Scientific Research Publishing

Journal of Software Engineering and Applications, 2024, 17, 109-128
https://www.scirp.org/journal/jsea
ISSN Online: 1945-3124
ISSN Print: 1945-3116

Auxiliary Software for Defining the Parameters of the Structural Organization of a Complex System

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How to cite this paper: Savic, B.M. (2024) Auxiliary Software for Defining the Parameters of the Structural Organization of a Complex System. *Journal of Software Engineering and Applications*, **17**, 109-128.
https://doi.org/10.4236/jsea.2024.172006

Received: December 21, 2023
Accepted: February 26, 2024
Published: February 29, 2024

Abstract

The developed auxiliary software serves to simplify, standardize and facilitate the software loading of the structural organization of a complex technological system, as well as its further manipulation within the process of solving the considered technological system. Its help can be especially useful in the case of a complex structural organization of a technological system with a large number of different functional elements grouped into several technological subsystems. This paper presents the results of its application for a special complex technological system related to the reference steam block for the combined production of heat and electricity.

Keywords

Complex System, Structural Organization, Auxiliary Software, Parameters

1. Introduction

The starting point for modeling and controlling processes within a system is structural process scheme that defines the structural organization of the functioning of the system under consideration. It is produced via the standard technical process scheme represented in the corresponding field of application which it is necessary to divide into the lowest functional parts. At the same time, the functional elements can be mutually grouped into corresponding higher technological subsystems which hierarchically complete the structural process scheme. It provides a basis for reading the organization of the structural process scheme of a reference complex system.

In this paper, it is considered, as a reference example of complex system, a project proposal for the reconstruction of the existing steam turbine unit for the production of electricity to the combined production of electricity and heat for the heating needs of the urban center, given by the supplier of this block[1].

The most important advantage of combined electricity and heat generation is in its potentially high efficiency of transformation of primary into secondary useful forms of energy [1] [2] [3], which has resulted in its greater application and faster development [4] [5]. The energy effect of combined energy production for steam turbine plants is often expresses through primary energy savings compared to the same separate production that can reach for newly designed plants up to about 30% maximum. For reconstructed existing steam turbine units, this percentage is certainly lower, but it can be significant, if it is cost-effective. In this case, the cost-effectiveness is related to the optimization of the entire heat supply system, which includes, in addition to the energy production unit, the system of transport of heating water and the consumer of heat energy, with its variable requirement [6] [7]. On the other hand, the positive effects of the application of combined energy production from existing out-of-town steam turbine plants can be expressed through the substitution of imported primary energy sources for heating purposes, as well as through positive environmental impacts in the urban environment.

As part of his doctoral thesis, the author has developed a computer program TURBOEX [8] [9] for the calculation of variable stationary regimes of steam turbine units for combined production of electricity and heat.

In addition to a number of original solutions in the development of applied methodology within the TURBOEX computer program (development of universal flow characteristic for the field of dry and wet steam, developed generalized forms of functions of heat transfer coefficients for surface heat exchangers [10], originally developed individual functions of thermodynamic states of higher accuracy, etc.), one of the important contributions is related to the development of a software loading system of different structural organization of steam turbine units. The software loading of such structural organization of the reference complex system is at beginning of the main program intended for solving its basic task in the field of application, and can represent a rather complicated part of the overall computer program.

To overcome this intricate procedure of software loading a structural organization of a complex system within the main computer program, the auxiliary software has been developed which considerably simplifies, standardizes and facilitates the realization of this task.

The two most important features of auxiliary software are related in the following:

- It is characterized by generality in relation to the type of technological system or area of application.
- The output is fully standardized through identification parameters that completely defined the structural organization of the system under consideration.

[1]Note technique (1986), Obrenovac 6 - 300 MW, Chaufage urbain, Domaine de functionement, Alstom, p. 7.

The developed auxiliary software is organized in two parts. The first and most important part forms a complete database of the identification parameters for all enclosed technological levels. The complete database of the basic elements in the complex system, obtained with the first part of the software, is used in the second part of the software to define their input and output connections.

Both of the previously mentioned software parts are organized on the simplest interactive data loading query. Due to the complexity of a complex system, it is foreseen in software—with a query so that the loading can be interrupted, and then continued without losing the previously loaded data and obtained current intermediate results. This makes it much easier to load the structural organization of the system within the auxiliary software.

The application of auxiliary software results excludes the need for software loading of the structural organization of the system in the introductory part of the main program.

However, the results provided by the auxiliary software can also help in building the organizational structure of the main software, the algorithm for the reference technological system (main program and specialized subroutines), as well as in solving specific technical tasks by using the necessary functional interconnections between individual program parts.

The auxiliary software is used for a reference technological system. It relates to the supplier's proposal for the reconstruction of the existing steam block for the production of electricity for the combined production of heat and electricity. A complete database of the identification parameters of structural organization for this reference system, obtained by using the first software part, is presented in this paper. Also, the complete database of the input and output connections of the basic elements, obtained by using the second software part, is presented to.

Finally, for three basic steady regimes of energy production in cogeneration, set by the supplier of steam block[1], the calculations were performed using the TURBOEX computer program. We compared the obtained calculation results with the supplier's design data.

Figure 1 shows a simplified block scheme of organization of the main program of the computer program TURBOEX, with the option of replacing the software loading of the structural organization of the system by including the identification parameters obtained by the auxiliary software—point 1.

It is important to underline that it is possible a software control of stream flow operation within the scope of the structural process scheme within the main computer program. So, the structural process scheme may include functional elements and connections that do not have to be active in some operating regimes—point 4 and 5.

This is the same for all other technological systems with their structural process schemes which can include elements and connections that are activated only in special cases to increase the reliability of the system due to the failure of some components or to achieve some special functions of the system.

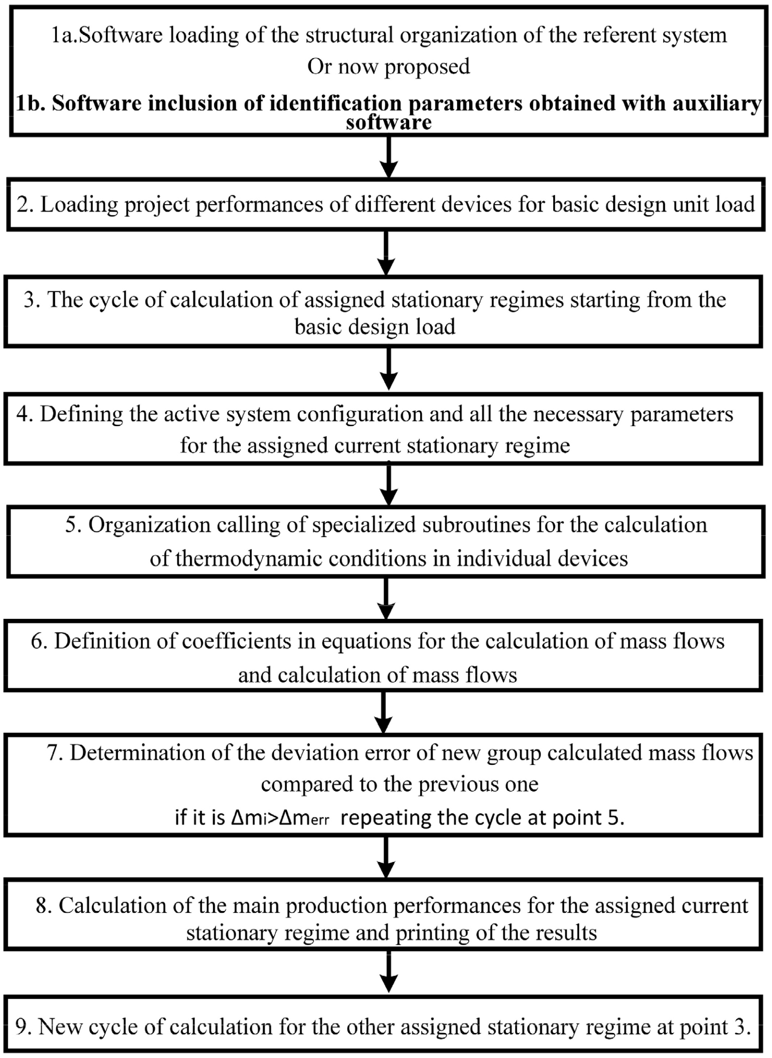

Figure 1. A simplified block scheme of organization of the main program of the computer program TURBOEX.

Analysis of the different structural organization variants of some reference systems can be in function of an optimal structural organization choice on set goal criteria based on the obtained results of the main computer program in the corresponding field of application.

2. Reference Technological System

The reference technological system is usually represented graphically in a suitable process scheme with standard symbols for the functional devices in the corresponding field of application. For the appropriate specialist professional area from the technological aspect, this presentation of the process scheme is the clearest for its reading. Figure 2 shows an example of a standard markings of the process scheme for a reference steam turbine plant for the production of electricity. With regard to this steam turbine plant, the supplier proposed the reconstruction of the existing steam block for the production of electricity for the

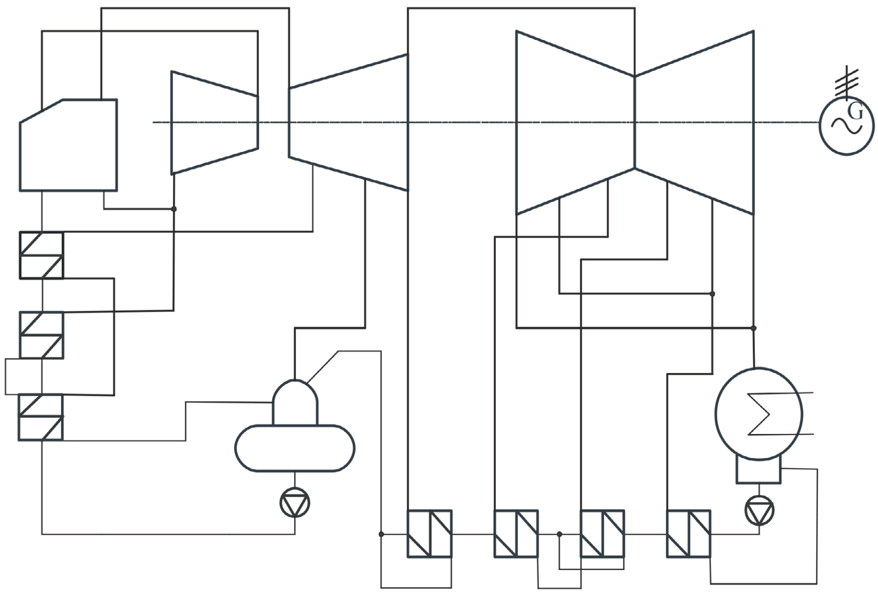

Figure 2. Standard marked process scheme of a steam block for the production of electricity.

combined production of heat and electricity with the aim of the smallest possible interventions on the turbine unit itself[1]. This solution envisages the installation of a butterfly control valve between the intermediate and low-pressure turbines for regulated steam extraction and the application of two-stage heating of the heating water, in the first stage from the regulated steam extraction from the outlet of the intermediate pressure turbine, and in the second stage from the existing unregulated steam extraction of the intermediate pressure turbine at the next higher pressure. The considered reference technological system is based on this project proposal.

3. Auxiliary Software

3.1. Structural Process Scheme

To define the structurally process scheme it is necessary to divide the standard technical process scheme into the lowest functional parts, that is, into simple (with one basic element) and complex functional elements (they can consist of two or more basic elements that cannot function independently). Surface heat exchangers within this scheme are defined as complex functional elements with two basic elements due to the separated flows of the heat transducer and receiver and the need to balance fluid current flows. This base is supplemented by grouped functional elements within technological subsystems at higher hierarchical levels.

Figure 3 presents the reference a structural process scheme, broken down to the lowest level of basic elements that are appropriately connected by input and output connections of fluid currents. Identification numbers for elements and connections are obtained using auxiliary software for the reference system.

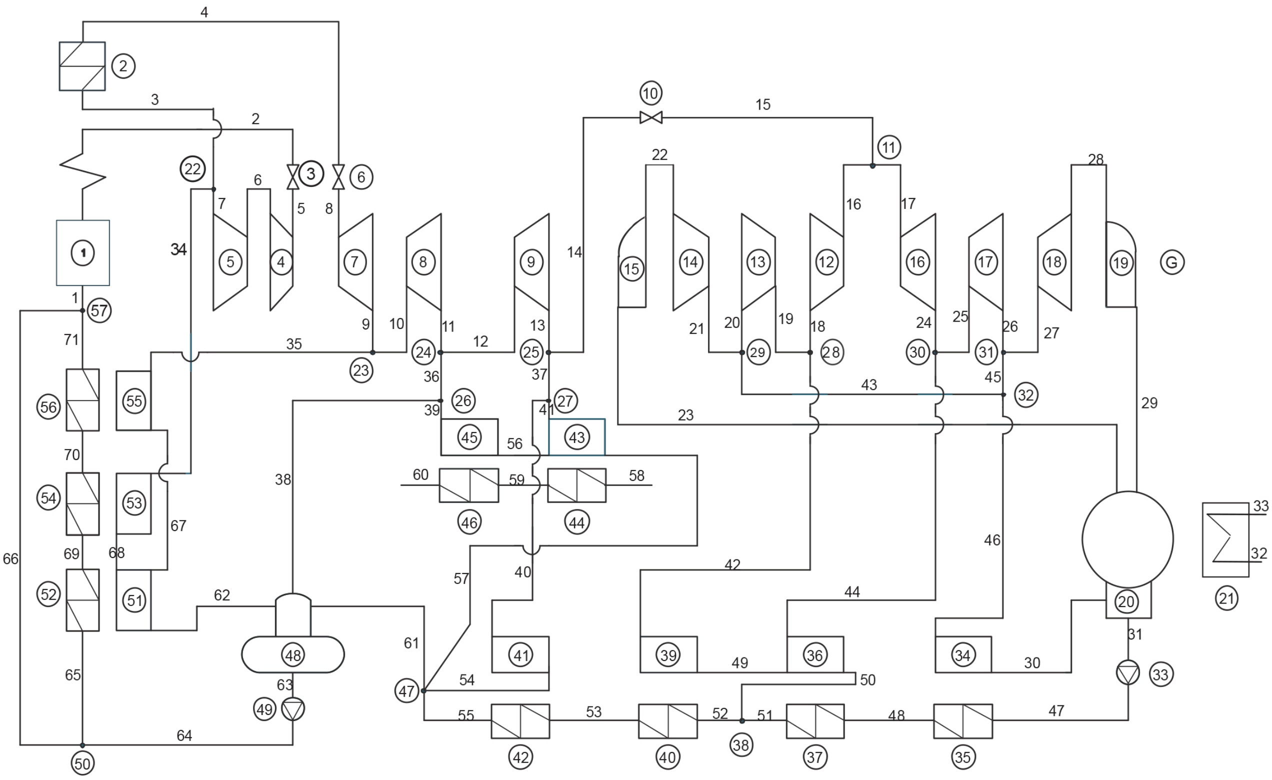

Figure 3. Structural process scheme for the reference steam block.

At the same time, functional elements can be mutually grouped into corresponding hierarchically higher technological subsystems, as parts of a complex device within the standard technological scheme. Thus, for example, a steam boiler, as a complex device of the first higher level, consists of two parts at the basic level, the first part of a steam boiler with an evaporator and a steam superheater, and the second part of a steam boiler with a reheat steam superheater—separated again due to different current flows by input and output connections. On the other hand, the steam turbine as a whole is of the second hierarchical level, which has four members: a high-pressure turbine, an intermediate-pressure turbine and a low-pressure turbine at the first hierarchical level, and between the intermediate and low-pressure turbines there is a butterfly control valve for regulated steam extraction at the basic level—Figure 4. Thus, for example, a high-pressure turbine, as a complex device at the first hierarchical level, consists of a main valve at the entrance, a governing stage, and a multi-stages flow part of the turbine at the basic level with a constant flow of steam for a certain steady regime.

3.2. Organization and Characteristics of Auxiliary Software

The developed auxiliary software is organized in two parts. With the first and most important part of the auxiliary software, all the necessary identification parameters are obtained for the complete definition of the structural organization of the reference system. The complete database of the basic elements in the

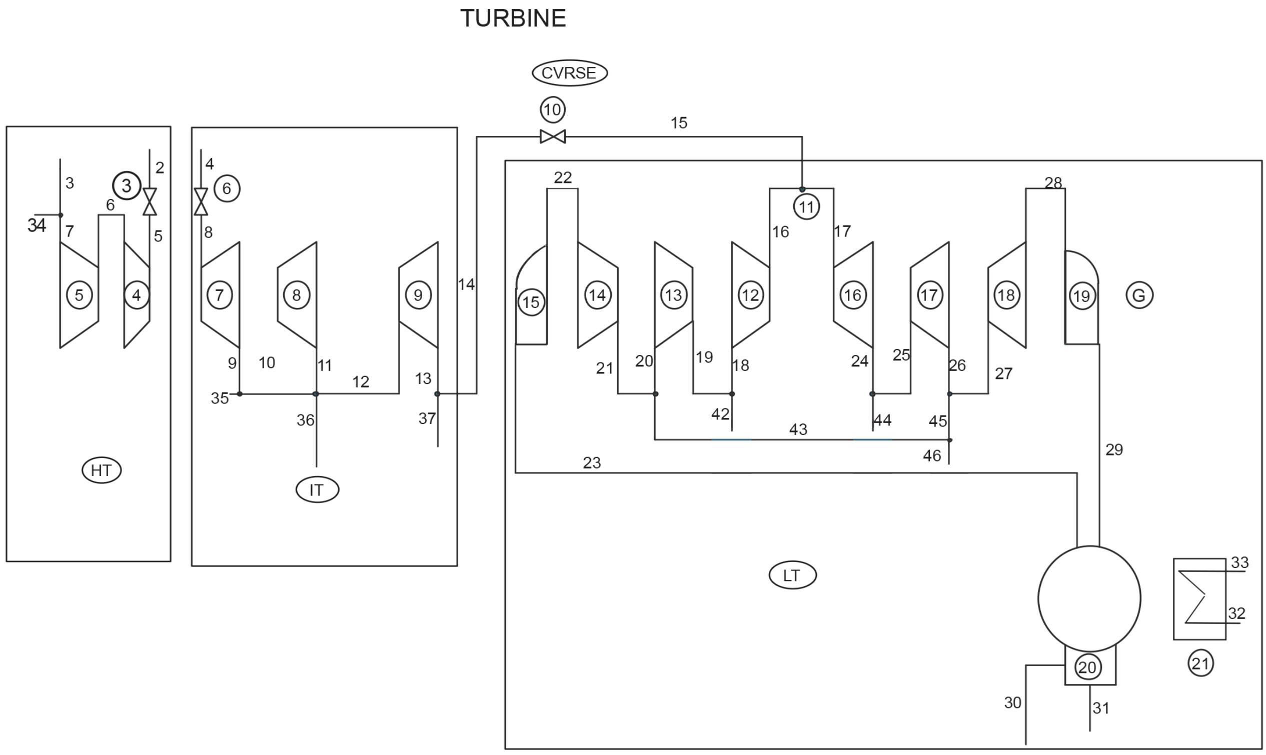

Figure 4. Steam turbine subsystem of the second hierarchical level.

complex system, obtained also with the first part of the software, is used in the second part of the software to define their input and output connections.

Both of the previously mentioned software has organized on the simplest interactive data loading query. Loading identification, both for elements and for their grouped hierarchical levels, is done in the most secure way through named tags (up to 8 characters). The same applies to element connections. For simple and complex functions elements are defined during loading their sequential function identification numbers. The functional types of state changes in the connections are also marked with their own sequentially loaded identification functional numbers.

In addition to the basic level with which simple and complex functional elements are defined, the possibility of their grouping into higher technological subsystems up to the third hierarchical level is foreseen. The reference complex technological system uses the second hierarchical level as the highest level, so we believe that with the third hierarchical level there is enough reserve to include possible more complex cases of technological systems.

Identification from the basic level of simple elements to the highest hierarchical level is double, starting from the loaded 8-character name and the identification number obtained as a result of the used auxiliary software. A special identification numerical sequence is formed for each level. In addition, for a component belonging to a subsystem, a sequential identification number is defined in the subsystem, which determines its place in the direction of the process within the subsystem.

Due to the complexity of a complex system, it is foreseen in software—with a query so that the loading can be interrupted, and then continued without losing the previously loaded data and obtained current intermediate results.

Software limitations are arbitrarily adopted, but in our opinion broad enough for most tasks.

Software arbitrarily adopted limits with a maximum of 500 basic elements, 200 complex elements, 100 technological subsystems at the first, 50 at the second and 20 at the third hierarchical level, a maximum number of 1000 connections of basic elements, a maximum number of 50 different functions for simple and complex elements (with up to a maximum of 10 contained basic elements), as well as the same maximum number of functions for different state changes in connections, are certainly widely set for the structures of the most complex systems.

3.3. Display of Results of Auxiliary Software

The results obtained by the first, most important part of the software, which defines the identification parameters of the structural organization of the reference technological system, are shown in tabular form in **Figure 5**. These results do not include the input and output connections of the basic elements that are implemented in the second part of the software, which otherwise uses the previously obtained database of the basic elements in the first part of the software.

Figure 5 also includes functional elements grouped within two technological subsystems of different hierarchical levels, the first for the steam boiler and the second for the steam turbine, which have already been described previously.

Within a subsystem, the results define all the necessary identification parameters of its structural organization starting from the lowest basic level of functional elements (simple and/or complex) to the highest level—**Figure 5**, which enable further simplified software manipulation at each level for a certain technological subsystem.

In order to make a desirable difference in the given names of elements and connections for the reference technological system, we arbitrarily chose to designate all elements and subsystems with uppercase letters, and the connections of basic elements with lowercase letters.

The results of the auxiliary software are completed by its second part, which defines the input and output connections for each of the basic elements defined by the first part of the software (an already created file with data on the basic elements is automatically used) **Figure 6**. Connections are loaded interactively by name (8 characters), which are mostly closed, but can also be open. The program recognizes previously loaded connections in the system, so a new identification number (for connections it is also a serial number) is added only to connections that did not exist in the system by previous loading.

By recognizing an already existing connection, the software shortens the loading procedure for other data about it, such as, for example, the identification number of the function for changing the state in it.

```
                                          SYSTEM ORGANIZATION STRUCTURE
  FUNCTIONAL ELEMENT         LEVEL1                LEVEL2             LEVEL3
SIMPLE-SEL COMPLEX-CEL
NUM.ID.-NAME  FUNCTION NUM.ID.-NAME NUMBER ORDER NUM.ID.-NAME NUMBER ORDER
  1 BOILER      1 SEL    1 BOILEREH     2     1
  2 REHEATER    1 SEL    1 BOILEREH     2     2
  3 HTMV        2 SEL    2 HT           3     1    1 TURBINE      4     1
  4 GOVST       3 SEL    2 HT           3     2    1 TURBINE      4     1
  5 HT1         4 SEL    2 HT           3     3    1 TURBINE      4     1
  6 ITMV        2 SEL    3 IT           4     1    1 TURBINE      4     2
  7 IT1         4 SEL    3 IT           4     2    1 TURBINE      4     2
  8 IT2         4 SEL    3 IT           4     3    1 TURBINE      4     2
  9 IT3         4 SEL    3 IT           4     4    1 TURBINE      4     2
 10 CVRSE       5 SEL                              1 TURBINE      4     3
 11 FLTI        6 SEL    4 LT          10     1    1 TURBINE      4     4
 12 LTL1        4 SEL    4 LT          10     2    1 TURBINE      4     4
 13 LTL2        4 SEL    4 LT          10     3    1 TURBINE      4     4
 14 LTL3        4 SEL    4 LT          10     4    1 TURBINE      4     4
 15 LTLEX       7 SEL    4 LT          10     5    1 TURBINE      4     4
 16 LTR1        4 SEL    4 LT          10     6    1 TURBINE      4     4
 17 LTR2        4 SEL    4 LT          10     7    1 TURBINE      4     4
 18 LTR3        4 SEL    4 LT          10     8    1 TURBINE      4     4
 19 LTREX       7 SEL    4 LT          10     9    1 TURBINE      4     4
  1 CONDEN      1 CEL    4 LT          10    10    1 TURBINE      4     4
 20 FHTE        6 SEL
 21 FIT1E       6 SEL
 22 FIT2E       6 SEL
 23 FIT3E       6 SEL
 24 FDEHW2      6 SEL
 25 FRH4HW1     6 SEL
 26 FLTL1E      6 SEL
 27 FLTL2E      6 SEL
 28 FLTR1E      6 SEL
 29 FLTR2E      6 SEL
 30 FLTLR2      6 SEL
 31 PUMPLP      8 SEL
  2 RH1         2 CEL    5 RH1RH2       2     1
  3 RH2         2 CEL    5 RH1RH2       2     2
 32 FRH3I       6 SEL
  4 RH3         2 CEL    6 RH3RH4       2     1
  5 RH4         2 CEL    6 RH3RH4       2     2
  6 HW1         2 CEL    7 HW1HW2       2     1
  7 HW2         2 CEL    7 HW1HW2       2     2
 33 FRHLPE      6 SEL
 34 DEAER       9 SEL
 35 PUMPHP      8 SEL
 36 FRHHPI      6 SEL
  8 RH5         3 CEL    8 RHHP         3     1
  9 RH6         3 CEL    8 RHHP         3     2
 10 RH7         3 CEL    8 RHHP         3     3
 37 FRHHPE      6 SEL
```

Figure 5. Original listing of results of the structural organisation parameters for the reference system.

With all the connections in the system defined, the structural organization of the system can now be presented in graphic form at the level of basic elements and connections with their own identification numbers—**Figure 3**, which has an important role in creating the balance of current flows and thermodynamic conditions for the reference technological system.

A display with the names of the basic elements and connections, which would be supplemented with the names and boundaries of complex functional elements, as well as the names of the present technological subsystems and their boundaries, would certainly completely explain the structural organization of the system, but it would significantly complicate the drawing, and it only depends on the need and skill user of the auxiliary software whether it will be performed.

```
                                  ELEMENT CONECTIONS (OPEN-OC or CLOSE-CC) IN ORDER
   ELEMENT                              1                    2                    3
 NUM.ID.-NAME   NUMBER NUM.ID.-NAME  FUNC. NUM.ID.-NAME  FUNC. NUM.ID.-NAME FUNC.
  1 BOILER      1  IN   1 wfb       CC  1
  1 BOILER      1 OUT   2 sbht      CC  2
  2 REHEATER    1  IN   3 sfrh      CC  2
  2 REHEATER    1 OUT   4 srhit     CC  2
  3 HTMV        1  IN   2 sbht      CC  2
  3 HTMV        1 OUT   5 shtmvgs   CC  2
  4 GOVST       1  IN   5 shtmvgs   CC  2
  4 GOVST       1 OUT   6 sgsht1    CC  2
  5 HT1         1  IN   6 sgsht1    CC  2
  5 HT1         1 OUT   7 sht1f     CC  2
  6 ITMV        1  IN   4 srhit     CC  2
  6 ITMV        1 OUT   8 smvit1    CC  2
  7 IT1         1  IN   8 smvit1    CC  2
  7 IT1         1 OUT   9 sit1e     CC  2
  8 IT2         1  IN  10 sfit2     CC  2
  8 IT2         1 OUT  11 sit2e     CC  2
  9 IT3         1  IN  12 sfit3     CC  2
  9 IT3         1 OUT  13 sit3e     CC  2
 10 CVRSE       1  IN  14 sfcv      CC  2
 10 CVRSE       1 OUT  15 scvlt     CC  2
 11 FLTI        1  IN  15 scvlt     CC  2
 11 FLTI        2 OUT  16 sfltl1    CC  2  17 sfltr1    CC  2
 12 LTL1        1  IN  16 sfltl1    CC  2
 12 LTL1        1 OUT  18 sltl1e    CC  2
 13 LTL2        1  IN  19 sfltl2    CC  2
 13 LTL2        1 OUT  20 sltl2e    CC  2
 14 LTL3        1  IN  21 sfltl3    CC  2
 14 LTL3        1 OUT  22 sltl3exl  CC  2
 15 LTLEX       1  IN  22 sltl3exl  CC  2
 15 LTLEX       1 OUT  23 sexlcon   CC  2
 16 LTR1        1  IN  17 sfltr1    CC  2
 16 LTR1        1 OUT  24 sltr1e    CC  2
 17 LTR2        1  IN  25 sfltr2    CC  2
 17 LTR2        1 OUT  26 sltr2e    CC  2
 18 LTR3        1  IN  27 sfltr3    CC  2
 18 LTR3        1 OUT  28 sltr3exr  CC  2
 19 LTREX       1  IN  28 sltr3exr  CC  2
 19 LTREX       1 OUT  29 sexrcon   CC  2
 20 CONDS       3  IN  23 sexlcon   CC  2  29 sexrcon   CC  2  30 crh1      CC 3
 20 CONDS       1 OUT  31 wconplp   CC  1
 21 CONDW       1  IN  32 wcwi      OC  4
 21 CONDW       1 OUT  33 wcwe      OC  4
 22 FHTE        1  IN   7 sht1f     CC  2
 22 FHTE        2 OUT   3 sfrh      CC  2  34 sfrh6     CC  2
 23 FIT1E       1  IN   9 sit1e     CC  2
 23 FIT1E       2 OUT  10 sfit2     CC  2  35 sfrh7     CC  2
 24 FIT2E       1  IN  11 sit2e     CC  2
 24 FIT2E       2 OUT  12 sfit3     CC  2  36 sdehw2    CC  2
 25 FIT3E       1  IN  13 sit3e     CC  2
 25 FIT3E       2 OUT  14 sfcv      CC  2  37 srh4hw1   CC  2
 26 FDEHW2      1  IN  36 sdehw2    CC  2
 26 FDEHW2      2 OUT  38 sfde      CC  2  39 sfhw2     CC  2
 27 FRH4HW1     1  IN  37 srh4hw1   CC  2
 27 FRH4HW1     2 OUT  40 sfrh4     CC  2  41 sfhw1     CC  2
 28 FLTL1E      1  IN  18 sltl1e    CC  2
 28 FLTL1E      2 OUT  19 sfltl2    CC  2  42 sfrh3     CC  2
 29 FLTL2E      1  IN  20 sltl2e    CC  2
 29 FLTL2E      2 OUT  21 sfltl3    CC  2  43 sfltl2e   CC  2
```

```
                                  ELEMENT CONECTIONS (OPEN-OC or CLOSE-CC) IN ORDER
   ELEMENT                              1                    2                    3
 NUM.ID.-NAME   NUMBER NUM.ID.-NAME  FUNC. NUM.ID.-NAME  FUNC. NUM.ID.-NAME FUNC.

 30 FLTR1E      1  IN  24 sltr1e    CC  2
 30 FLTR1E      2 OUT  25 sfltr2    CC  2  44 sfrh2     CC  2
 31 FLTR2E      1  IN  26 sltr2e    CC  2
 31 FLTR2E      2 OUT  27 sfltr3    CC  2  45 sfltr2e   CC  2
 32 FLTLR2      2  IN  43 sfltl2e   CC  2  45 sfltr2e   CC  2
 32 FLTLR2      1 OUT  46 sfrh1     CC  2
 33 PUMPLP      1  IN  31 wconplp   CC  1
 33 PUMPLP      1 OUT  47 wplprh1   CC  1
 34 RH1S        1  IN  46 sfrh1     CC  2
 34 RH1S        1 OUT  30 crh1      CC  3
 35 RH1W        1  IN  47 wplprh1   CC  1
 35 RH1W        1 OUT  48 wrh1rh2   CC  1
 36 RH2S        2  IN  44 sfrh2     CC  2  49 crh3      CC  3
 36 RH2S        1 OUT  50 crh2      CC  3
 37 RH2W        1  IN  48 wrh1rh2   CC  1
 37 RH2W        1 OUT  51 wrh2e     CC  1
 38 FRH3I       2  IN  51 wrh2e     CC  1  50 crh2      CC  3
 38 FRH3I       1 OUT  52 wfrh3     CC  1
 39 RH3S        1  IN  42 sfrh3     CC  2
 39 RH3S        1 OUT  49 crh3      CC  3
 40 RH3W        1  IN  52 wfrh3     CC  1
 40 RH3W        1 OUT  53 wrh3rh4   CC  1
 41 RH4S        1  IN  40 sfrh4     CC  2
 41 RH4S        1 OUT  54 crh4      CC  3
 42 RH4W        1  IN  53 wrh3rh4   CC  1
 42 RH4W        1 OUT  55 wrh4e     CC  1
 43 HW1S        2  IN  41 sfhw1     CC  2  56 chw2      CC  3
 43 HW1S        1 OUT  57 chw1      CC  3
 44 HW1W        1  IN  58 hw1i      CC  5
 44 HW1W        1 OUT  59 hw1hw2    CC  5
 45 HW2S        1  IN  39 sfhw2     CC  2
 45 HW2S        1 OUT  56 chw2      CC  3
 46 HW2W        1  IN  59 hw1hw2    CC  5
 46 HW2W        1 OUT  60 hw2e      CC  5
 47 FRHLPE      3  IN  55 wrh4e     CC  1  54 crh4      CC  3  57 chw1      CC 3
 47 FRHLPE      1 OUT  61 wfdei     CC  1
 48 DEAER       3  IN  61 wfdei     CC  1  38 sfde      CC  2  62 crh5      CC 3
 48 DEAER       1 OUT  63 wdephp    CC  1
 49 PUMPHP      1  IN  63 wdephp    CC  1
 49 PUMPHP      1 OUT  64 wphpe     CC  1
 50 FRHHPI      1  IN  64 wphpe     CC  1
 50 FRHHPI      2 OUT  65 wfrh5     CC  1  66 wrhhpbp   CC  1
 51 RH5S        2  IN  67 srh7rh5   CC  2  68 crh6rh5   CC  3
 51 RH5S        1 OUT  62 crh5      CC  3
 52 RH5W        1  IN  65 wfrh5     CC  1
 52 RH5W        1 OUT  69 wrh5rh6   CC  1
 53 RH6S        1  IN  34 sfrh6     CC  2
 53 RH6S        1 OUT  68 crh6rh5   CC  3
 54 RH6W        1  IN  69 wrh5rh6   CC  1
 54 RH6W        1 OUT  70 wrh6rh7   CC  1
 55 RH7S        1  IN  35 sfrh7     CC  2
 55 RH7S        1 OUT  67 srh7rh5   CC  2
 56 RH7W        1  IN  70 wrh6rh7   CC  1
 56 RH7W        1 OUT  71 wrh7f     CC  1
 57 FRHHPE      2  IN  71 wrh7f     CC  1  66 wrhhpbp   CC  1
 57 FRHHPE      1 OUT   1 wfb       CC  1
```

Figure 6. Original listing of results of the connections of the basic elements for the reference system.

However, the basic graphic representation of the structural identification of the system—**Figure 3** is certainly important, because it enables the visual location spatial reading of the obtained results with the main software through the input and output states in the connections for the reference technological system.

4. Computer Program TURBOEX

4.1. The Separate Procedures for Solving

One of the most important task that is set to perform for this technological system are the calculations of the different steady regimes of the steam turbine unit and its energy performances.

The characteristic of this computer program is in the separate procedures for solving mass flows in all and thermodynamic conditions in individual parts and devices of the steam turbine unit. In addition to the necessary control of the processes in these devices, as well as the possibility of possible modification of their specialized software modules, the separate solution procedure facilitates the use of the existing nonlinear functions that describe the processes in these devices.

The system of equations for the calculation of mass flows consists of a system of independent equations for mass flows—continuity equations and a supplementary number of balance energy equations for heat exchange in surface heat exchangers.

Equations for determining thermodynamic conditions are included within the solution of input-output states from individual devices or plant parts within specialized subroutines for those units.

The separate solution procedure is by its nature iterative at the basic level. For the calculation of thermodynamic conditions in each iteration step, the previous values of mass flows that satisfy the system of mass equations are used. As long as the deviations of the values of the previous group of mass flows in relation to the values of the new group are not below the set error of deviation of the mass flow, the procedure is repeated. The calculation of a given steady regime is completed by establishing the balance of each functional element for itself and all together within the considered technological system.

4.2. Software Loading of Structural Organization

The initial basis of the development of auxiliary software is related to the development of the computer program TURBOEX within the framework of the doctoral thesis [8] [9].

At that time, the originally applied concept was essentially the same as that of the auxiliary software, and referred to the breakdown of the technological process scheme into the lowest functional elements and its graphical representation in the form of a structural process scheme down to the level of basic elements and their connections. However, the identification numbers of the basic elements and connections (special strings) within the structural process scheme were set in advance in an arbitrary order. The definition of the structural organization of the system and its identification parameters within the computer program TURBOEX is realized by software loading of appropriate input data for different types of functional elements belonging to the reference technological system through their predetermined numerous marks on the structural scheme. Based on a completely defined structural organization at the level of basic elements, data for their input and output connections is also loaded in software. Also, the definition of a subsystem within the subject system is realized by software loading data for the associated group of elements in the appropriate order.

Figure 7 shows a structural process scheme for a reference steam turbine unit for energy production in cogeneration previously signified as used for steady regime calculations within the TURBOEX computer program.

This system concept of displaying the structural process scheme and, according to it, loading its corresponding structural organization, provides the computer program TURBOEX with the most important feature of generality in relation

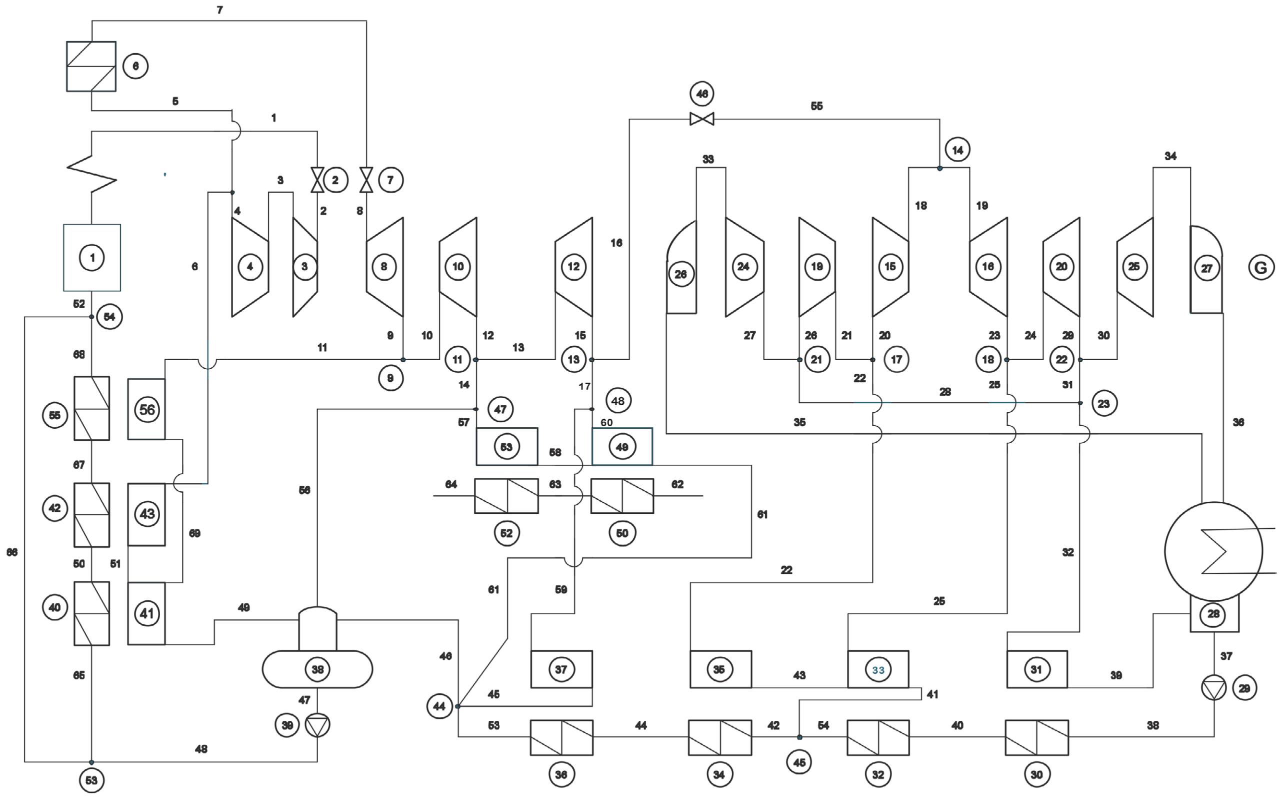

Figure 7. Structural process scheme applied within the TURBOEX programme.

to the possibility of considering different configurations of process scheme of a steam turbine unit.

Comparing Figure 3 and Figure 7 differences in identification numbers for the same elements and connections obtained by auxiliary software and the pre-set numbers are observed.

Also, there is a difference in that the turbine condenser in Figure 7, as a surface heat exchanger, shown as a simple functional element. Certainly, in the printed results of the steady regime calculations obtained using the TURBOEX program, beside the state results for all input and output connections, the results for the input and output state of the cooling water of condenser are shown at the bottom of the table in Figure 8.

However, if this technological system in the setting is considered in principle, like any other, it is necessary for the consistent use of auxiliary software to treat the condenser as a complex functional element with a separate pipe part belonging to the cooling water system, as in Figure 3. This can be particularly interesting if the reference complex system were to be expanded to include the entire cooling water system in order to optimise the condensing conditions of a steam turbine plant [11] [12] [13].

4.3. The Properties and Possibilities

TURBOEX software features the following properties, which only partially depict the structure and possibilities it has to offer:

TOTAL NUMBER OF ITERATION STEPS = 12
RELATIVE MASS FLOW RATE OF FRESCH STEAM= 1.00

PIPE	FL.RATE	P-IN	T-IN	H-IN	P-OUT	T-OUT	H-OUT
1	1.00000	186.84210	545.00	3394.60	177.50000	540.00	3390.98
2	1.00000	168.62500	536.42	3390.98	168.62500	536.42	3390.98
3	1.00000	110.88440	469.00	3278.73	110.88440	469.00	3278.73
4	1.00000	42.00987	333.07	3046.60	42.00987	333.07	3046.60
5	.91452	42.00987	333.07	3046.60	39.87523	333.07	3052.22
6	.08548	42.00987	333.07	3046.60	40.74958	331.80	3046.60
7	.91452	39.87523	542.00	3540.51	37.74057	540.00	3538.07
8	.91452	36.98576	539.37	3537.39	36.98576	539.37	3537.39
9	.91452	22.60879	461.79	3380.31	22.60879	461.79	3380.31
10	.85962	22.60879	461.79	3380.31	22.60879	461.79	3380.31
11	.05491	22.60879	461.79	3380.31	21.66600	461.25	3380.31
12	.85962	10.51242	355.67	3169.68	10.51242	355.67	3169.68
13	.77293	10.51242	355.67	3169.68	10.51242	355.67	3169.68
14	.08668	10.51242	355.67	3169.68	10.51242	355.67	3169.68
15	.77293	5.36850	275.52	3013.07	5.36850	275.52	3013.07
16	.52837	5.36850	275.52	3013.07	5.36850	275.52	3013.07
17	.24456	5.36850	275.52	3013.07	5.36850	275.52	3013.07
18	.26410	3.69526	273.27	3013.28	3.69526	273.27	3013.28
19	.26427	3.69526	273.27	3013.28	3.69526	273.27	3013.28
20	.26410	1.45783	181.49	2836.08	1.45783	181.49	2836.08
21	.23601	1.45783	181.49	2836.08	1.45783	181.49	2836.08
22	.02809	1.45783	181.49	2836.08	1.41045	181.36	2836.08
23	.26427	.45595	88.67	2660.77	.45595	88.67	2660.77
24	.24480	.45595	88.67	2660.77	.45595	88.67	2660.77
25	.01947	.45595	88.67	2660.77	.44154	88.56	2660.77
26	.23601	.15785	54.99	2524.89	.15785	54.99	2524.89
27	.22461	.15785	54.99	2524.89	.15785	54.99	2524.89
28	.01139	.15785	54.99	2524.89	.15785	54.99	2524.89
29	.24480	.15785	54.99	2524.88	.15785	54.99	2524.88
30	.23341	.15785	54.99	2524.88	.15785	54.99	2524.88
31	.01139	.15785	54.99	2524.88	.15785	54.99	2524.88
32	.02279	.15785	54.99	2524.88	.15443	54.53	2524.88
33	.22461	.03637	27.42	2360.56	.03637	27.42	2360.56
34	.23341	.03637	27.42	2360.55	.03637	27.42	2360.55
35	.22461	.03637	27.42	2373.44	.03637	27.42	2373.44
36	.23341	.03637	27.42	2373.51	.03637	27.42	2373.51
37	.48081	.03637	26.42	110.77	.03637	26.42	110.77
38	.48081	19.71919	26.63	113.25	19.71919	26.63	113.25
39	.02279	.15443	54.53	228.18	.15443	54.53	228.28
40	.48081	19.71919	52.70	222.11	19.71919	52.70	222.11
41	.04756	.44154	78.29	327.74	.44154	78.27	327.74
42	.52837	19.71919	77.19	324.60	19.71919	77.19	324.60
43	.02809	1.41045	109.60	459.67	1.41045	109.61	459.67
44	.52837	19.71919	107.24	450.95	19.71919	107.24	450.95
45	.03987	5.20744	153.33	646.53	5.20744	153.30	646.53
46	.82509	19.71919	149.73	631.85	19.71919	149.73	631.85
47	1.00000	9.85960	179.20	759.55	11.85960	179.20	759.68
48	1.00000	233.55260	184.25	793.56	233.55260	184.25	793.56
49	.14038	20.77147	214.28	917.39	20.77147	214.25	917.39
50	1.00000	233.55260	212.71	918.32	233.55260	212.71	918.32
51	.08548	40.74958	251.52	1093.15	40.74958	251.07	1093.15
52	1.00000	233.55260	254.83	1107.62	233.55260	254.83	1107.62
53	.52837	19.71919	149.18	629.51	19.71919	149.18	629.51
54	.48081	19.71919	77.12	324.29	19.71919	77.12	324.29
55	.52837	3.69526	273.27	3013.28	3.69526	273.27	3013.28
56	.03452	10.51242	355.67	3169.68	9.85960	355.09	3169.68
57	.05216	10.51242	355.67	3169.68	9.46118	354.73	3169.68
58	.05216	9.46118	177.42	751.69	9.46118	177.43	751.69
59	.03987	5.36850	275.52	3013.07	5.20744	275.29	3013.07
60	.20469	5.36850	275.52	3013.07	4.83165	274.76	3013.07
61	.25685	4.83165	150.52	634.36	4.83165	150.49	634.36
62	1.48252	20.00000	70.00	294.46	20.00000	70.00	294.46
63	1.48252	20.00000	148.22	625.36	20.00000	148.22	625.36
64	1.48252	20.00000	167.75	710.00	20.00000	167.75	710.00
65	1.00000	233.55260	184.25	793.56	233.55260	184.25	793.56
66	.00000	233.55260	184.25	793.56	233.55260	184.25	793.56
67	1.00000	233.55260	249.61	1083.62	233.55260	249.61	1083.62
68	1.00000	233.55260	254.83	1107.62	233.55260	254.83	1107.62
69	.05437	21.66600	278.53	2968.21	20.77119	277.28	2968.21

HEAT ENERGY PRODUCTION [kW/(kg/s)] = 616.047
ELECTRIC ENERGY PRODUCTION [kW/(kg/s)] = 1090.418
HEAT RATE OF STEAM TURBINE UNIT = 1.59844
HEAT RATE OF ELECTRIC ENERGY PRODUCTION = 2.28125
TEMPERATURE OF COOLING WATER AT INPUT OF CONDENSER C= 15.0
TEMPERATURE OF COOLING WATER AT OUTPUT OF CONDENSER C= 21.05
HEAT ENERGY OF CONDENSATION [kW/(kg/s)]= 1039.0

Figure 8. Original listing of results for one of the given combined production regimes.

- Implementation of separate procedures for solving of mass flow rates in all and thermodynamic conditions in specialized subroutines allows for the most efficient control of the calculation process. Furthermore, such program organization, based on the modular principle, facilitates improvement of specialized software modules, which has been the case for some modules in comparison to its initial version.
- TURBOEX software has universal application in terms of configuration of a steam turbine unit process scheme.
- Different turbine power control are possible: with throttle governing, with nozzle governing and with sliding pressure.
- Boiler feed pump powered by an auxiliary steam turbine supplied with steam from the main turbine can be included.
- For the steam turbine units used for cogeneration, calculation of energy production can include up to four control valves used for regulation of steam extractions.
- Production of steam for the needs of different industrial consumers can be considered.
- Regime load calculations with set values of fresh steam mass flow rates ensure the utmost reliability of calculations. Calculations are possible with absolute or relative values of fresh steam mass flow rates (in relation to the nominal value of fresh steam mass flow rate) which is more convenient for analyses.
- Combinations of steady regime loads calculations can be achieved in arrays starting with nominal designed regime load, followed by regime loads with changes in fresh mass flow rate, altered conditions of condenser operation, changes in input conditions of exchangers for district heating, control of regulated steam extractions, by-passing of high-pressure feed water heat exchangers, as well as changes in operating states of different parts of a steam turbine unit. The influence of different deviations in input parameters on operation and performances of a steam turbine unit can also be analyzed, which may be of importance for the control of steam turbine unit operation.

4.4. Summary of the Results of the TURBOEX Computer Program

The basic performance of the reference steam block is related to the rated generator power for which it was designed—Figure 1. By loading the detailed data for that regime (provided by the supplier of the steam block via the process balance scheme[1]), the basic nominal performances of all the functional elements that make it up are defined. In Table 1, only basic data related to this design regime are given.

Since the reference steam block was considered to be reconstructed for combined energy production, and for which the supplier provided the previously described solution, it was necessary to load the design data for the heating water heaters for the predicted basic regime of combined energy production with which their nominal performances were defined[1].

Table 1. Basic data for the design load.

Steam turbine unit	"Nikola Tesla"-A4	
Rated generator power	(MW)	308.5
1) Fresh steam		
- Pressure	(bar)	177.5
- Temperature	(˚C)	540
2) Reheat steam		
- Pressure	(bar)	37.91
- Temperature	(˚C)	540
3) Pressure of condensation	(bar)	0.048

The initial calculation is related to the designed nominal regime for electricity production. Also, on the basis of this starting regime load, all steady reference regimes for electricity production given by the supplier are calculated.

The main characteristic of combined energy production from steam blocks are a potentially large number of operating steady regimes related to changes in the flow of fresh steam, the input state of the heating water (changes in temperature and flow), management by regulated steam extraction, possible partial bypass of the heating water heaters (usually at low heat requirements for heating) and with complete or partial bypass of regenerative high-pressure feed water heaters to increase the production of electricity and heat. However, block supplier companies in practice usually significantly reduce the range of possible operating regimes in combined energy production. Except in cases of justifiably present technological limitations, other reasons (difficulties in defining possible regimes and easier process control) usually do not have to justify this approach. In this regard, the supplier of the steam block provided data only for three basic steady regimes of combined production for the same heating water temperature at the entrance of 70˚C and with distinct heating water flows (450.7; 365.0 and 233.2 kg/s) and corresponding heating power (180; 150 and 100 MW), and with the same nominal fresh steam flow rate of 246,205 kg/s at the turbine inlet[1].

It should be noted that in the case of production of heat and electricity in cogeneration by steam turbine plant, the choice of optimal regimes is related by whole water cycle, which includes also in addition hot water transport pipelines and heat energy consumers and their changing requirements [6].

Calculations were performed using the TURBOEX computer program also for these three basic regimes of energy production in cogeneration. The calculation procedure is iterative and ends with the calculation of the appropriate steam flow through the butterfly control valve of regulated steam extraction, which obtains the set value of the heating water flow. The original listing of the final result for one of the given basic regimes of combined energy production with a flow of heating water of 365 kg/s is shown in **Figure 8**.

All mass flows, as well as the produced energy, were calculated and expressed as relative values in relation to the flow of fresh steam for the nominal regime (246,205 kg/s).

The data are read for the input and output states in the connections according to the structural scheme given in **Figure 7**.

We compared the obtained calculation results for the three basic set regimes using our TURBOEX computer program with the supplier's data—**Figure 9**.

The diagram is defined by two factors of combined energy production: on the left side with the ratio of produced heat and electricity in combined production, and on the right side with the ratio of produced electricity in combined production and in the basic design load of electricity production. A very good agreement between both data sets is observed.

The supplier's data and our calculations were made for the design state of the steam block, although it would be more realistic to consider to some extent the changed functional state of the steam block due to its longer multi-year engagement. Unfortunately, there are no empirical analyses on the operation and condition of the reference steam block in the past period.

The diagnosis of operating conditions, control of economy and operation state of different components are most important tasks in the additional analyses of processes [14] [15].

However, with our software system DIORES [16], the operation diagnosis was performed for another steam block, of similar power and configuration, with archived source databases on its operation over a period of several years. It was determined that the changes in the operating state of the turbine were not implemented with the same intensity for the different functional parts of the turbine. This fact indicates the great importance of the need to structurally break down the complex steam block system into its basic functional elements within the present technological subsystems (in this case the turbine) for monitoring and diagnosis of their operating condition.

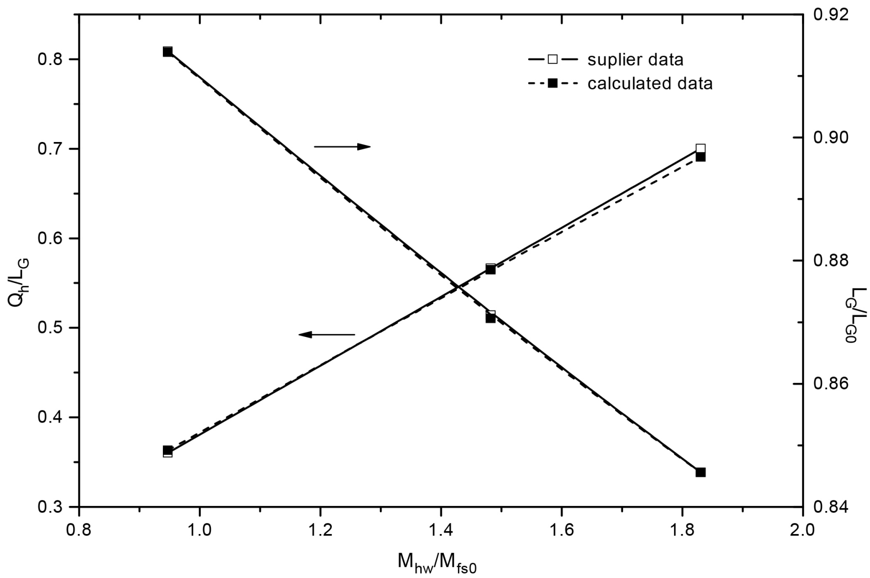

Figure 9. Comparison of calculation results and supplier's data for the given regimes of combined production of heat and electricity.

Realizing the importance of the application of operating diagnostics of the steam block and the need to predict the regime and performance based on its determined changed state, an additional upgrade of the TURBOEX computer program was carried out, which can include these changes in the operating condition. In a possible realization of on-line optimal control of the steam block according to its available state, the upgraded program could play a significant role.

5. Conclusions

As a reference technological system, the project proposal for the reconstruction of the existing steam turbine unit for the production of electricity to the combined production of electricity and heat, given by the supplier of the block, was considered[1]. The supplier proposed the reconstruction of the existing steam turbine unit with the aim of the smallest possible interventions on the turbine unit itself. This solution envisages the installation of a butterfly control valve between the intermediate and low-pressure turbines for regulated extraction and the application of two-stage heating of the heating water. The structural process scheme of the organization of the functioning of this system is based on this project proposal.

For this solution, the supplier envisaged only three design steady regimes of combined electricity and heat production, although the possible number of available regimes could have been higher.

As a basic software for this technological system, we use our computer program TURBOEX for the calculation of variable stationary regimes of combined production of electricity and heat from steam turbine units, which is described in detail in the paper. The software loading of such structural organization of the reference complex system is at beginning of the main program, and can represent a complicated part of the overall computer program.

To overcome this intricate procedure of software loading a structural organization of a complex system within the main computer program, and also from the other reasons listed below, the auxiliary software has been developed which considerably simplifies, standardizes and facilitates the realization of this task.

The following reasons are at the same time advantages for the application of auxiliary software:

- To facilitate and simplify the loading of the structural organization of a complex system.
- Generality in relation to the type of technological system or area of application.
- The output is fully standardized through identification parameters.
- Identification parameters fully define the structural organization for each level.
- The possibility of a very complex systems with a large number of different functional elements and technological subsystems.
- Loading of structural process scheme is organized upon the simplest interactive query, in a very comfortable way for user.

- Facilitates the construction of the structural organization (algorithm) of the basic computer program in the subject area of application.
- The application of auxiliary software results excludes the need for software loading of the structural organization of the system in the introductory part of the main program.

Complete results for identification parameters and connections for the reference system, obtained by using auxiliary software, are presented in this paper.

Calculations were performed using the TURBOEX computer program for three basic steady regimes of energy production in cogeneration, set by the supplier of steam block[1]. A very good agreement of the results of the calculations and data of the supplier was obtained.

It is important to underline that it is possible a software control of stream flow operation within the scope of the structural process scheme within the main computer program. The structural process scheme may include some elements and connections that do not have to be active in some operating regimes of the considered technological system. So, for example, for a given reference system in the regime of electricity production only, the hot water heaters and the connections to them would be turned off. In the case of unavailability of the line of regenerative high-pressure feed water heaters or in the case of the need to achieve a possible rotational reserve of electricity production, their bypass line to the boiler would be included. On the other hand, it could be included in the regime of combined energy production to increase the production of heat and electricity. All these regimes were calculated using our computer program TURBOEX and through a unique structural process scheme that takes into account all the mentioned cases.

This is the same for all other technological systems, which with their structural process scheme can include elements and connections that are activated only in special cases to increase the reliability of the system due to the failure of some components or to achieve some special functions of the system.

Auxiliary software can have a special place in defining the parameters of the structural organization of complex systems with a large number of different functional elements grouped into several technological subsystems. For example, related to the task of diagnosing the real operating state of a steam block based on the acquisition of a large number of measurement signals during a longer period of its operation [16]. This can be further used during the possible development of a system for on-line optimal management of the operation of the steam block according to its current actual state.

It should be noted that this kind of auxiliary software could also be used in cases of complex functional systems that are not of a technological nature.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Muhlhauser, H. (1982) Heating Turbines—A Contribution to the Improved Utilization of Primary Energy. *Brown Boveri Review*, **11**, 423-430.

[2] Schwarzenbach, A. (1990) Parity Factors for Economic Comparisons in Cogeneration Plants. *Brown Boveri Review*, **3**, 166-172.

[3] Lisin, E., Sobolev, A., Strielkowski, W. and Garanin, I. (2016) Thermal Efficiency of Gogeneration Units with Multy-Stage Reheating for Russian Municipal Heating Systems. *Energies*, **9**, 269. https://doi.org/10.3390/en9040269

[4] Kasilkov, V.E. and Kholodkov, S.V. (2017) Cogeneration Steam Turbines from Siemens: New Solutions. *Thermal Engineering*, **64**, 184-189. https://doi.org/10.1134/S0040601517030041

[5] Shibaev, T.L. (2020) A Review of Trends in Development of Cogeneration Steam Turbine Units. *Thermal Engineering*, **67**, 903-908. https://doi.org/10.1134/S0040601520120071

[6] Savić, B. and Stojaković, M. (1992) Computer Program "TRANSFER" for Analyses of Hot Water Cycle in Cogeneration District-Heating Power Plant. *ICHMT 2nd International Forum on Expert Systems and Computer Simulation in Energy Engineering*, Erlangen, 17-20 March 1992, 22-3-1, 22-3-6.

[7] Vasiljević, N., Savić, B., Stojaković, M. and Damnjanović, S. (1993) Energetic Effects of Belgrade District Heating from Power Plant "Nikola Tesla"-A, Feasibility Study 06.14-14/93 for "JKP Belgrade Generating Station". Faculty of Mechanical Engineering, Belgrade, p. 57. (in Serbian)

[8] Savić, M.B. (1989) Contribution to the Energy Basis of the Development and Integration of Combined Heat and Electricity Production into the Power System. Ph.D. Thesis, University of Belgrade, Belgrade, p. 166. (in Serbian)

[9] Savić, B. (1990) Mathematical Modeling and Computer Simulation of Processes in Energy Systems. Hemisphere Publishing Corp, 815-828.

[10] Savić, B. (1994) Methodology for Thermic Calculations Surface Heat Exchangers Involved in Computer Program TURBOEX for a Steam Turbine Unit Load Calculations. Proceedings of TERMOHIDRAULIKA'94-Termohydraulic Processes in Energetic, Faculty of Mechanical Engineering, Belgrade, 13. and 14. Oktober 1994, D.4-1, 10. (in Serbian)

[11] Vasiljević, N., Savić, B. and Stojaković, M. (1991) Research of Optimal Design and Operating Conditions of the Condenser Part of Steam Turbine Units. Investigation Study, University of Belgrade, Belgrade, p. 120. (in Serbian)

[12] Stojaković, M., Vasiljević, N. and Savić, B. (1995) Steam Power Plant Efficiency Enhancement by Means of "Cold-End" Optimization during Exploitation. 57th *Annual Meeting, American Power Conference*, **57-1**, 560-565.

[13] Kromhout, J., Goudappel, E. and Pechtl, P. (1997) Economic Optimization of the Cooling Water Flow of a 540 MW el Coal Fired Power Plant Using Thermodynamic Simulation. *Power-Gen Europe* 97, Madrid, May 1997, 204-222.

[14] Beebe, R. (2003) Condition Monitoring of Steam Turbines by Performance Analyses. *Journal of Quality in Maintenance Engineering*, **9**, 102-112. https://doi.org/10.1108/13552510310482361

[15] Aronson, K.E., Brodov, Yu.M. and Novoselov, V.B. (2012) Development of a System for Monitoring Technical State of the Equipment of a Cogeneration Steam Turbine Unit. *Thermal Engineering*, **59**, 944-947. https://doi.org/10.1134/S0040601512120026

[16] Savić, B. and Jovanović, R. (2011) Software System "DIORES" for the Operation Diagnosis of Steam Power Plant Unit. *Energy*, **36**, 1187-1195. https://doi.org/10.1016/j.energy.2010.11.028