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A Systemic Approach for Energy Efficiency. The Case of a Steam Generation Process

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1. Introduction – The main objective of this work is to present a method that combines the models of systems engineering with the balances of matter and energy of an industrial plant or one of its processes. This approach allows energy efficiency to be calculated at the appropriate level of abstraction of the plant, not well described in other approaches.

The systemic approach allows the engineers to determine the context or boundary of the facility where the energy efficiency analysis is to be performed, but also the methods of calculation or simulation that must be chosen, using the laws of thermodynamics and the equations of fluid mechanics, determining numerically the losses of energy, reversibility, efficiency and other parameters of interest.

There are various examples of calculation and simulation methods in the literature. Some of these methods applied to coal power plants are summarized below.

In some cases, energy efficiency calculation models of a coal power plants use the indirect method that requires the calculation of the losses in the boiler, where one of the major problems to be considered is the change of quality and type of coal [1].

Others use simulation models based on more complex computer tools using the principles of coal combustion, heat transfer in boiler elements, matter and energy balance and thermodynamics of the steam cycle [2].

The use of linear programming algorithms is another alternative to optimize the efficiency of a coal power plant at full capacity, where flows and extractions in turbine stages and fuel consumption are considered as control variables [3].

Another approach uses Modelica to create a software library that contains models of complex thermal power plants with CO_2 capture in static and dynamic modes of operation. The software library is structured according to the main functional groups of the physical processes considered [4].

The above approximations mainly use the enthalpy balance for the calculation of the efficiency, but in other methods the exergy balances are used, which allows to determine the most efficient process according to the less loss or destruction of available work [5].

We propose a method that combines the models of systems engineering with the balances of matter and energy to be calculated at the appropriate level of abstraction of the thermal power plant. That is to say, applying the matter and energy balances to the level of decomposition of the plant or installation, where the available equations and correlations allow to calculate the dependent variables.

This paper is composed of five sections including this introduction. Section 2 describes the proposed method for performing the energy efficiency analysis of an installation or part thereof. Section 3 shows the models and equations generated by the application of the method to the illustrative case of the steam generation system of one of the groups of a coal power plant. We present some of the systems engineering models obtained and how they are integrated with the equations that govern the process. Section 4 describes the results obtained and the practical recommendations that could be given based on these results. The paper concludes with a section summarizing the main contributions.

2. A Model Based Systems Engineering Method – Systems engineering, as currently practiced in the field of complex products, relies on the use of defined models with standard notations supported by various computer tools for design and modeling. The standard notation most used by the systems engineering community is the SysML (Systems Modeling Language) notation [6].

SysML allows to create a coherent model of a complex system or product that, through different views, represents various aspects of such a system: Structural composition and interconnections between the constructive elements of the system. Behavior and functionality of the system; constraints on physical and performance properties; assignment and traceability between the elements supported in the different views of the model and modeling of requirements, design elements and tests [7].

From the point of view of the application to energy efficiency, structural diagrams are important, particularly the block definition diagram and the internal block diagram. The block definition diagram describes the structure or decomposition of a part or a complete system. The internal block diagram shows the internal structure of a block: its parts, their interfaces and connectors between them.

Another diagram, which is part of SysML that may be used in the energy efficiency assessments, is the parametric diagram. Parametric diagrams are used to show relationships or equations between parameters and value properties of the blocks that make up the system.

The constraint block is used to define the equations assigned to the various parts of a system and is complemented by the necessary parametric diagrams representing the use of these equations in a context of analysis. In some cases, as in the example below, the use of the parametric diagram is simplified because the equations are executed with a particular computer tool.

SysML is a standard notation but not a method that dictates a system engineering process to be applied. We have adapted the method ISE & PPOOA (Integrated Systems Engineering and Pipelines of Processes in Object Oriented Architectures), used in the engineering or reengineering of complex products [8], for the evaluation of the energy efficiency of industrial installations. The steps of this iterative method, which we call ISE & PPOOA / Energy are summarized below:

• Step 1. Identify the context and boundaries of the system to be analyzed.

• Step 2. Obtain the functional and physical architecture models of the system of interest, using SysML notation and according to the ISE & PPOOA method.

• Step 3. Identify the main flows of matter and energy between identifiable system blocks.

• Step 4. Detail the equations, graphs, tables and correlations that determine the unknown values of the major flows of matter and energy.

• Step 5. Determine the degrees of freedom of the evaluated system to know if it is possible to solve it. If it is not possible because the degrees of freedom are greater than zero, the context and boundaries of the system are redefined and steps 2, 3 and 4 are repeated.

• Step 6. Solve the equations and correlations with the necessary computer tools.

Summarizing the above steps involve the identification of the system to be analyzed and the representation of the system architecture with system modeling techniques, particularly using the block definition diagrams and the internal block diagrams supported by the SysML standard. Steps 3 and 4 are performed by identifying the main flows of matter and energy using the information of interfaces and connectors found in the internal block diagrams that model the physical architecture of the system. For each flow what is known and not known is determined. In step 4 the equations, equalities and correlations are elaborated to obtain the unknown values in each one of the flows. Also, if necessary, process restrictions can be associated with some of the variables such as maximum temperature or pressure values. SysML constraint blocks, mentioned above, are used to show how the properties associated with the flows of matter and energy are constrained [6]. Step 5 establishes whether the number of equations and correlations identified in step 4 are sufficient to determine the dependent variables. In order to have a unique solution, the analyzed system should have zero degrees of freedom, that is the number of variables, including the quantities of matter and energy balances, should be equal to the number of equations combined with any other correlation used. If the number of degrees of freedom is positive, the system cannot be solved, forcing back to step 2 and performing logical groupings of physical blocks, see plant equipment, to reduce the number of dependent variables. Finally in step 6 the equations and correlations are solved using the appropriate computer tools.

3. Models and Equations of the Steam Generation System – The models presented below illustrate the results of the application of steps 2, 3 and 4 of the ISE & PPOOA / Energy system engineering method described in the previous section.

Figure 1 represents, by means of a block definition diagram in SysML notation, the constituent parts of the Steam Generator. This diagram could have more levels of decomposition if needed. The whole, that is to say the generation of steam system, has a composition relation represented by black diamonds with its parts.

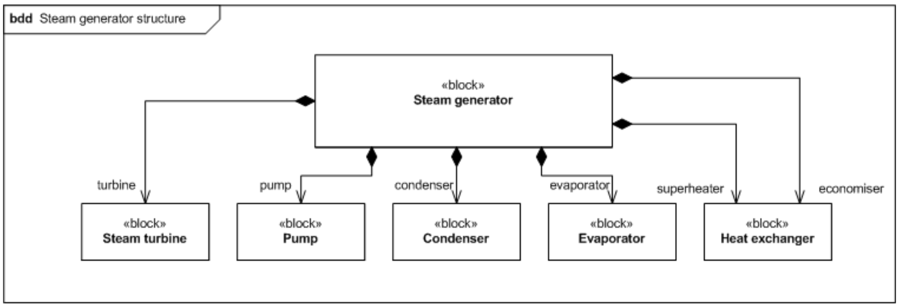

Figure 1. Steam generator block definition diagram

The parts are represented by blocks that can perform more than one role, for example the block heat exchanger can have the role of superheater or economizer.

The identification of the functions of the plant as a system is one of the main issues of the step 2 of the method. The functional decomposition of the generation of steam is represented using a SysML block definition diagram as the functional hierarchical tree (Figure 2).

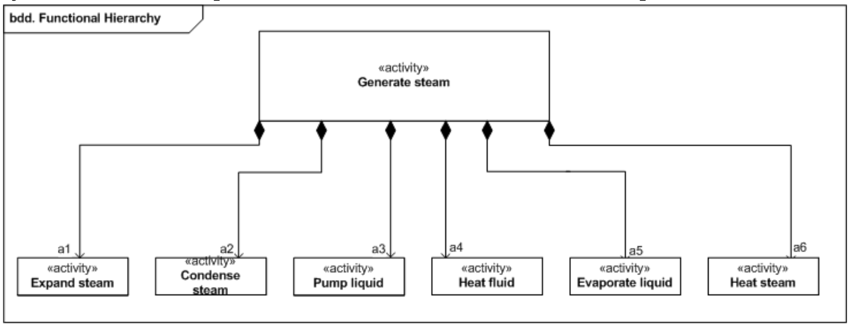

Figure 2. Functional hierarchy block definition diagram

Figure 3 shows a model of how the parts of the steam generator are interconnected with each other. This is done using an internal block diagram where flow ports and connectors are represented in SysML notation. Each flow is designated as m [ ], and can be an inflow or outflow to a block. The flow m_flue-gas, goes through the heat exchangers (superheater and economizer) and the evaporator. Finally, the refrigerant flow m_coolant is shown in the condenser, which will exchange heat with the flow m [2], becoming m [3] already condensed.

The blocks of Figure 3 also include the functions represented in Figure 2, which the physical parts of the steam generator perform. This functional allocation is very useful as information to replace one part or equipment with another with the same functionalities and interfaces if needed. The block definition diagrams with constraint blocks, which we will call constraints diagrams here, show the relationships or equations between variables and value properties of interest of the blocks or parts, which in this case make up the steam generation system.

Figure 4 represents a logical block that includes three physical equipment: economiser, evaporator and condenser. This logical block has been created following the guidelines of step 5 of the ISE & PPOOA /

Energy method in order to have zero degrees of freedom and to be able to solve the equations. The equation governing the behavior of the three clustered physical blocks is:

$$q = m[1]\ x\ (h[1] - h[4])$$

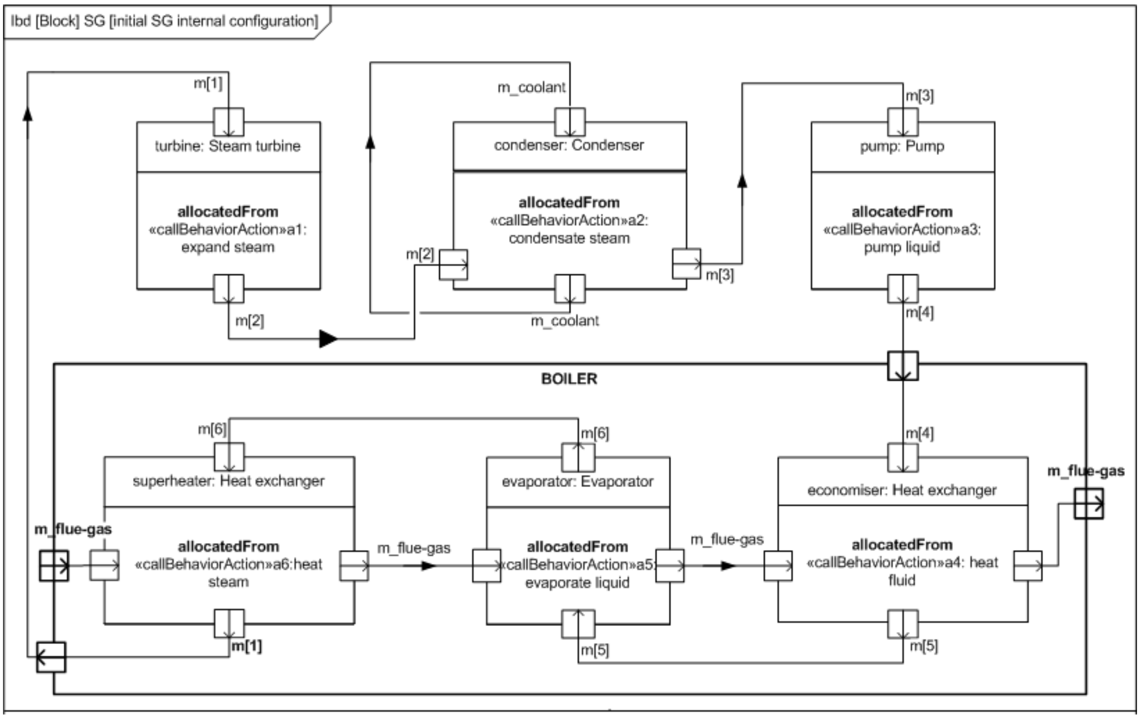

Figure 3. Steam generator internal block diagram

Where q is the heat supplied by the boiler or logic block that comprises economiser, evaporator and superheater, m [1] is the flow rate that flows through these three blocks, as shown in Figure 3, h [1] is the enthalpy of the boiler output, that is the enthalpy of the superheated steam at the outlet of the superheater and h [4] is the input enthalpy to the boiler or enthalpy of the fluid at the economiser inlet.

The equation governing pump behavior is:

$$Powp = m[1]x\ (h[4] - h[3])$$

Where it appears as new variable h [4] which is the enthalpy of the fluid at the outlet of the pump also shown in Figure 3.

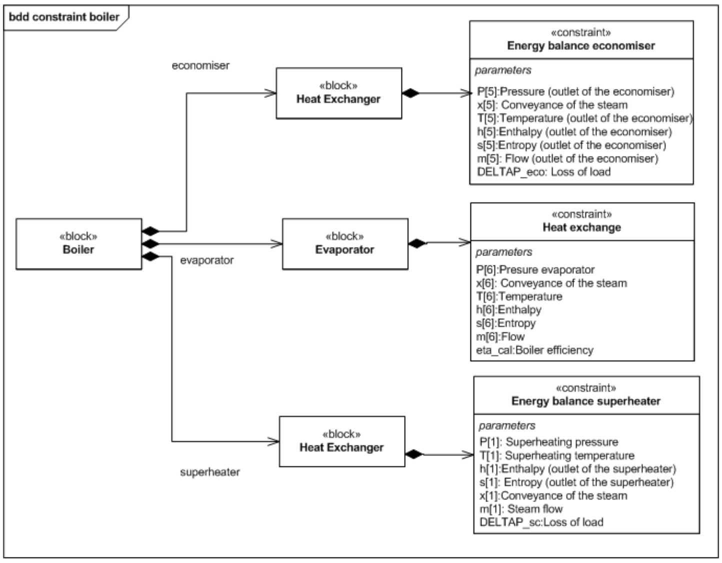

Figure 4. Boiler constraints diagram

The model of Figure 5 shows the constraints diagram of the steam turbine, in which case the power produced is reflected in the equation:

$$Powtb = m[1]x\ (h[1] - h[2])$$

Where h [2] is the enthalpy of the fluid at the exit of the turbine. It is important to note that the enthalpies for this and the previous equations are tabulated and depend on variables that will be parameterized in the execution of the simulation.

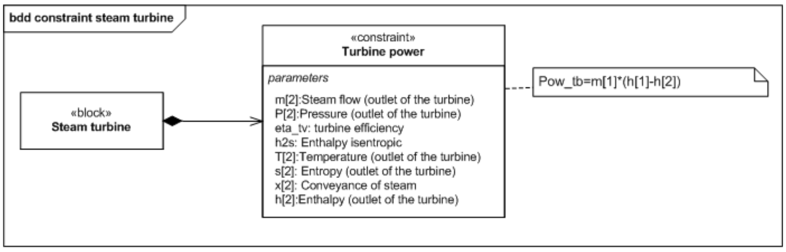

Figure 5. Steam turbine constraints diagram

Figure 6 is the constraint diagram of the condenser whose energy balance is reflected in the equation:

$$m_{steam} x\ (h[3] - h[2]) + m\_coolant\ x\ (hout - hin) = 0$$

Where m_steam is the steam flow rate that reaches the condenser and coincides with m [2] shown in Figure 3. As new variables appear hin and hout which correspond to the enthalpies of the coolant at the inlet and outlet and whose flow is m_coolant.

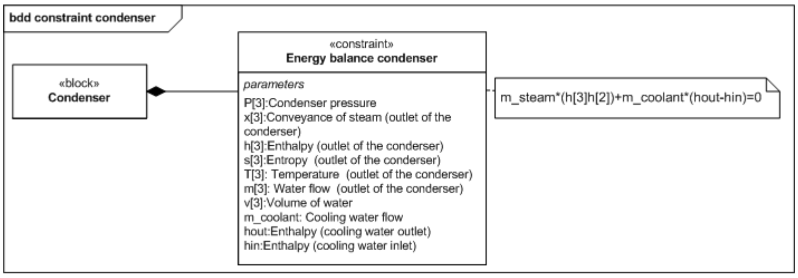

Figure 6. Condenser constraints diagram

4. Results and Discussion – In order to simulate different situations in the steam cycle, "Engineering Equation Solver" (EES) has been chosen. In addition it stores thermodynamic properties which facilitates the work and the necessity to go to tables or thermodynamic diagrams, which for this example would be required.

In order to execute the computer tool, some preliminary data of the coal power plant to be analyzed are needed, in this case the public data of a coal power plant of the northwest of Spain have been chosen. Once the results for the given conditions have been obtained and the model has been observed to be coherent and realistic, since it fits quite well with the actual conditions of the plant, it is possible to analyze which parameters would lead to an improvement in the performance of the plant cycle. For this purpose, three parameters have been selected. According to the results obtained, it is decided how these changes could be implemented in practice and if they are of economic interest.

The first parameter that has been selected is the superheat temperature, Tsh or T [1] in Figure 4. Thermodynamically, it is verified how the steam cycle efficiency increases when the hot source temperature is reached. The studied cycle allows to work with a temperature of superheat equal to 538ºC obtaining a thermal efficiency of 38,81%. If this temperature could be increased, the performance could be improved. But this is not easy, it must be considered the temperature limit imposed on steam is defined by the thermal stress conditions of the materials used.

The second parameter to be considered is the superheat pressure, Psh or P [1] in Figure 4. It is verified that the increase in the superheated steam pressure conditions leads to an increase in cycle efficiency. The cycle studied allows to work with a superheating pressure equal to 162 bar obtaining a thermal efficiency of 38.81%. If this pressure could be increased, the performance could be improved. It is necessary to take into account the stress conditions of the materials used. It can be concluded that it is not worthwhile to implement this improvement.

Finally, the third parameter to be studied is the condensation pressure, Pcond or P [3] in Figure 6. The pressure at which the condenser works in this case is 0.067 bar. Using the characteristic curves of the condenser, Figure 7, we analyze for a given load which is the most effective condensing pressure. The

temperature of the cooling water of the water-steam cycle of the selected plant enters the condenser at 18 ° C. If the load is approximately 350 MW, the condensing pressure can be reduced to approximately 0.058 bar. Introducing this new value it is observed that it would obtain a greater thermal efficiency of the cycle.
It is observed that bringing this improvement to practice can be a good option, since only one would have to act on aspects of the plant operation.

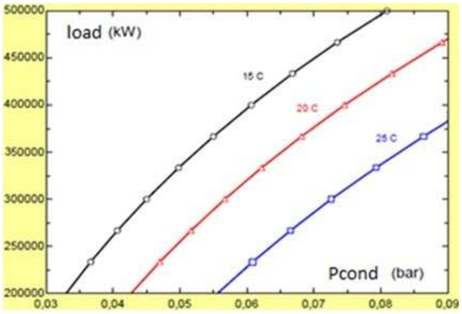

Figure 7. Condensing curves applied

5. Conclusions – Actions to improve the energy efficiency of an installation or part thereof may be carried out through operational changes, equipment upgrades or replacement. It is obvious that a purely technical approach would not suffice when economic and environmental considerations have to be taken into account.
The ISE&PPOOA/Energy method, presented in this paper combines the model based systems engineering with the matter and energy balance concerns, involving several activities integrated in a single engineering process, such as the definition of a context for the efficiency analysis, the modeling of the system to be analyzed and the resolution of the matter and energy balance equations at the appropriate level of abstraction represented by the block definition diagrams.
This method allows a study of alternatives that can range from the tuning of operating parameters to replacing equipment for a more efficient one but equivalent in functionality and interfaces with other elements of the installation, which is reflected in the internal block definition diagrams obtained by the application of model-based systems engineering.
The models are built with SysML standard notation that supports their wide understanding. The method used allows to describe the plant with the detail level needed for the efficiency analysis more rigorous that sketches but less detailed that the engineering deliverables for building the plant.

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