

## Modeling the energy consumption of chemical batch plants using a combined top-down/bottom-up approach

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### Abstract

A top-down approach was used to investigate, whether or not it is possible to correlate the overall energy/utility consumption with the total amount of chemicals produced in a chemical batch plant. This approach was suitable for monoprodukt batch plants but not for multiprodukt and for multipurpose batch plants that produce a large variety of different products.

For one of these latter plants, detailed measurements of steam, brine and electricity consumption on apparatus level (bottom-up approach) were undertaken and corresponding models for single unit operations were built. These models describe the most important physico-chemical phenomena of the different unit operations but also comprise empirical terms accounting for apparatus-specific energy losses. This leads to a bottom-up model of a multipurpose plant which was tested for different periods. The model results showed good agreement with the measurements and demonstrated the applicability of the postulated approach. It was therefore possible to analyze the consumption of the different energy carriers in more detail on the basis of the bottom-up modeling results.

The obtained models can be used to forecast energy requirements and to allocate energy costs to different products in multipurpose/multiprodukt chemical batch plants. Furthermore, they can be used for optimization purposes and for the design of new, energy efficient chemical batch processes.

**Keywords:** energy consumption, batch plant, modeling, process intensification

### 1. Introduction

In contrast to continuous processes, studies on energy consumption or energy saving potentials for batch processes are limited and corresponding methods are not yet well established (e.g. Linnhoff, 1993; Klemes et al., 1997; Heyen and Kalitventzeff, 1997). Furthermore, such studies are often focused on heat-integration (e.g. Bouhenchir et al., 2001) and therefore rely on available storage capacity or constant production schedules. The use of these methods in batch production is limited because most of them are considered as too complicated, lengthy, demanding, and complex to be of practical interest for most of the cases encountered (e.g. Stoltze et al., 1995).

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No models are available in the literature to compute the energy consumption of multipurpose batch processes, accounting for the consumption caused by the chemical process itself, the consumption due to the equipment specification and especially the losses of the different apparatus. We developed such models on the basis of extensive measurements in a multipurpose batch plant. This bottom-up approach is also needed for the modeling of the energy consumption of the whole building when the correlation between overall energy/utility consumption and the total amount of chemicals produced, i.e. a top-down approach, is not suitable. Both approaches and their applicability will be discussed in the following.

## **2. Top-down approach for modelling energy consumption in chemical batch plants**

### **2.1 Methodology**

Consumption of the different utilities was measured on building level. These data were collected on a monthly basis. Besides these energy consumption data, the production output (tons of products) of the different buildings was determined on a monthly basis as well. For each utility, a model that computes the energy consumption of a building as a function of the specific consumption per ton of product was postulated:

$$E = A * PO + B \quad (1)$$

where,  $E$  is the overall consumption of a specific utility in a specified period,  $A$  is the specific utility consumption per ton of products,  $PO$  is the production output on a weight basis during the period specified (including all products and intermediates leaving the plant, excluding solvents and aggregate), and  $B$  is the so-called base consumption of the building. The base consumption is the consumption of a warm production building that is ready to start production but in which no production process is actually running (i.e., base consumption measures infrastructure consumption and infrastructure losses).

### **2.2 Results**

The consumption of the utilities electricity, steam and brine was investigated in different buildings. Figure 1 shows the results obtained for electricity. These investigations exclude the electricity consumption for cooling purposes since this is investigated separately.

The electricity consumption of Buildings 1 and 2 is barely correlated with the monthly production because the different production processes vary in reaction time and in batch size, which is not always correlated with equipment size. For buildings 3, 5 and 6 good correlations between electricity consumption and amount of chemicals produced are obtained. Although in Building 3 about 160 different chemicals are produced, the production processes are quite similar. In Building 5, each production line is exclusively constructed for one product originating from the same family. Therefore the product mix stays constant over the year. Also building 6 shows a good correlation between electricity consumption and production output. Since only one specific product is produced in this building and the production process is highly automated, the

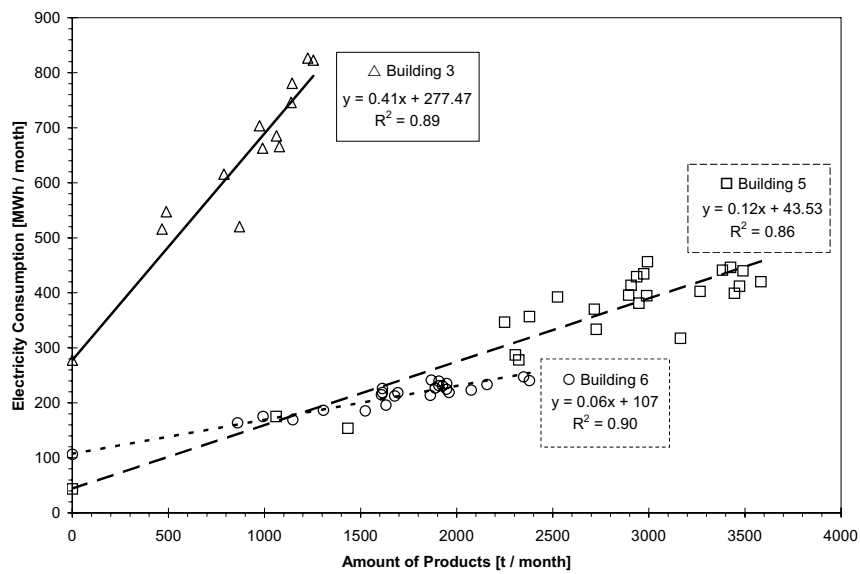
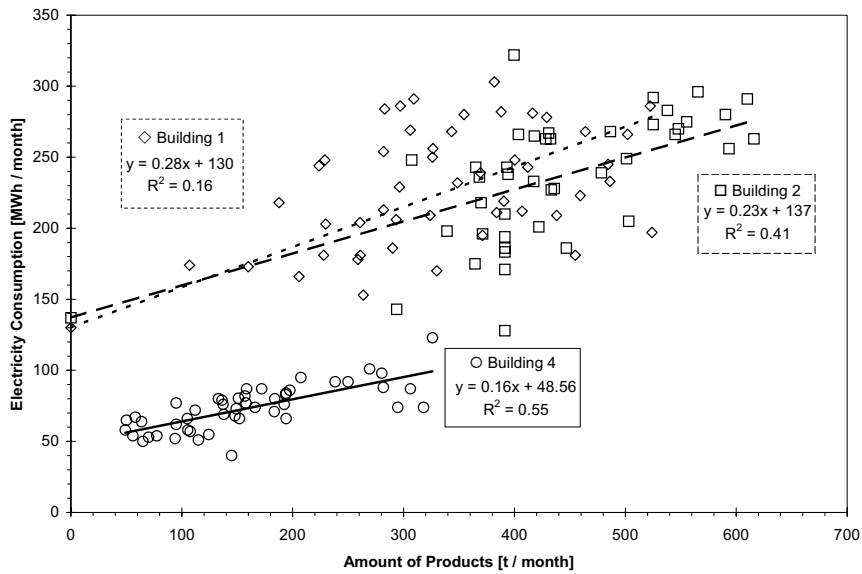


Figure 1: Top-down approach: electricity consumption (without cooling) of different buildings as a function of the amount of chemicals produced per month.

differences between different batches are minimal. Therefore, this set of data shows the highest correlation coefficient. Building 4 is a drying plant. The drying of different chemical products shows differences in drying time and initial moistness. The equipment sizes in this building do not vary largely. The electricity consumption is

dominated by motors for vacuum pumps and stirring and the differences between products are minor. Overall, a medium range correlation coefficient results.

The high flexibility of a multipurpose batch plant implies a high flexibility of the infrastructure equipment. The equipment is therefore built to handle the highest possible requirement of the plant. This explains the high base consumption of Buildings 1 and 2 as shown in Figure 1. The lower percentage of the base consumption of Building 3 as compared to Buildings 1, 2 and 4 can be explained by the large motors of the big reactors in this building and the limited variability of the produced chemicals (which makes it easier to size the utility equipment).

Similar results were also found for the utilities steam and brine (Bieler et al., 2003). In summary, for plants with only minor changes in production mix, it is possible to obtain a good description of energy consumption by the use of Equation (1). The energy consumption per ton of product depends significantly on the plant usage. The higher the plant usage, the smaller is the ton-specific energy consumption because of the constant base-consumption of the building, thus providing possibilities to optimize the production plan of such buildings.

### 3. Bottom-up approach for modelling energy consumption in chemical batch plants

#### 3.1 Methodology

In Building 1 from Figure 1, in which the top-down approach failed, extensive measurements of single apparatus and unit operations were conducted leading to simple, adaptable models for the consumption of steam, electricity, and brine. These single apparatus and unit operation models are summed up according to the production schedule and the corresponding process step procedures or the production reports. These models describe the most important physico-chemical phenomena of the different unit operations but also comprise empirical terms accounting for apparatus-specific energy losses. As an example, Equation (2) describes the steam consumption (subscript  $St$ ) of a batch reaction vessel (subscript  $RV$ ):

$$E_{i,RV,St}^P = \left\{ \left( m_{RM} \cdot \left[ c_P^{RM} \cdot \Delta T_{RM} + \Delta H_R^{RM} \right] + m_{ES} \cdot \Delta H_V^{ES} \right) + \left( \left[ m_A \cdot c_P^A + m_W \cdot c_P^W \right] \cdot \Delta T_A \right) + \left( K \cdot A \cdot \Delta T_{Am} - \eta \cdot \gamma \cdot P_N \right) \cdot t \right\} \cdot f \quad (2)$$

where  $E_{i,RV,St}^P$  is the production dependent steam consumption (either 5 or 15 bar) of a reaction vessel,  $m$  represents the masses of the reaction mass, the evaporated solvent (subscript  $ES$ ), the apparatus, or the water in the heating/cooling-system (subscript  $W$ ), respectively,  $c_P$  represents the heat capacities of the reaction mass, of the material of the apparatus, or of the water of the heating/cooling-system, respectively,  $\Delta T$  represents the temperature increases of the reaction mass, the apparatus or the temperature difference of the apparatus to the ambient temperature (subscript  $Am$ ), respectively,  $\Delta H_R$  is the reaction enthalpy (note that negative values of  $\Delta H_R$  represent exothermic reactions),  $\Delta H_V$  is the heat of vaporization,  $K$  is the loss coefficient,  $A$  is the surface area of the vessel,  $\eta$  is the efficiency of the stirrer motor,  $\gamma$  is the ratio of actual power

to nominal power consumption of the stirrer,  $P_N$  is the nominal power of the stirrer motor,  $t$  is the batch time, and  $f$  is a conversion factor of  $1/(3600 \text{ s / h})$  to convert kJ into kWh. The full model is given in Bieler et al. (2004).

### 3.2 Results

The model results showed good agreement with the measurements and demonstrated the applicability of the postulated approach (Bieler et al., 2004). It was therefore possible to analyze the consumption of the different energy carriers in more detail on the basis of the bottom-up modeling results.

In Figure 2, the steam consumption of Building 1 is analyzed with the bottom-up model for the period of one month using input data from the process step procedures (PSP) of the chemicals produced in this period. The total modeled steam consumption for this month is 1,354 MWh. This is the actual, modeled, consumption, since reaction and stirrer input reduce the modeled consumption for about 80 MWh and about 23 MWh, respectively. The hatched fields in Figure 2 represent the consumptions not directly related to the chemistry of the process (i.e., base consumption, losses, etc.). This consumption is responsible for about 63% of total steam consumption. Activities for achieving steam savings should therefore concentrate not only on the actual production process but should also deal with the reduction of the base consumption, the losses, the heating of the vessels, etc. It can be seen from Figure 2 as well that the apparatus group *Reactors & Nutsche Dryers* is responsible for the main part of the steam consumption (mainly because of the large losses). The base consumption in the bottom-up model can either be obtained by measurements or as parameter  $B$  (see Equation (1)) from the application of the top-down model.

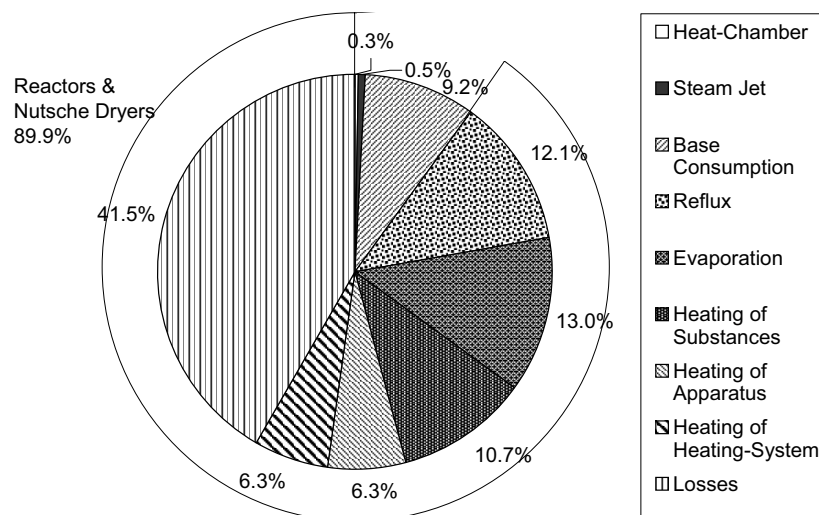


Figure 2: Bottom-up model: overall steam consumption (5 & 15 bar) in Building 1.

Figure 3 shows that the assumption of similar specific energy consumption for all of the different products as postulated in the top-down model is not true for the specific steam consumption in Building 1. The products vary widely in the specific steam consumption for the different unit operations. The number of synthesis steps given in Figure 3 together with the steam consumption of the different products shows that no correlation is possible. Like the different products, different synthesis steps require different amounts of energy. Top-down approaches are therefore not applicable in such a case. The modeling of one month and one week for two products (G and J) shows the accuracy of the model for both periods (see Figure 3).

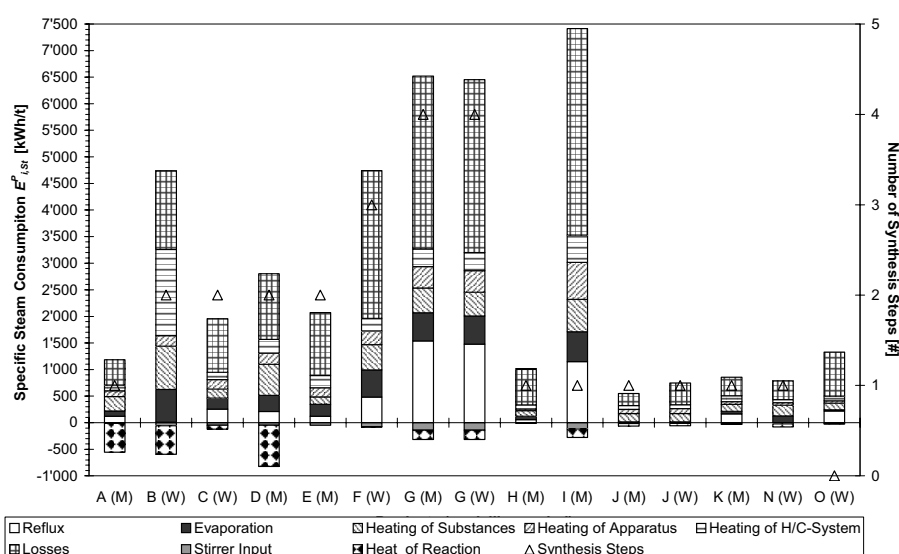


Figure 3: Specific steam consumption of thirteen different products A, ..., O calculated for one week (W) and for one month (M).

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