Piecewise-Steady-State Modelica Simulations for the Conceptual Design Phase of Industrial Processes

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Abstract

The conceptual design of industrial processes is challenging as relatively little information about the eventually selected equipment and their operation is known in this early design stage. Furthermore, the systems are increasingly integrated with themselves, and their design must be addressed systematically. Simulation can assist in better understanding the effects of design decisions on the resulting system performance. To facilitate the simulation of industrial processes in this early design phase, this paper proposes an approach to modeling system components specifically aimed at employing known key design parameters and assuming steady-state behavior of the process for a certain period of time (e.g. one hour). A solution over a longer period of time (e.g. for a year) can then be obtained by simulating a multitude of such shorter periods, leading to the piecewise-steady-state solution. The proposed approach is developed with an exemplary case study, based on a real industrial site. The resulting model computes the annual load profile within the range of seconds for the given case study.

Keywords: Piecewise-Steady-State, Conceptual Design, Process Simulation, Energy Systems

1 Introduction

The design and the optimization of industrial processes must be addressed systematically. In the conceptual design phase, engineers evaluate how different process-requirements can be fulfilled with various technologies and with different combinations of possible unit operations. This generally includes the design of heat exchanger networks including energy conversion units such as (absorption) heat pumps, gas turbines, or (organic) Rankine cycles. However, the plant design is restricted to consider a limited number of operating points due to its requirement of manual execution of specific steps. Nevertheless, many processes are undergoing changes over time, such as annual load variation or intra-day operation changes. This also applies with increasing intensity to energy supply systems, especially when considering (local) renewable energy sources. In the conceptual design phase, it may neither be of high relevance nor appropriate to attempt to address these fluctuations with detailed dynamic simulations of the processes as this level of detail may be too intensive on engineering cost, while the necessary boundary conditions and especially process parameters are neither known nor relevant in this phase. Therefore, the processes can often be described sufficiently accurately when assuming piecewise-steady-state behavior of the process over a certain period of time, in which the operating conditions do vary only negligibly and which are significantly longer than the dynamic response of the individual components. The evaluation of a multitude of such periods allows for the quantitative analysis of the system through a larger period of time. The, in this phase, unknown system dynamics can therefore be neglected and the models can be reduced to their steady-state characteristics.

Modelica is often used for the simulation of such thermal systems. As it can be seen on the Modelica Library overview (Modelica Association 2023a), various libraries – open-source and commercial – address these systems specifically. Furthermore, Modelica software developers are developing an increasing amount of functionalities specifically targeting the steady state evaluation of models. These tools mainly target the calculation of one steady-state operation point. In this way, they may also be used to simulate design points of industrial processes. In the conceptual design phase, the customarily required set of parameters describing the physical entity of each system component is, however, not known.

The research gap addressed in this paper is the change in the modeling requirements compared to existing libraries when simulating industrial processes in the conceptual design phase. Using an example from a waste incineration plant, this paper describes how Modelica may be used as a simulation framework to model the steam turbine process with corresponding heat utilization based on its steady-state characteristics and available design parameters. The simulations are performed to analyze the performance of the system on an annual basis. The novelty introduced is the use of piece-wise steady-state modelica models that employ design reference values as system parameters instead of estimated physical properties that are not known in the given design-phase.

2 Case Description

The analysis described in this paper is part of an ongoing project and lays the foundation for comparing system performance considering different yet to-be-defined system

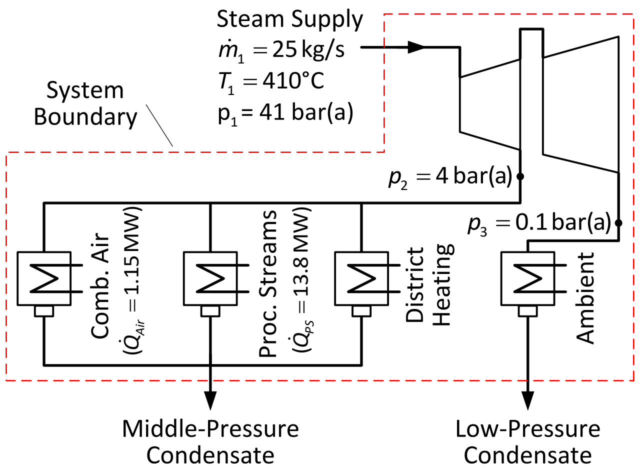

Figure 1. Schematic of the system under consideration.

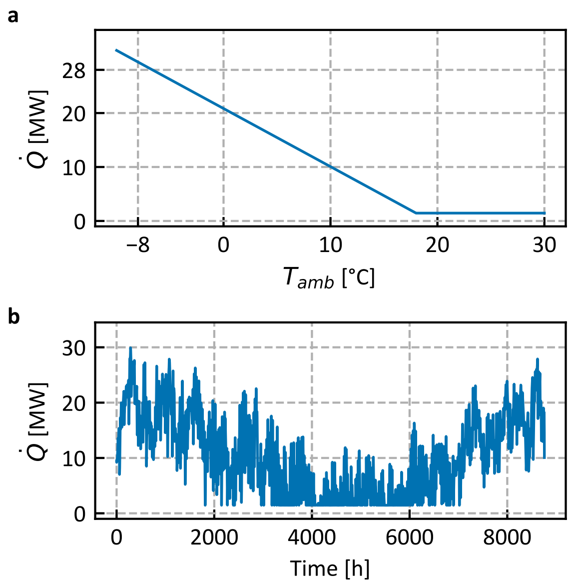

Figure 2. Heat load curve (a) and annual load profile of the assumed district heating network (b) when applying the heat load curve of (a)

configurations. Various energy conversion units may be included in the analysis in the future step. The core part of the analysis, the steam turbine and heat utilization process of a waste incineration plant, is described subsequently. The data is anonymized and simplified from the real case under investigation by the authors.

Overall, the core part of the system (depicted in Figure 1) is governed by the supply of steam from a waste incineration furnace, which can be assumed to work continuously over the year, delivering steam at $p_1 = 41\,\text{bar}$ and $T_1 = 410\,°\text{C}$ with a mass flow rate of $\dot{m}_1 = 25\,\text{kg/s}$. Subsequently, the steam is expanded in a two-stage steam turbine. The turbine considered is equipped with a steam bleed on the medium pressure level at $p_2 = 4\,\text{bar}$ (between stages one and two). Different heating demands are to be covered by this bleed steam, including combustion air preheating, a district heating network and various process streams (summarized in one aggregated heating demand called process streams). While most processes are due to their link to the main waste furnace constant, the district heating demand varies by nature. To account for this variation, in this early design phase, a simple linear heating curve, specified by a heating limit of $T_{HL} = 18\,°\text{C}$ and a nominal heating load of $\dot{Q}_{nom} = 28\,\text{MW}$ at the nominal ambient temperature for the heating system design of $T_{amb,nom} = -8\,°\text{C}$ is assumed. This nominal ambient temperature corresponds to the climatic conditions in Zurich (SIA 2010), the heating limit is chosen based on the experience of the authors with similar systems. To account for the domestic hot water consumption, a constant load of 1.5 MW is added to the heating curve. This value corresponds to a split of 84 % space heating demand and 16 % domestic hot water demand based on the Swiss end-energy consumption statistics (Kemmler and Trachsel 2022). The annual load profile is then calculated with the design reference year data of the Meteonorm database (Meteotest AG 2023) for Zurich which provides the hourly averages of the ambient temperature. Since district heating systems possess rather large inertia (storage, volume of the pipes and inertia of the heat consumers), a rolling-mean filter was applied with an assumed four hours averaging window. Figure 2 shows the assumed heating demand in relation to the ambient temperature in the form of the heat load curve and as the resulting hourly profile, which is later imported into the Modelica simulation.

The remaining streams are defined by their constant heat load as follows:

- Combustion air preheating: $\dot{Q}_{Air} = 1.15\,\text{MW}$
- Process Streams: $\dot{Q}_{PS} = 13.8\,\text{MW}$

3 Model Description

Since the parameters of the physical entity of the planned components in the system under consideration are only specified in later design phases, the models used in the proposed simulation approach must be formulated differently than typically seen in thermal energy system simulation. In the case of a condenser, for example, it shall be prescribed that the steam be condensed fully to its bubble point or subcooled to a given temperature. Thus the model shall accept corresponding parameters instead of the parameters of an eventually selected component, such as its heat transfer area or its heat transfer coefficient. Naturally, this specification affects the resulting models' structure and reduces their universal applicability. Additionally, boundary conditions must be chosen such that the overall model is well-defined. Considering these restrictions, an overview description of the derived models is given in the following sections.

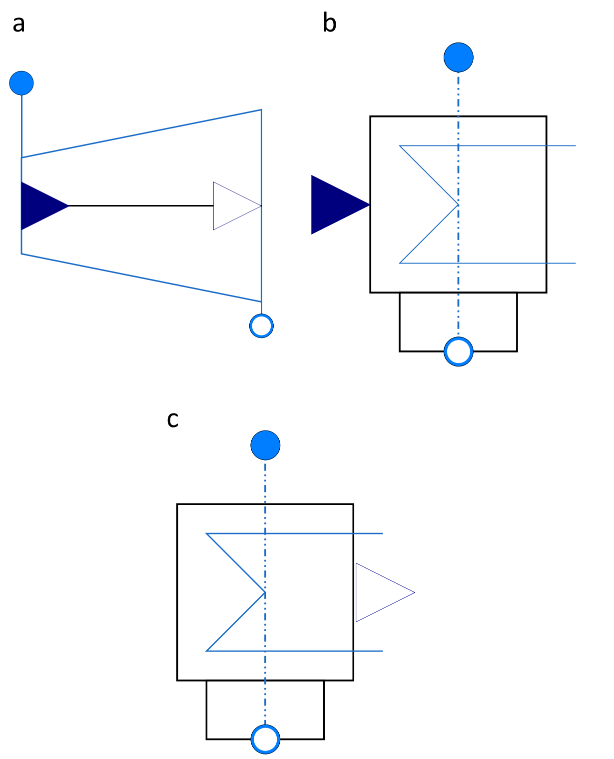

Figure 3. Icon of (a) one turbine stage, (b) of the condenser with prescribed heat flow rate and (c) of the low-pressure condenser after the second turbine stage.

3.1 Steam Turbine

In the considered model, the individual turbine stage is modeled based on typically available design parameters:

- Outlet pressure p_ω
- Isentropic efficiency η_s
- Combined mechanical and electrical efficiency $\eta_{el.+mech.}$

Based on these three parameters and the given inlet conditions governed in the overall model (see section 3.4), the model can be implemented to describe the steady-state characteristics of the turbine stages as follows (See e.g. Baehr and Kabelac (2012) for further references):

$$P_{el} = \dot{m}\,(h_\alpha - h_\omega)\,\eta_s\,\eta_{el.+mech.} \quad (1)$$

Where P_{el} is the generated electric power of the turbine stage, $\dot{m}$ the steam mass flow rate, h_α and h_ω the specific enthalpies at the in- and outlet of the turbine, respectively. Using the isentropic efficiency, h_ω is expressed as follows:

$$h_\omega = h_\alpha - (h_\alpha - h_{\omega,s}(p_\omega))\eta_s \quad (2)$$

Where $h_{\omega,s}(p_\omega)$ is the enthalpy at the outlet of the turbine if the expansion to p_ω would occur isentropically.

The turbine stage is therefore parameterized with its efficiencies and the outlet pressure of this stage. These values can be obtained at the very beginning of any design process of a steam turbine process.

3.2 Steam Condensers

To model the utilization of the middle-pressure steam (after the first turbine stage) for different heating requirements, a set of condenser models was developed (see Figure 3b and Figure 3c).

For the simplest case of a prescribed heat flow (Figure 3b), the model requires only the outlet condition of the condensate (temperature or steam quality) as a parameter. The prescribed heat flow is implemented as an input signal to the block.

In the given case study, the pressure losses can be neglected as there are no subsequent components after the condensers, but could also be later integrated as an additional parameter of the models.

Therefore, the outlet enthalpy on the steam side of the condenser can be calculated with the specified outlet temperature or steam quality and the pressure at the inlet (prescribed by the upstream component). With this known outlet enthalpy h_ω the energy balance is as follows:

$$\dot{Q} = \dot{m}\,(h_\alpha - h_\omega) \quad (3)$$

With the described case of a prescribed heat flow rate $\dot{Q}$ for the middle-pressure condensers, the mass flow rate $\dot{m}$ is calculatable, and Modelica's equation-based modeling concept can be applied directly.

The resulting variation of $\dot{m}$ directly employs the typically used control concept of a mass flow variation with a throttle valve on the steam side. However, no control parameters have to be specified in this, proposed way.

The condenser of the low-pressure steam after the second turbine stage must be modeled slightly differently, as the heat flow rate may not be specified by an input, but it is the result of the condensation of the entire steam flow after the second turbine stage. With a slight alteration of the condenser model described above, this objective can be achieved. The energy balance (Eq. 3) remains the same. The only alteration in the Modelica code is removing the heat flow rate input. Additionally, the mass flow rate of this component must be specified in the overall model, utilizing the proper boundary conditions as described in the following section. Again, the only parameter needed for this component is the outlet temperature or the steam quality of the condensate.

3.3 Boundaries and Data Sources

The boundaries are adapted from the Modelica Standard Library (Modelica Association 2023b) but altered to prescribe pressure, enthalpy and mass flow rate at the steam source and none of them at the condensate sink. Therefore, they must be used together to result in a well-defined system of equations.

The heat load of the district heating system is imported from the *Combi Time Table* block of MSL 4 (Modelica Association 2023b) utilizing the Extern Data Library (Beutlich and Winkler 2021) to facilitate data exchange with the external data source.

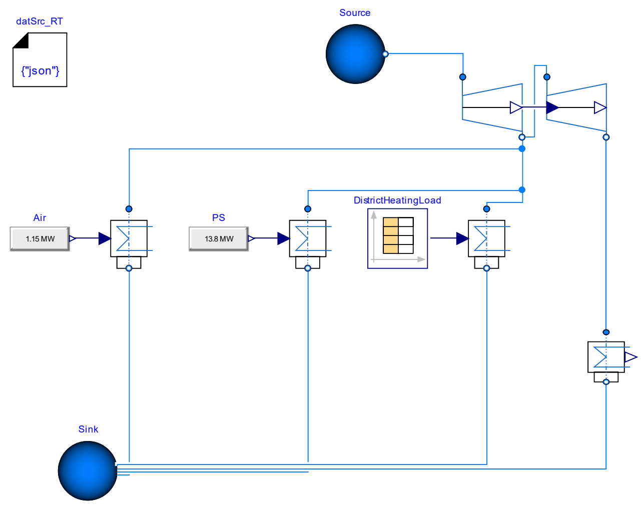

Figure 4. Complete model of the considered part of the steam turbine process with two turbine stages and four condensers.

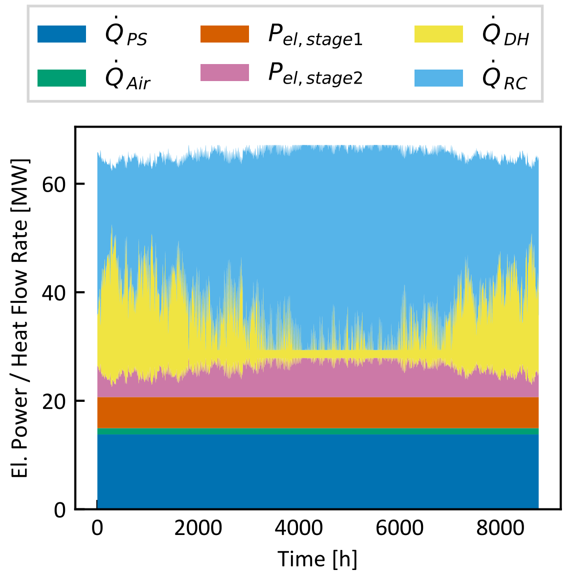

Figure 5. Stack plot of extracted heat flow rates and electric powers from the system.

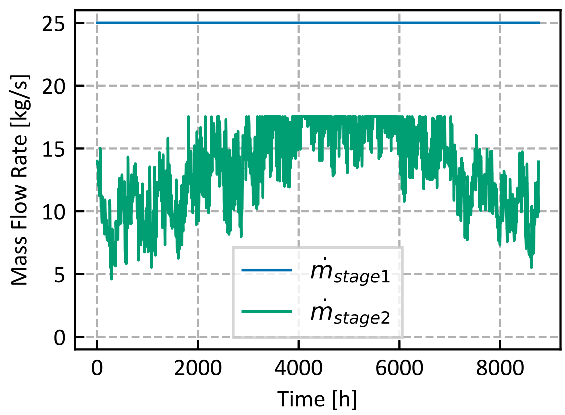

Figure 6. Mass flow rates through the two turbine stages throughout the year

3.4 Resulting Overall Model

When modeling the overall process as shown in Figure 1 with the components as derived in the previous sections, the Modelica model of Figure 4 is resulting. For the following simulation study, the parameters according to Table 1 have been set, where the outlet conditions of the condensers are prescribed with the respective temperature T or steam quality x:

Table 1. Used parameter values in simulation study

Variable	Value
η_s	0.8
$\eta_{el.+mech.}$	0.9
$p_{\omega,2}$	p_2
$p_{\omega,1}$	p_3
$T_{\omega,cond,Air}$	50 °C
$T_{\omega,cond,PS}$	70 °C
$T_{\omega,cond,DH}$	100 °C
$x_{\omega,cond,RC}$	0 (bubble point)

Annual system simulations were performed to evaluate the functionality and performance of the described modeling approach. The steady-state solution of each timestep (in this case, one hour) is computed. The calculated steady-state solutions for each hour of operation are then analyzed to create an overview of the resulting operating points of the eventual system. The specification of the boundary conditions is given in section 2 and the parameterization is given in section 3.4.

4 Simulation Results

This initial simulation aims to validate the model's functionality and to perform first investigations of the effects of varying middle-pressure steam utilization on electricity production. Using Dymola® 2023 with the Dassl (Petzold 1993) algorithm and the Visual Studio 2019 C++ Compiler, a total CPU-time for the integration of approximately 1.5 seconds results on a Notebook with an i7-1265U CPU and 16 GB of RAM.

Figure 5 shows the duties of the different components under consideration. Electricity and heat extracted from the process are added up in the vertical of the stack plot to give an overview of the shares of the different quantities over time. It can be seen that roughly 65 MW of heat or electricity is extracted from the plant throughout the year. The total extracted load varies slightly as the condensate leaves the system at different enthalpy levels, and the turbines' mechanical and electrical efficiency $\eta_{el.+mech.}$ leads to further losses. The condensate of the middle-pressure steam is leaving the system in the range of 50-70 °C, while the condensate of the low-pressure steam at the recooler is leaving the system at 46°C (i.e., the bubble temperature at 0.1 bar) (See section 3.4). The plot's three lowest entries depict the constant heat extraction for the process streams, the combustion air preheating and the electricity extracted through the first turbine stage. Thereafter, there is mainly a trade-off between heat utilization for the district heating network and electricity production with the second turbine stage. The recooling heat flow corresponds with the electricity production of the second stage, as there is a direct link between the two components.

When analyzing the turbine more thoroughly by studying the steam mass flow rate of each turbine stage as shown in Figure 6, it can be seen that i) the mass flow rate of the first stage is expectedly not varying as no steam consumers are in parallel to this stage, an ii) the steam mass flow rate through the second stage varies greatly in the chosen concept. A part load ratio in terms of the mass-flow rate of 26% would result (minimum vs. maximum of mass flow rate in stage 2). Since this might pose challenges for the detailed design of the turbine and the corresponding controls, changes in the conceptual design may be investigated to improve system operability.

5 Discussion

The chosen approach of piecewise-steady-state system simulation for the considered steam process leads to a relatively lightweight model that computes annual load simulations in the scale of seconds. To be able to obtain these results, the overall model must be formulated in a way, that the given physical relationships are sufficient. The Modelica modeling concept assists in formulating such models as the balance equations can almost directly be entered in the respective Modelica source code. The graphical representation and interactive connection of the different components allow additionally the adaption of changes of the components and model re-utilization for similar applications.

The chosen approach for system parameterization using the design values such as isentropic efficiency and condenser outlet temperatures instead of the physical quantities like heat transfer area or turbine geometry enables the modeling of the system as it should be designed in the later design phase without having to fine-tune component specifications with the latter sets of parameters. The presented case-study demonstrates the applicability of the proposed modelling approach, while more sophisticated design tasks must be addressed in the future to showcase the ability of such models to support design decisions. Comparing to the traditional design workflow where only few data points are calculated manually the herein proposed approach offers insight into a large range of possible operating conditions and enables the study of the individual process parameters in detail. This approach thus allows to make design decision based on the performance in various operating conditions and enables additionally the quantification of the performance of the system for a representative period of time (e.g. one year).

On a numerical point of view, the removal of the dynamics of the models should allow for the use of lower-order integration methods to further reduce the computation time. A comparison of different integration methods is thus also needed in the future.

6 Conclusion

In this paper, a novel approach for the simulation of thermal energy systems in the conceptual design phase has been presented. It was shown, that the models should be formulated differently when simulating a process in the conceptual design phase than in later phases. The developed simulation models consisting of steam turbines and condensers enable piecewise-steady-state Modelica simulations for the analysis of the annual performance of the example case-study in the scale of seconds in integration time. The main contributions can be summarized as (i) the formulation of the components to be compliant with the available parameters and (ii) the implementation as simplified models treating the systems as piecewise-steady-state in their behavior. Further development of the chosen approach is identified in the development of a general-purpose model library and in the extension of the available unit operations with a focus on energy conversion units. Furthermore, more exhaustive case studies need to be analyzed to demonstrate the viability of the chosen approach. This would also allow to identify possible challenges in the solvability of models with the proposed approach and to derive more general modelling guidelines.

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