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Framework for the Quantification of the Process Flexibility in Industrial Processes

Abstract: This paper presents a framework for quantifying process flexibility in energy-intensive industrial (EII) sectors, such as metal manufacturing, wastewater treatment, and glass container manufacturing. The methodology involves four steps: identifying energy flexibility sources, creating an optimization model, calculating upper and lower energy consumption limits, and validating the model's functionality. The framework is applied to two EII processes: a feeder process in a glass container factory and an aeration process in a wastewater treatment plant. The optimization model minimizes energy consumption while maintaining process constraints, and the results are validated through more accurate models and real-world testing. This approach aims to enhance the profitability of factories by leveraging variations in electricity prices and novel electricity market flexibility products and services.

Keywords: flexibility, optimization, demand response

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1 Background

The energy sources used by industry are becoming increasingly volatile. This has created a need to identify flexibility potentials, especially in processes within energy-intensive industrial (EII) sectors, e.g. metal manufacturing, wastewater treatment, and glass container manufacturing. Knowing the flexibility potential of processes enables using the variations in electricity prices and novel products and services of the electricity market to improve the profitability of factories.

Flexibility sources external from the process are, for example, solar panels, material storage, or batteries. In addition to these sources, it is also beneficial to identify and model the internal flexibilities of the processes in question. However, quantifying the internal process flexibility is not as apparent as quantifying external flexibility such as the capacity of the battery or a storage container.

Previously, the running methods of continuous processes have been well established and the internal flexibility of the processes has been used mainly to ensure robustness. In this case, the need for flexibility has been very predictable and constant. However, in the future, the flexibility potential used can vary very significantly on a daily basis.

2 Aims

To challenge the established methods of process control, a credible, teachable and reproducible framework is needed to quantify the implicit flexibility in each process. In this work, this universal framework for flexibility quantification is created, and its applicability is tested by implementing it to two different EII processes: A feeder process for a glass container factory and the aeration process of a waste water treatment plant.

The framework needs to be able to calculate the optimal energy consumption and the possible upper and lower limits for the energy consumption during each time step.

3 Materials and Methods

The designed framework consists of four steps:
1. Identifying the energy flexibility sources from the process
2. Creating the optimization model for the process
3. Using the created optimization model to calculate the upper and lower limits of energy consumption for each time step
4. Validating the functionality and outputs of the optimization model

In the first step, the process state-of-the-art is thoroughly studied with the help of process engineers, op-

erators, and literature. The aim is to find overcapacity or physical storages, which would imply that there is flexibility in the process. The process of identifying the flexibility potentials are studied more thoroughly in [1]

The next step is to formulate the governing equations of the process using mass and energy balances. Often, the existing process equations might be complex or non-linear, which, for the sake of computational efficiency, need to be simplified or approximated to be linear. Any optimization methods and formulations are applicable as long as they converge reliably within the allocated time and are deemed accurate enough in the validation step. Additionally, in the third step, the process constraints are assessed and then formulated into the optimization model.

After the optimization model is developed, it is first used to calculate the minimum energy consumption of the process for the desired optimization horizon. This is the baseline with which the upper and lower limits of the process are then described. Using the cost structure of the optimization model, we then proceed to weigh each step with higher and lower costs compared to the other step costs. Higher cost result giving the lowest limit for energy usage during that step and lower cost giving the highest limit for energy usage during that step. These limits are calculated for all steps in the optimization horizon.

The calculated limits and the corresponding decision variable values are then given as an output of the flexibility quantification to e.g decision support system (DSS) or energy management system (EMS). Before deployment and integration to the control system, the given values have to be validated to be accurate enough in the validation step. If the model is not accurate enough, it will be refined by returning to step two of the quantification sequence. After the model is validated, it is ready to be deployed and integrated into the process control system[2].

In the next two subsections we implement this framework into two different EIIs: Glass container manufacturing and wastewater treatment.

3.1 Feeder process flexibility quantification

In the feeder process, the input is the molten glass stream coming from the furnace into the feeder system. The output is the gob of glass, which is later formed into a glass container. In this study, the incoming glass flow is heated from the top of glass flow by gas burners. There are five of these heating zones from input to output. At the final zone, there are nine temperature measurements arranged in three different heights and widths of the flow for controlling the homogeneity of the temperatures.

As the first step, the flexibility potential was identified to be in the thermal capacity of the glass. At certain times, the glass flow can be heated or left to cool while still retaining the temperature homogeneity target at the final zone.

Second step is to create the optimization model. The cost function (eq 1.) minimizes the energy consumption via gas consumption and the glass heterogeneity in the final zone for the whole time horizon.

$$\min w_1 \cdot \sum_{\substack{z \in Z \\ k \in K}} c_k g_{z,k} + w_2 \cdot \sum_{\substack{i,j \in \{1,2,3\} \\ k \in K \\ z \in S}} \frac{V_k + H_k}{\max(T_{k,z_f})} \quad (1)$$

where g is the decision variable, representing the gas openings for each heating zone. c is the cost vector that defines the cost of energy usage for each time step k. Second term minimizes the temperature differences in vertical V and horizontal H directions in the final zone z.

The heat transfer equations that define the main optimization problem constraints can be formulated as in (eq 2.)

$$\text{s.t.} \quad T_{i,j,z}(k+1) = T_{i,j,z}(k) + \overline{\alpha}_{i,j,z} \cdot \Delta \overline{T}_{i,j,k},$$
$$\forall i \in I, \forall j \in J, \forall z \in Z \quad (2)$$

where α-vector includes all the heat transfer coefficients for the element i,k,z and $\Delta \overline{T}$-vector has all the corresponding temperature differences for that element. By changing the weights in the cost vector c, the model quantifies the flexibility potential in the process.

The model is constructed as 3x3x5 uniform temperature glass volume elements. Each element is modeled as a plug flow with ideal mixing. Heat transfer equations for convection, conduction, and advection are written as constraints of the optimization problem represented with matrix A. There are constraints for each of the six sides of every volume for every time step in the whole optimization horizon. Other constraints are the allowed maximum and minimum temperatures for each volume.

In the fourth step the cost for energy usage is varied and the corresponding flexibility potentials are recorded and sent for validation. The suggested gas openings are then validated first in an accurate computational fluid dynamics model for the process and then in the real process.
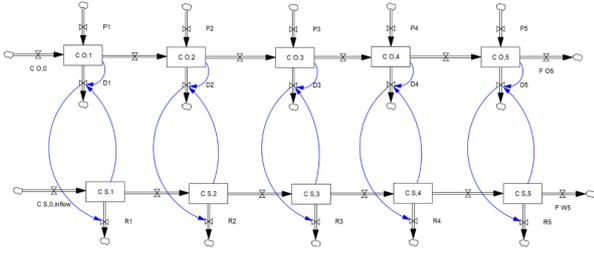
Fig. 1. Aeration process formulation with two parallel flows. Upper flow is the oxygen flow and the lower flow is the organic material.

3.2 Aeration process flexibility quantification

The wastewater treatment plant that this framework was tested on uses the prevalent active sludge process to remove the organic material of septic sewage and municipal wastewater. As the aeration process is the main consumer of energy in this plant, it was chosen as the best subprocess to test the designed framework on. In the aeration tank, the incoming sewage and wastewater from the primary sedimentation flows through lanes one to five, before exiting into secondary sedimentation. On every lane there is a group of mechanical aerators that increase the amount of dissolved oxygen which the bacteria in the active sludge needs in turn to consume the organic material in the wastewater.

The identified flexibility source needed in step one is here the overcapacity of the aerators, since they do not have to be used at maximum power at all times. The average hydraulic retention time is approximately 20 hours so there is a possibility to delay the aeration into the later lanes while still retaining the target concentration of biochemical oxygen demand (BOD).

In the second step of the framework the optimization model of the aeration process was formulated. This was done as two parallel mass flows of organic material and dissolved oxygen that affect each other as seen in (kuva). The underlying flow of active sludge, that is recirculated into the aeration tank from the bottom of secondary sedimentation, was approximated out of the optimization model to increase the calculation speed. This approximation was based on the tight DO constraints in each lane which should assure that the critical amount of active sludge will remain in the process at all times.

The objective function minimizes the combined aerator usage over the time horizon of next N hours as seen in (eq. 3)

$$\min \sum_{i=1}^{N} c_k \cdot x_k \tag{3}$$

where c is the cost vector of each time step k of energy usage. x is the decision variable for combined usage of all aerators in the tank. Optimization is constrained by the mass flow equations for sewage and oxygen consentrations and hard limits for DO consentration and BOD output from the tank.

Cost vector in the (eq. 3) is then used in the third step of the framework to calculate the energy flexibility potentials from the process as explained. The calculated results are then validated from non-linear active sludge model (ASM1) based simulator before deployment and integration.

Acknowledgement

References

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