Multi-objective Approach to Analysis of Industrial Energy Systems

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ABSTRACT: Industrial energy systems are manifold and often highly integrated and thus complex to analyse. Existing software tools mostly cater for specialists and process planning engineers with the focus on production capability and robustness. This paper presents a software tool for the simulation and analysis of industrial production processes that is tailored to engineers with little experience in simulation such as energy consultants or energy managers. The tool is capable of performing the necessary calculations while focusing on energy consumption issues. The software allows different “perspectives” on a process chain, so that it can be analysed considering different aspects of the process such as economy, ecology or efficiency. To simplify the modelling and simulation process, methods for debugging of equation based modelling languages have been integrated in the tool. Furthermore analysis modules allow benchmarking of different variants against each other. The production of milk is used as an example to demonstrate the functionality of the software.

Keywords: industrial production, process chain, energy system, simulation, analysis, equation based language, energy efficiency

1. INTRODUCTION

Increasing costs and ecological considerations make energy efficiency crucial for nearly every producing company from small-scale enterprises to global corporations. The analysis of industrial energy systems often reveals measures for higher energy efficiency at lower production costs.

The term industrial energy system covers the energy related aspects of the production process as well as the energy supply system for the process. Analysis of such an industrial energy system is very complex, since multifaceted technologies interact closely with each other. Varying objectives of an analysis complicate the task as well: Constantly rising energy prices have made energy costs of a production process a key issue for operating companies and a major target for cost reduction efforts. Ecological evaluation of the processes is drawing the attention of process operators and customers alike. It comes along with understanding the energy related aspects of the processes and the energy supply system itself. More information about the performance of a process can be gained by taking thermodynamic key figures such as exergetical efficiencies into account.

A consequence of multiple objectives that are evolving around industrial energy systems is the need for efficient analysis of industrial energy systems. Efficiency of the analysis is also crucial because the results have to pay off the costs of the analysis itself.

Existing process engineering software tools can help users in planning, dimensioning and analysing their production processes in detail. A good example of such a tool is the Aspen software package [1]. These software tools are often not easy to use and for a short comparison of different variants to complex. Software tools for simulation and optimization of energy supply systems such as Ebsilon [2] are in a similar way unsuitable for the given task. They can only provide an optimized energy supply system based on a given load for a fixed production process. But the interaction of the characteristics of production with the energy supply system often remains unclear.

A software tool for analysis of industrial energy systems is presented to overcome the described hurdles of an efficient analysis. It caters for energy consultants and energy managers who lack a simple tool in order to optimize the energy relevant figures of a process.

2. BASIC CONCEPT

The developed tool addresses users that don't have much experience with simulation and usually don't have enough time to perform an extensive analysis of the energy system. Focus was set on energy intensive production processes like in the pulp and paper, chemical or food industry. Furthermore the tool focuses on the interactions between different process steps and not on optimizing single devices in the system. Possible applications may be the optimization of internal heat recovery, the dimensioning of cogeneration plants, the evaluation of a new technologies or the uncovering of energy paths through a production process.

2.1 Modelling and Simulation

The core component of the tool is the simulator, which is capable of calculating energy consumption, CO_2-emissions and other key figures for a given energy system. It is based on simple models of the technologies including energy and mass balances and characteristic diagrams. Different states of operation of the energy system are considered using multiple independent time steps, which are steady-state. The technology models and material properties are organised in so called "components". The component database can be extended using a modelling language that has been designed for this purpose.

2.2 The TOP-Energy Framework

A graphical user interface (GUI) is a necessary requirement for user-friendly and effective operating software. The presented tool is therefore tied to the TOP-Energy framework [3]. This toolkit for optimization of industrial energy systems provides a MS-Windows standard GUI which can be used intuitively by most users. The presented software also benefits from the TOP-Energy flow sheet editor, which allows graphical assembling of a system of given components and medium and energy flows between the components. The flow sheet editor is also capable of displaying results from the different "perspectives".

2.3 The concept of "perspectives"

The model of a component contains different "perspectives", i.e. sets of equations which characterise different aspects such as energy-, economy- or ecology-related figures. The segregation of the models into those perspectives allows a clearer overview, because only the aspects that are important for the users are simulated and evaluated. This assures an efficient analysis and a multi-purpose applicability. The concept of perspectives demands a decomposition of the simulated equation system, because not all parameters are always known by the user and the equation system may not be well-constrained.

2.4 Debugging of Equation Systems

Equation systems describing industrial energy systems are often very complex. But most of the users of this tool are not very experienced with simulation, because it is not their main task. Hence, methods for debugging equation systems are integrated in the tool. The equation system is decomposed in small blocks. The user is provided with information about over- or under-constrained parts of the system similar to [4]. The given information includes hints about which parameters are missing and what equations are possibly redundant or conflicting.

3. MODELLING AND SIMULATION

The simulation and modelling process is based on process chains that are composed of single components. Thus, the database of all components can be extended by the user. A modelling language and a flexible simulator are therefore essential for the practical value of this tool.

3.1 Process Modelling Language

Industrial production processes often contain feedbacks of mass or energy flows into the process which makes the use of algorithm based languages very hard. Therefore an equation based language has been designed. The so called Process Modelling Language (PML) has been derived from the Modelica [5] language.

The language allows the specification of stationary or quasi-stationary nonlinear models. At present the different time steps are independent of each other, which will be improved in the future. All variables and constants are modelled with their unit. The software uses the unit-conversion capabilities of the Engineering Type Library, which is included in the TOP-Energy Framework [3].

Assignments can be used in addition to equation based statements. These assignments can only be evaluated in one direction; hence the output variables are always the same. Furthermore functions from external libraries can be used in the simulator. Thus complex component behaviour or material properties can be simulated using external simulators. The equations and assignments belonging to different perspectives are entered in different sections, but as they are seldom independent of each other, one equation system is generated out of all equations. As the user only provides the information that is needed for his certain analysis, the overall equation system is mostly under-constrained. Therefore it is decomposed in a well-constrained and an under- and possibly an over-constrained system. The handling of these equation systems is described in the following section.

3.2 Simulation

The workflow of the simulation is shown in the following diagram.

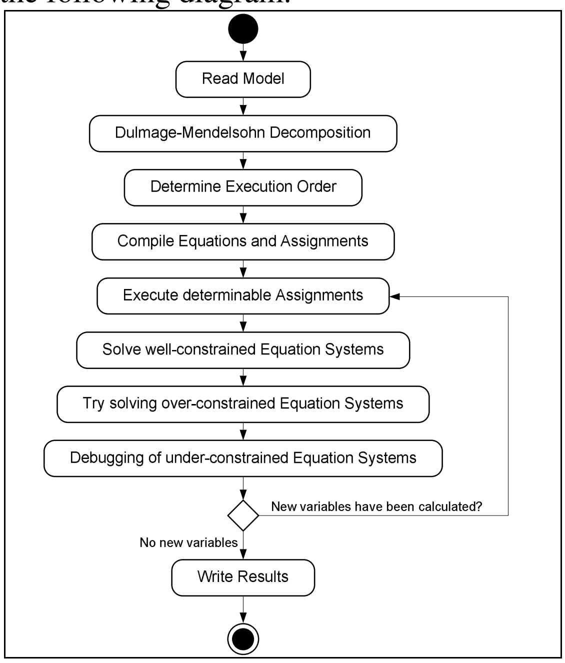

Figure 1: Workflow of the simulation

First the model is read and the equation system is congregated from the different components. Then the equation system is decomposed using the Dulmage-Mendelsohn decomposition [7]. This algorithm generates over-, under- and well-constrained equation blocks. The resulting blocks and assignments are sorted in a way, that variables calculated in one block can be used in the next one as input. The blocks and the assignments are translated to C-Code and compiled to a dynamic link library for faster execution. Algorithms with fully determined right hand sides are executed first. In the next step the well-constrained equation systems are solved using the Newton-Raphson method [6]. Finally the over- and under-constrained equation systems are examined. This is explained in chapter 3.4 and 3.5. If new variables have been calculated, the process is started again with executing assignments, otherwise the results are written back and the simulation is finished.

If an equation system contains time dependent variables, the calculation of the results is done for every time step individually. The resulting variables are thus time dependent as well.

3.3 Dulmage-Mendelsohn decomposition

The decomposition described by Dulmage and Mendelsohn [7] is used to generate debugging information and to speed up the simulation. The Dulmage-Mendelsohn decomposition uses a transformation of the equation system to a bipartite graph to decompose the overall equation system in smaller equation systems. The vertices of this graph can be divided in two disjoint sets of vertices, where one set represents the equations and the other represents the variables. The vertices are connected by an edge, if a variable is contained in an equation.

Figure 2 shows an artificial example of such a graph representing an equation system with 7 equations and 7 variables. Furthermore one possible maximum matching is displayed. A maximum matching is a matching that contains the largest possible number of matched edges and is usually not unique. The maximum matching can be used to determine whether a system is well-, over- or under-constrained. This is described in chapter 3.4.

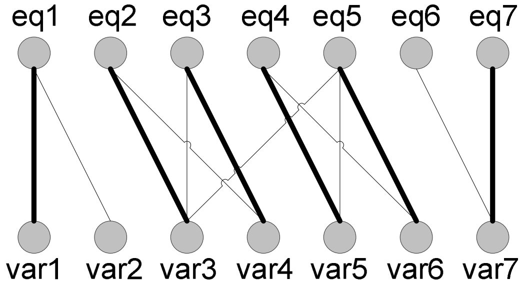

Figure 2: Bipartite graph and one maximum matching of the adjacency matrix in table 1

The advantage of this approach is that the graph provides information about possible calculation orders of the variables which can be used to deal even with over- or under-constrained equation systems.

	var1	var2	var3	var4	var5	var6	var7
eq1	1	1					
eq2			1	1			
eq3			1	1			
eq4					1	1	
eq5			1		1	1	
eq6							1
eq7							1

Table 1: Adjacency matrix of the graph in figure 1

In table 1 the adjacency matrix of the graph in figure one is shown. It can be seen, that the equation system has been separated into 4 subsystems. The well-constrained parts of this systems are the systems containing (eq2, eq3) and (eq4, eq5), which can be solved from the left to the right. Furthermore there is an under- and an over-constrained system in this example. The over-constrained system contains 2 equations (eq6 and eq7) and only 1 variable (var7) while the under-constrained equation system contains variable 1 and 2 in one equation (eq1). This matrix is used to provide the user with information about the unsolvable parts.

3.3 Under-Constrained Equation Systems

Usually under-constrained equation systems result from missing input parameters that have to be determined by the user. In complex models it is often hard to tell which parameters are needed to complete a certain equation system and calculate certain variables. Therefore the under-constrained parts of the equation system are analysed using graph-theoretical approaches. The bipartite graph of the given subsystem is traversed recursively to find all possible permutations of input variables that would make the subsystem solvable.

In the example above the error message would tell the user to enter var1 in order to calculate var2 respectively to enter var2 to calculate var1, both using eq1. This algorithm also works with complex correlations between the variables. It can propose sets of variables that are necessary to calculate a certain variable. The user can then choose a variable set that is known or easy to measure.

3.4 Over-Constrained Equation Systems

Over-constrained equation systems can be a result of an inconsistent model of the process but often result from redundancies. Examples for both cases are given below:

$$\begin{aligned} a+4&=6 \\ 6-a&=4 \end{aligned} \quad \text{Redundant system can be solved}$$

$$\begin{aligned} b+4&=6 \\ 6-b&=3 \end{aligned} \quad \text{Inconsistent unsolvable system}$$

Redundant equation systems are often a consequence of mathematical loops in the model and can be obviated by removing certain equations from the system. Instead of warning the user to remove these equations by hand, they are eliminated automatically by the solver to find a non-redundant equation system.

Over-constrained equation systems lead to unmatched equation nodes in the corresponding bipartite graph. This can be seen in the example in figure 2. Here eq6 and eq7 form an over-constrained equation system and eq6 is unmatched.

Over-constrained equation systems are solved by enumerating all maximum matchings in the bipartite graph as described in [8]. The resulting matchings are solved ignoring unmatched equations until one of the systems is free of redundancies. The redundancy of an equation system is tested by changing the start values. If one equation system gives different results for different start values, the system is not well-defined and may contain redundancies.

In the example in figure 2, eq6 or eq7 can be ignored. The resulting 1x1 equation system is solved and the results are tested for consistency with the unused equation.

4. EVALUATION TOOLS

A lot of simulation tools lack a user-friendly evaluation of the results. Again, simulation is not the main task of energy consultants and managers. Thus, evaluation of simulation results can be time-consuming, if the important values have to be found among numerous variables. Hence the presented software provides two separated tools which enhance user-friendly and efficient evaluation of process simulation results.

The first tool is called eVariant. It is designed to readout, structure and visualise key results of <u>one</u> process simulation. The values of pre-selected simulation results are imported from the process simulation. They are structured according to the different perspectives. Hence, it is possible to evaluate only those results that are important for the user’s objective. The key figures are visualised in tables and charts which can both be exported to standard data processing software.

The general goal of many industrial energy system analyses is the comparison of varying systems. Differences can be alternative process technologies, boundary conditions or composition of the components. The second evaluation tool is therefore designed to compare key results of several process simulations. This tool is called eValuate. It uses the key figures of up to 4 eVariant data sets. Again, the comparison results are visualised in tables and charts. Key benchmark numbers can be calculated in order to find the most suitable system for the user's objective.

4.1 Evaluation of Simulation Results

The physical component models used in the process simulation include pre-defined "interface"-variables. These variables are read out by eVariant. The values of the interface-variables are calculated by the process simulation. The variables are regularly included in every component model but only set by the process simulation if it is demanded by the user's physical model equations. The following variables were defined as key figures for the different perspectives:

Mass perspective:
The only interface variable of the mass perspective is the mass flow of streams. Using the mass flow of every material stream in the system, generation, flows and losses of all occurring substances can be analysed in eVariant.

Energy perspective:
Energy flow is similar to the mass flow the key variable of the energy perspective. eVariant can identify main consumers of different energy forms (electricity, heat, material bound enthalpy) within the industrial energy system allowing the deduction of saving potentials.

Exergy perspective:
Exergy key variables are the electrical exergy flow, exergy of heat flow and exergy bound to material streams (chemical and thermal). Using these variables, eVariant calculates the rates of exergy destruction and enables the rating of components according to their exergetical efficiencies.

Economy perspective:
The key figures of the economy perspective are different costs which can occur in components of industrial energy systems. According to [9], cost types are capital-linked, consumption-linked, operation-linked payments, other costs and possible savings. These variables allow economic evaluation of a system according to standard methods such as the capital value or annuity method.

Ecology perspective:
The ecology perspective key figures are direct and indirect flows of global warming potential (GWP). Here, direct GWP is a flow of a substance that generates green house gases inside a balance boundary. Indirect GWP is linked to energy or material flows and accounts for the GWP generated by the production/generation of the material or energy flow outside of the balance boundary.

eVariant delivers information about "consumers" and "producers" of the different flows inside the balance boundary as well as information about flows leaving or entering the balance boundary. This information can for example be used in an ABC-Analysis. The balance boundary may vary depending on the objective of an analysis. Especially economical evaluations often use balance boundaries like cost centres that are very uncommon for energetic evaluations.

The user can decide for every component within its industrial energy system if it should be inside or outside of the balance boundary. Consequently, the balance boundary can easily be changed for a different kind of analysis.

5. EXAMPLE: MILK PRODUCTION

To show the capabilities of the simulator the production process of milk has been analysed. This production chain is very interesting because of the high degree of heat recovery and the high energy intensity. The modelling detail of the process steps is very low and covers simple energy or mass balances. Most of the other correlations are given by characteristic diagrams.

The simulated process covers all steps from the raw milk to the consumable fresh milk. Figure 3 shows the model of the production process, as it is displayed in the TOP-Energy Software. The raw milk comes from the left and is preheated to 60°C. Afterwards it is separated in cream and skim milk. The skim milk is put through a microfiltration and a bactofugation to extend the shelf life. The fresh milk that is produced is called ESL-milk (extended shelf life). The cream is heated up to 125°C and mixed with the skim milk to adjust a certain fat content. Afterwards the milk is heated up to 75°C and cooled down to 3°C again. In Figure 3 the heating and cooling of cream is displayed in the upper half and the skim milk flows in the lower half of the figure.

5.1 Modelling of Process Steps and material properties

The fresh milk production process basically consists of heat exchangers, pumps, separators and mixers. In the separators low and high fat milk are separated from each other so that in the process of standardisation a specific fat content can be set. The heat exchangers are modelled with a constant heat transfer coefficient and a constant heat exchanging area. Pumps are modelled using a characteristic curve that is fitted to measured data.

All parameters have been determined using measured data from a milk production site in Germany. The specific electricity consumption for the separation has been measured to 1.35kWh/kg and is considered to be constant. Other electricity consumptions are also considered to be mass dependent and have been measured.

Most types of milk can be modelled as ideal solution of water, fat, carbon hydrates, proteins and mineral nutrients [10]. Raw milk for example consists of 87.5% water, 3.8% fat, 4.7% carbohydrates, 3.3% proteins and 0.7% mineral nutrients.

5.2 Results

The described process has been analysed using the tool. The model contained 1782 equations, 140 assignments and 1733 variables. It could be reduced to 1686 (1x1)-blocks and 8 bigger blocks using the Dulmage-Mendelsohn decomposition. 120 under-constrained blocks could not be solved, but debugging messages where generated for the variables in these blocks.

The simulation results show that the degree of heat recovery is very high. The heat flows are illustrated in TOP-Energy by enhanced energy and process flow sheets, as shown in figure 3.

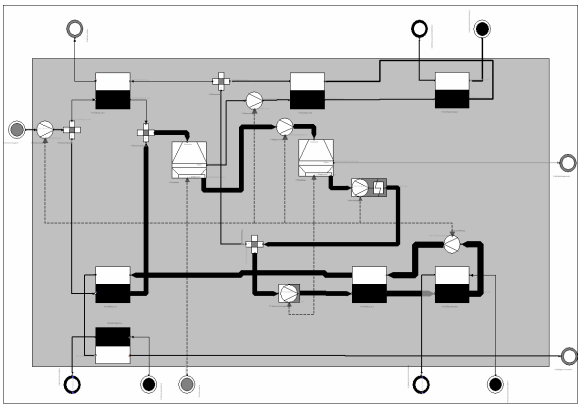

Figure 3: Enhanced energy and process flow sheet of the milk production process

Enhanced energy and process flow sheets of each perspective illustrate the specific key figures mentioned in 4.1. Figure 3 shows the energy perspective of the production process. The thickness of the lines is proportional to the energy flow. It can be seen that most of the energy circulates in the lower right part of the process, which represents the pasteurisation process.

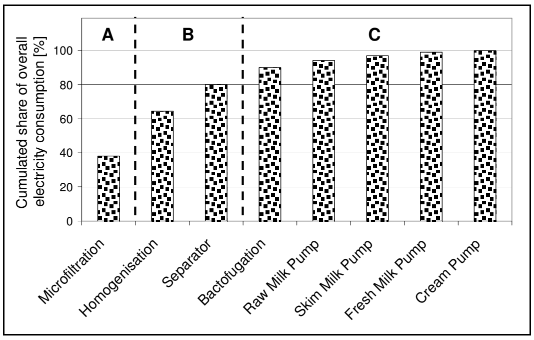

Figure 4: ABC-Analysis of electricity consumption in the diary production

Figure 4 shows the result of an ABC-Analysis of the electricity consumption of the process as it is produced by eVariant. It becomes clear, that most of the electrical energy is consumed by the microfiltration. A reduction of the electrical energy in this process is probably most effective.

As the extension of the shelf life provided by the microfiltration leads to a higher margin and the microfiltration system was quite new, an optimization of the homogenisation has been recommended instead. The homogenisation operated at high pressures that led to high electricity consumptions. A reduction of the pressure led to a higher energy efficiency.

6. SUMMARY

Using the new eProc simulation tool, industrial energy systems can easily be modelled and simulated. The simulator is tailored for the simulation and analysis of process chains with focus on energy optimisation. Using graph-theoretical approaches, the simulator is capable of generating meaningful error messages for equation based languages. Taking the production of fresh milk as an example it could be shown that standard process components and compound properties can be simulated. The simulation revealed an optimisation potential in the analysed milk factory.

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