves it step by step away from its mother task). You can use any of enabled items on horizontal menu of the screen.

Edit

This allows you to select any of already existing variants of given task and updates its settings.

Save

This enables you to save current (i.e. just created or selected for editing) variant to a database of variants.

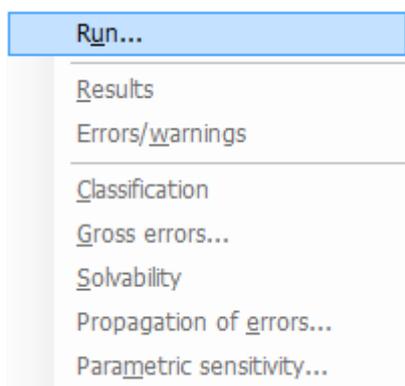
Parameters

This allows you basic administration of task's variants by means of special panel. This panel supports operations like:

- Changing variant header and parameter. Values of the parameter have the meaning as follows:
 - 0 - Calculations will start with non-reconciled data
 - 1 - Calculations will start with non-measured data reconciled in mother task
 - 2 - Calculations will start with all data reconciled in mother task
- Deleting unused variant in the whole. If so, the history database of the task is updated accordingly.
- Comparing each variant with mother task to view all differences introduced.

Calculate

This menu item opens a submenu which allows you to solve any of the existing variants and analyze calculation results. The submenu looks like this



At the beginning, only the Run command is enabled. It provides you with a starting panel which enables you to select a variant of interest and set some parameters for RECON's solver. When done, press the OK button. After the variant is solved, the rest of submenu becomes available.

Calculate with import

Functionality of this menu is the same as in previous case. Difference is that now model calculations are based on values updated by data import.

Leave

This allows you to leave the screen for administration of variants and restores normal working mode of the application.

APPENDIX 4: SIMULATION CONFIGURATION

In RECON simulation calculations are conditioned by the existence of **two text files** that are created manually (by means of Notepad). Both files must be located in the same directory as the simulated task. The extensions of these files are

- CFG - the configuration file containing variables important for simulation
- DAT – the data file containing values of input variable for which this simulation should be done.

File names

The name of both files' body is composed of three parts, namely the:

- task name
- attribute "@S"
- simulation version (non-negative integer).

For a model file MyTask.BDT the body of the file name may look e.g. like "MyTask@S1" (simulation file for MyTask.BDT, simulation version No 1).

Since the name of the two files is the same, they **must differ in their extension**.

Configuration file - Extension CFG

The file with the "CFG" extension consists of three rows:

- the first row contains a text description of given simulation set
- the second row contains an input variable or a list of input variables (input variables should be of M or F type)
- the third row contains a list of output variables

Variables are written in a form that is consistent with the syntax of the user-defined equations (see Syntax of user-defined equations/functions in RECON's help), e.g. the temperature *MyTemperature* is written as ***T<MyTemperature>***, etc. The UDE configuration panel can be used for configuration of simulation files.

Variables on the row are separated by commas. Input variables must be measured and/or fixed, the output variables should be non-measured. The degree of redundancy should be zero (task without reconciliation).

Data file - Extension DAT

The file with the "DAT" extension contains input data for simulation steps. Again, items on each row are separated one another by a comma

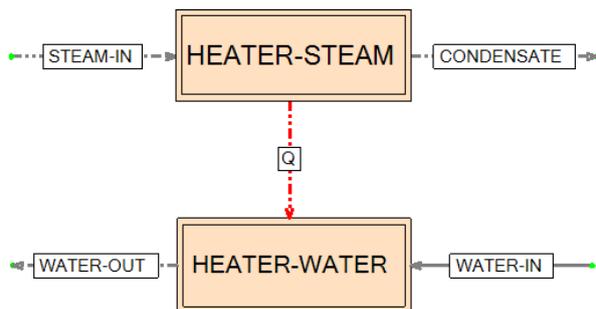
The first row symbolizes the individual Input variables. All other rows contain values of the input variables, one row for one simulation step (model solution). The values must be entered with a decimal point (separation of thousands is not allowed). Each

simulation step starts with accepting values from respective row; this is performed in a way similar to a data import from external data sources.

After all simulation steps are performed, the results of calculations are displayed via Excel. Simulated task is then put into the state it was before the simulation was started.

The simulation configuration and running is illustrated by the following example:

In the next figure is a flowsheet consisting of a cold stream of water WATER-IN heated by condensing of saturated steam STEAM-IN.



Parameters of both streams (T and P of water and P of the steam) are measured. Mass and energy balances of the two nodes represent 4 equations. Further two equations are the calculation of the equilibrium temperature in the HEATER-STEAM node and the definition of the Heat transfer coefficient (HTC). Such system generates a redundant system of equations with DoR = 1 (6 equations and 5 unmeasured variables). Selected results of DR are presented below:

Task: heater1 (steam heater DR)

Number of independent equations	6
Number of user-defined equations (UDE)	2
Degree of redundancy	1
Qmin	3.3753E+00
Status (Qmin/Qcrit)	0.878972

S T R E A M S

Name	Type	Inp.value	Rec.value	Abs.error	
CONDENSATE	NO	1.000	4.057	0.049	KG/S
STEAM-IN	MC	4.050	4.057	0.049	KG/S
WATER-IN	MC	93.000	92.866	0.990	KG/S
WATER-OUT	NO	100.000	92.866	0.990	KG/S

E N E R G Y S T R E A M S

Name	Type	Inp.value	Rec.value	Abs.error	
Q	NO	10.000	7.624	0.093	MW

T E M P E R A T U R E S

EQUIL	NO	210.000	214.897	0.243	C
FW-IN	MC	190.000	190.619	0.728	C
FW-OUT	MC	210.000	209.324	0.717	C

P R E S S U R E S						
FW	MC	22.000	22.000	0.050	MPAG	
STEAM	MC	2.000	2.000	1.00E-2	MPAG	
A U X I L I A R I E S						
HTC	NO	500.000	599.943	43.570		
R E D U N D A N T M E A S U R E M E N T S						
Type	Variable	Adjustability				
MF	STEAM-IN	0.012762	0.518	0.576	0.685	KG/S
MF	WATER-IN	0.009729	11.850	13.178	15.670	KG/S
P	FW	0.000000	124.332	138.268	164.420	MPAG
P	STEAM	0.000025	2.336	2.598	3.090	MPAG
T	FW-IN	0.271831	2.406	2.675	3.181	C
T	FW-OUT	0.282683	2.367	2.632	3.130	C

End of results

To change DR to Direct calculation one of redundant measured variables must be changed to unmeasured. A decision depends on further use of the simulation model. It is important to realize that the selected variable can not be used as input in further studies. Let's select the mass flow STEAM-IN. After that the system is Just determined.

Task: heater1 (steam heater simulation)

Number of independent equations	6
Number of user-defined equations (UDE)	2
Degree of redundancy	0
Qmin	0
Status (Qmin/Qcrit)	0

In the simulation we plan to study the influence of HTC (fouling) on heater's performance. The next step is to interchange the unmeasured HTC with some other variable. Let's select the couple **HTC** \leftrightarrow temperature **FW-OUT**. After this interchange the task is observable and solvable.

The value of HTC identified by DR was 599.9 W/m²/K. The target is to create operating curves of important variables for

HTC = 300, 400, 500, 600, 700 and 800 W/m²/K.

The output variables of the simulations will be:

heat flux Q

temperature FW-OUT

steam flow STEAM_IN.

The configuration file [HEATER1@S1.CFG](#) then reads

Heater simulation - input is HTC

[V<HTC>]

[S<Q>],[T<FW-OUT>],[S<STEAM-IN>]

Note: Brackets can be omitted.

and the data file [HEATER1@S1.DAT](#) reads

HTC
300
400
500
600
700
800

The file of simulation's result in Excel looks like this:

Task: HEATER1 (steam heater simulation)

Simulation #1 [Heater simulation - input is HTC]

Series	V<HTC> [1] Input	S<Q> [MW] Output	T<FW-OUT> [C] Output	S<STEAM-IN> [KG/S] Output	S<WATER-IN> [KG/S] Output
1	300	5.284256679	202.9851352	2.811920334	93
2	400	6.343354623	205.5700869	3.375499892	93
3	500	7.173598716	207.5921117	3.817299068	93
4	600	7.82458443	209.1748222	4.163709183	93
5	700	8.335059315	210.4142041	4.435349036	93
6	800	8.735350053	211.3850038	4.648356416	93

Similarly it is possible to create a simulation task #2 where the input is the flowrate of the stream WATER-IN.

Task: HEATER1 (steam heater simulation)

Simulation #2 [Heater simulation - input is FW-IN]

Series	S<WATER-IN> [KG/S] Input	S<Q> [KG/S] Output	T<FW-OUT> [C] Output	S<STEAM-IN> [KG/S] Output	V<HTC> [1] Output
1	80	6.635929575	208.9067868	3.531188289	500
2	90	7.058108556	207.8835095	3.755843096	500
3	100	7.425468474	206.9400452	3.951326943	500
4	110	7.747504077	206.0741211	4.122692286	500
5	120	8.031790886	205.2806417	4.273970301	500

These two simulation tasks could be also implemented as a single task where both input variables changes independently according to some plan. Such solution can be used for example for preparing multidimensional graphs (response surfaces).

Let's suppose that we want to simulate the heater for the rectangular grid HTC (400,500,600) and WATER-IN (80, 90) (6 cases, simulation variant 3). Then the file HEATER1@S3.CFG reads_

Heater simulation - input is HTC and FW IN

[V<HTC>],[S<WATER-IN>]

[S<Q>],[T<FW-OUT>],[S<STEAM-IN>],[S<WATER-IN>]

and the file HEATER1 @S3.DAT reads

HTC,FLOW-FW-IN

300,80

300,90

400,80

400,90

500,80

500,90

APPENDIX 5: ABOUT RECON

Description

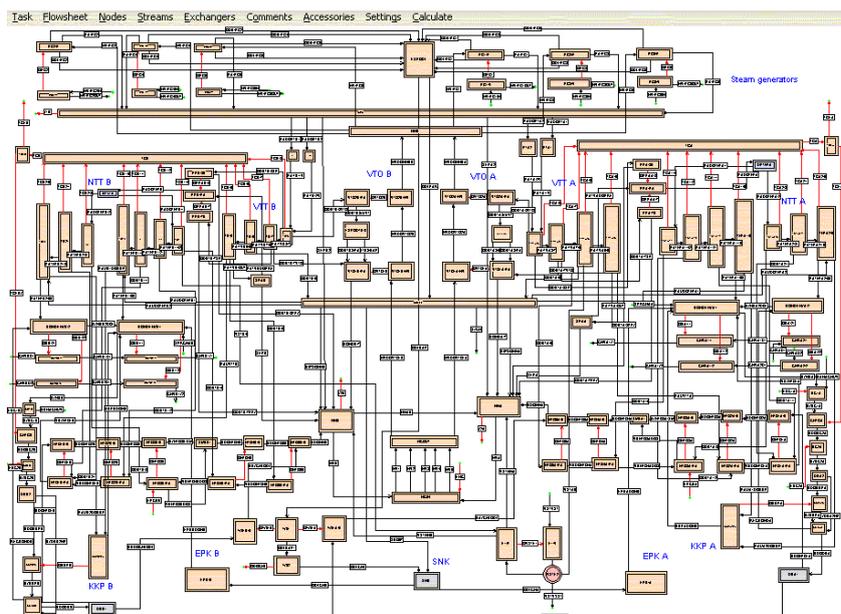
RECON is a comprehensive interactive software for mass, energy and momentum balancing of complex chemical and power plants on the basis of measured or otherwise fixed data. It is designed primarily for data reconciliation and validation, which has been obtained from operating processes. RECON can also be used for classical balancing in the stage of the process design and for simulation of plant's performance under changed conditions.

What is data reconciliation?

Reconciliation is a method for extracting all information present in plant data. Reconciliation is based on statistical adjustment of redundant process data to obey laws of nature (mass and energy conservation laws). Results are enhanced by calculated unmeasured variables. As a result, a new consistent more precise data set is obtained. Moreover, data reconciliation serves as a basis for other important activities:

- Finding confidence intervals for results (error propagation analysis)
- Detection and elimination of gross measurement errors
- Measurement planning and optimization.

RECON can be used to treat measured data before its further usage for other purposes (simulation, optimization, control, ...). Brief survey of reconciliation theory is contained in Recon's User Manual of the application.



Graphical User Interface of RECON

Features

RECON is a PC oriented software with user friendly facilities. Problems (tasks) are defined interactively in the graphical user interface. RECON is aimed at single or multi-component material and energy balancing of complex systems at steady or unsteady (dynamic) state, without or with chemical reactions (reactor balancing). It is also capable to perform momentum balancing based on hydraulic calculations of flow in pipeline systems. RECON reconciles measured flow rates, concentrations, temperatures and other process variables and calculates unmeasured variables. Problem (task) is commonly defined by creating a process flowsheet and defining process variables like flow rates, temperatures, pressures, etc. The flowsheet comprises nodes, mass and energy streams, and heat exchangers. In this way it is possible to build a system of any complexity. Users are also allowed to complete (or even replace) balancing model by their own equations.

Typical tasks solved by RECON

- mass and energy balances of chemical and refinery plants
- natural gas processing
- distribution systems of utilities
- detailed balancing of chemical plants (multi-component systems with chemical reactions)
- monitoring industrial heat exchange systems (crude preheat trains and similar systems)
- balancing steam systems
- monitoring and on-line thermodynamic analysis of power generation systems (turbine efficiencies, low and high pressure preheats, condenser heat transfer, etc.)
- combustion processes (industrial furnaces, coal and gas fired boilers)
- balancing water treatment in power plants (softening, demineralization,)
- thermal sea water desalting
- flow of liquids and gases in pipes and pipeline systems including their hydraulics
- detailed mass and energy balance of nuclear plants (primary and secondary circuits, advanced assessment of nuclear reactor power)

Variables

The following information on task variables must be specified:

- Classification of variables (measured, unmeasured, fixed)
- Values of measured and fixed variables
- Estimates (guesses) of unmeasured variables (for nonlinear problems only)
- Uncertainty (Maximum errors or standard deviations) of measured variables.

Capabilities

- Data import and pre-processing
- Calculation of unmeasured variables
- Reconciliation of redundant measured variables
- Analysis of input data as concerns its consistency
- Confidence intervals of results
- Statistical analysis focused on detection and identification of gross measurement errors
- Detailed classification of variables (redundant / non-redundant, observable / non-observable)
- Measurement placement optimization
- Parametric sensitivity
- Database of historical data useful for monitoring operating plants
- Reporting module based on user-defined templates in MS Excel
- Monte Carlo simulation
- Data mining.

RECON's architecture

RECON consist of the following parts:

- Configuration of models in GUI
- Calculation engine which is optimized as concerns speed and memory requirements. 2 methods of solution are available: Successive Linearization and Sequential Quadratic Programming. A special feature of RECON is the existence of the calculation engine also in the form of an ActiveX object which can be called from customer's proprietary software. In this way a customer can fully manage data processing
- Recon Manager for configuring and coordinating data processing
- Database and files containing Metadata (data about models, users,)
- Database of operational data. This can be either standalone for RECON (Access, Oracle or MS SQL Server) or fully integrated with customer's databases or historians (PI, PHD, InSQL, AIM*, Oracle, MS SQL Server,) - this solution has important advantages.

Operational data can be entered manually or imported from 1 or more other sources (historians, databases, Excel or text files).

Data pre-processing

Imported data can be pre-processed on the basis of several techniques (limits on input variables, limits on control variables). There is also a Basic-like editor for general data pre-processing calculations.

User defined equations

Aside of problem configuration in the Recon's GUI the user can define his own model equations. There is a Basic-like editor for writing new model equations. User can use conditional programming with logical variables. It is possible to use in equations complex thermodynamic functions, physical properties, etc. User defined equations can be used also for defining model inequalities.

Chemical reactors

Chemical reactors can be modeled by 2 ways: The standard method uses chemical reactions (stoichiometric coefficients) stored in Recon's reaction bank. Sometimes reactions in the system are not well known (e.g. burning of coal). In this case user can use the second method based on the so-called reaction invariant chemical reactor. In this case only the knowledge of atomic composition of components is required.

Gross errors treatment

There are 3 steps of Gross Errors (GE) treatment:

1. detection
2. identification
3. elimination

GE detection - finding the GE presence. The data quality is continuously monitored via the Status of data quality (SDQ). This variable should be under normal situation below 1. Values of SDQ above 1 signal the presence of some Gross Error (either an instrument or model error). SDQ is based on so-called Global chi-square test testing the value of the least square function minimized during DR.

There are several methods available for GE identification:

1. Values of normalized adjustments (NA). Suspect measurements are those with the highest NA. Such flows are marked in color on the flow-sheet.
2. Successive elimination of suspect measurements. Suspect variables from the step 1 are automatically set one by one as unmeasured. Variables with the largest decrease of SDQ are suspect.
3. Measurement credibility. Values calculated in the step 2 are compared with limits set on variables. If the calculated value is not probable or feasible, this suspect is excluded from the set of suspects
4. Nodal test. In the case of mass balance the imbalances around individual nodes or their combinations can be statistically tested. Streams around suspect nodes are suspect. This method is suitable also for finding the frequent model errors - leaks or neglected mass accumulation.
5. Covariance matrices of adjustments are available for detailed analysis of the gross error identification problem.

The steps in GE identification are semi-automatic. All this serves as a Decision Support System for the user.

GE elimination. We do not recommend and support the automatic elimination of gross errors. This function offered by some providers of DR software frequently leads

to wrong decisions. Good data can be deleted and the wrong ones remain with formally good balances. This opinion is supported also by balancing theory. GE elimination should be done by the DR system administrator with further actions (instrumentation repair etc.).

Data mining

A long term use of RECON enables one to create a historical database of validated process data. Such database represents an invaluable source of information which can be utilized in many areas (creation of empirical models, optimization, etc.). Such activities are usually denoted as data mining.

The new data mining module of RECON enables one to analyze easily large data sets and to find hidden relationships among data. By a few key strokes a user can easily create multiple regression models among process variables. Attention is also paid to the statistical analysis of process data and to removal of outliers.

MonteCarlo simulation

Statistical theory of data reconciliation is exactly valid for linear models only. Any use of statistical theory to general nonlinear models is limited to a small neighborhood of the final solution. In practice this means that standard deviations of measurement errors should be "small" enough to justify acceptable validity of results (reconciled values, confidence intervals, gross errors detection, etc.). Analytical solution of this problem is not feasible in practice.

The only way how to tackle this problem is the Monte Carlo simulation. This solution is based on repeated simulation of the measurement process. The starting point is an errorless data set (a base case). Individual "measured" data sets are generated by adding random errors to the base case data. In this way a real measurement is simulated many times with the following data reconciliation. Results can be statistically evaluated and compared with theoretical values.

Reporting engine

RECON enables one to create reports in the MS Excel environment. The solution is based on Excel templates prepared by users. These templates contain links to RECON's database. In this way any user can define unlimited number of report templates which can be later used for generation of reports. The complexity of these reports is limited by Excel's capabilities only. Reports can be generated either in the interactive way by a user or automatically at a pre-defined time.

Model Variants

There can be many variants of one RECON model. For example there can be several modes in which a plant operates (some subsystems can be disabled, etc.), several modes of calculation (data reconciliation, simulation, ...). Such model variants can be developed and maintained under one "mother" model. All variants are saved in one database. This simplifies development and maintenance of the whole set of tasks.

RECON's connectivity

RECON can be connected to process data information systems based on the Oracle, MS SQL, PI System, Industrial SQL server, PHD, AIM* and MS Access databases as well as to MS Excel, .DBF or .TXT files.

RECON's physical property database

RECON contains the following databases of physical properties:

- The IAPWS IF 97 database of properties of steam and water
- Properties of hydrocarbons and other chemicals according to API procedures
- Standing Katz method for Natural Gas compressibilities
- Critical parameters of components for density and viscosity calculations of gaseous mixtures
- User defined physical property models

RECON languages

- Czech
- English
- German
- Spanish
- Russian

Running RECON

RECON can be run in the following modes:

- Interactive solving of one task
- On-line monitoring of industrial processes
- Automatic processing of historical data
- As ActiveX DLL called from other programs.

Hardware Requirement

RECON is the 32 bit MS Windows application which can be installed on any PC or server operating under MS Windows 95 or higher (98, NT, 2000, XP, Vista, Windows 7, Windows 10 for 32 and 64 bit systems).

Available versions

Version	Mass balance	Energy balance	Momentum balance	User-defined equations	DB connectivity	Active X object (DLL)
Lite*	x	x	x	x		
Academic**	x	x	x	x		
Full	x	x	x	x		
Professional	x	x	x	x	x	x
Trial***	x	x	x	x	x	

* max 20 nodes, 50 streams, 5 heat exchangers, 5 components and 10 user-defined equations

** for non-commercial purposes only

*** valid for 1 month