The Identification of Utility Constraints in a Batch Manufacturing Facility

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Abstract. Batch manufacturing is an appropriate production technique in the case of high-value added and low volume products such as specialty chemicals, pharmaceuticals and cosmetics. Although batch manufacturing can easily utilise the available utilities, i.e. heating and cooling resources, having shared heating and cooling utilities can introduce constraints in the scheduling of batch manufacturing processes. Such constraints result from the limited heating or cooling resources available at the manufacturing time of a batch. Utility constraints can lead to longer manufacturing time. In addition, the constraints in the utility system can lead to excessive fuel gas consumption or higher electrical loads especially, in case of having high production orders. In this work, the identification of constraints in the utility system of a healthcare batch production facility is performed. Heating and cooling demands for products are quantified based on the digitized batch manufacturing records and the production schedules for the studied period. The total heating and cooling rates are compared against normal and maximum duties of heating and cooling supply systems to identify the cases of excessive utility demand.

Keywords. Batch manufacturing, utility constraints, data analytics

1. Introduction

Manufacturing of high value-added and low volume products is preferably achieved in batch manufacturing environments due to the ease of utilising the available resources [1]. Processing of raw materials in a batch manufacturing facility producing speciality chemicals, paints, cosmetics or pharmaceutical products requires different heating and cooling demands. Depending on what heating and cooling target temperatures are specified in the product manufacturing recipe, the required process heating and cooling resources are determined. Heating can be achieved through electrical or solar heating systems as well as through external heating mediums such as steam or hot water. Cooling, in most cases, is achieved by using external refrigerant or cooling water. In several batch manufacturing environments, utilities such as heating and cooling are shared by many process equipment. The availability and consumption of such utilities need to be observed to ensure that they do not exceed their maximum limits [2]. Unlimited utilities is not the typical situation in most industrial facilities. Limited shared utilities can present a bottleneck in the manufacturing process, which can result in increased production duration, decreased production throughputs and increased environmental loads for the production facility. These issues demonstrate the importance of studying and analysing the levels of the available utilities in a batch manufacturing facility. The terms utility and resource can be mutually used since the concept of “Resource Task-Network” or RTN was introduced by Pantelides to represent the real plant entities (equipment, utilities, labour…etc.) in mathematical models [3]. Additionally, utilities such as steam, cooling water, manpower and electricity are considered as renewable resources, which are completely restored when the task finishes [4]. When the total demand of a certain utility, or a resource, over a time period approaches or exceeds the maximum amount of the available utility, then that utility represents a constraint for the manufacturing process [5]. Behdani *et al.* categorised the utility constraints into three categories; utility consumption, availability and supply constraints and proposed a formulation to optimise the demands and supply of utilities based on optimal scheduling [6].

In this work, heating and cooling demands for a batch manufacturing facility are quantified after digitising the manual batch manufacturing records. The total heating and cooling rates for all the batches manufactured between April 2017 and April 2018 are analysed. To identify if utility constraints are present in the studied manufacturing facility, the maximum heating or cooling rates will be compared with the normal and maximum capacity of their supply. If the energy demand is close to or higher than the maximum capacity of the energy supply, then that utility represents a constraint. Reasons for excessive heating or cooling rates are also suggested.

2. Methodology

In the studied batch manufacturing facility, topical healthcare products are manufactured in various mixing vessels depending on the required volume of each product. After raw materials are added to the mixing vessels, heating and cooling are applied to achieve the required target temperatures, which differ depending on the manufactured batch. In order to achieve the required temperatures, heating and cooling water are circulated through an external jacket surrounding the mixing vessel. Heating water is supplied by utilising a gas-fired boiler while cooling water is produced by a refrigeration unit. The hot water produced by the gas-fired boiler is used to heat the water sent to the mixing vessel via a heat exchanger as shown in Figure 1. A similar concept produces the cooling water for the mixing vessels via a refrigeration package.

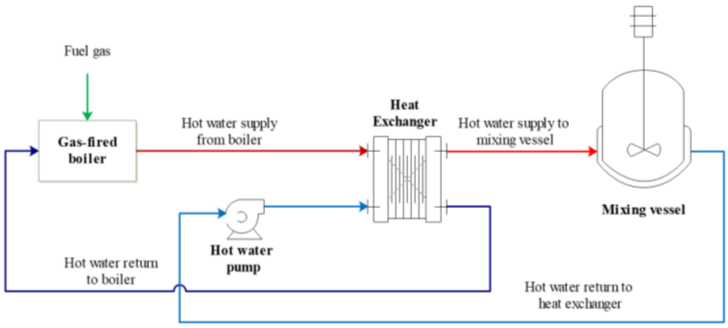


Figure 1. Schematic drawing for hot water supply system to a mixing vessel.

The data of the manufactured batches between April 2017 and April 2018 is collected from the manual batch manufacturing records then digitised in order to analyse the data using MATLAB. The digitised batch records include the batch size, in-service vessel, heating start/end times, cooling start/end times in addition to the initial and final temperatures. For some products, the actual temperatures after heating were not recorded so, these values were assumed based on the guidelines in their batch manufacturing standards. The digitised data is used to quantify the required heating and cooling demand by using Equation 1, which gives the energy ($Q_{req,i}$) required to heat or cool a batch i between initial and final temperatures. By dividing the energy required ($Q_{req,i}$) by the difference between heating or cooling start and end time, the heating or cooling rate ($q_{req,i}$) is calculated as illustrated by Equation 2.

$$Q_{req,i} = m_i C_{P,i} \left(T_{final,i} - T_{initial,i} \right) \tag{1}$$

$$q_{req,i} = \frac{Q_{req,i}}{t_{end,i} - t_{start,i}} \tag{2}$$

Where $Q_{req,i}$ is the energy demands for heating or cooling batch i in kJ, m_i is the batch i mass in kg, $C_{P,i}$ is the specific heat of the batch i content in kg/kJ.°C, $T_{initial,i}$ and $T_{final,i}$ and are the initial and final temperatures of batch i respectively in °C, $t_{start,i}$ and $t_{end,i}$ are the start and end time in minutes for heating or cooling respectively and $q_{req,i}$ is the required heating or cooling rate of batch i in kJ/min.

The initial temperatures for the batch content were required to calculate the heating rate however, these values were not available in the batch manufacturing records. As water, which is the main raw material used in the studied products, is stored in outdoor tanks, the initial batch temperature was assumed to be 15.5 °C in the summer and 7.7 °C in the winter. These values correspond to the average outdoor water temperature in Sligo [7].

After heating and cooling demand and rate are quantified for each manufactured batch i, the profiles of the total heating and cooling rate over the period are plotted in Figure 3 and 4. This requires the calculation of the total heating or cooling rate at every minute. As parallel batches can be manufactured simultaneously, the total energy demand per minute can be calculated by adding the required heating or cooling rate for all the parallel batches being manufactured at the same minute. To determine the total energy rate ($q_{total,t}$) at every minute t, individual heating or cooling rate ($q_{req,i}$) for each batch i are added after assuming that $q_{req,i}$ is linear with respect to time. Figure 2 illustrates an example of the total energy rate for three batches where the area under the curve represents the total energy demand in kJ.

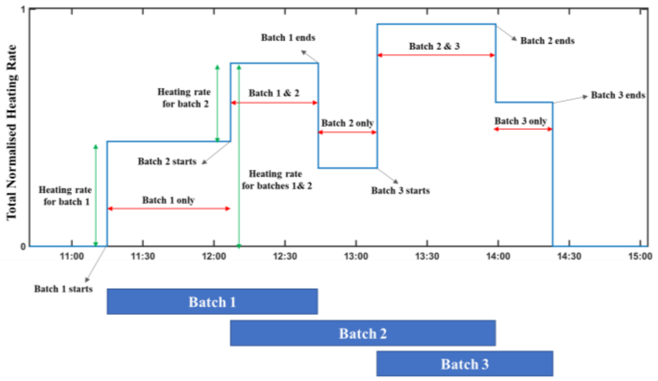


Figure 2. Example of total heating profile for multiple batches.

The total heating or cooling rate ($q_{total,t}$) at every minute t is compared against three values; 60 percent (%), 80 percent (%) and 100 percent (%) from the maximum duty of energy supply packages. These values are chosen to represent different utilisation ratios of heating and cooling systems. This works as a reference to identify which energy supply system is more constrained by referring to these values. The production periods that require high energy demand are identified as those that approach the total capacity of the energy supply system.

3. Results

The profiles of heating and cooling demands are shown in Figures 3 and 4. In each figure, 60 percent (%), 80 percent (%) and 100 percent (%) of the maximum duty of the heating and cooling utility supplies are indicated. In Figure 3, the heat profile is plotted based on two different initial temperatures, which equal 7.7 °C and 15.5 °C. It is rational that the lower the initial temperature, the higher the required heating load. So, the heating rate values based on 7.7 °C are always higher the values calculated on the basis of 15.5 °C. After investigating the six cases when the heating rates exceeded the 100 percent (%) line, it was found that there are discrepancies in the recorded heating start and end times for the batches manufactured at the dates of these cases. The recorded data reveals unlikely short heating times, which resulted in very high heating rates. There are several cases when the required heating utility exceeded the 60 percent (%) of the maximum duty of the heating supply system while there are fewer cases that exceeded the 80 percent (%) line.

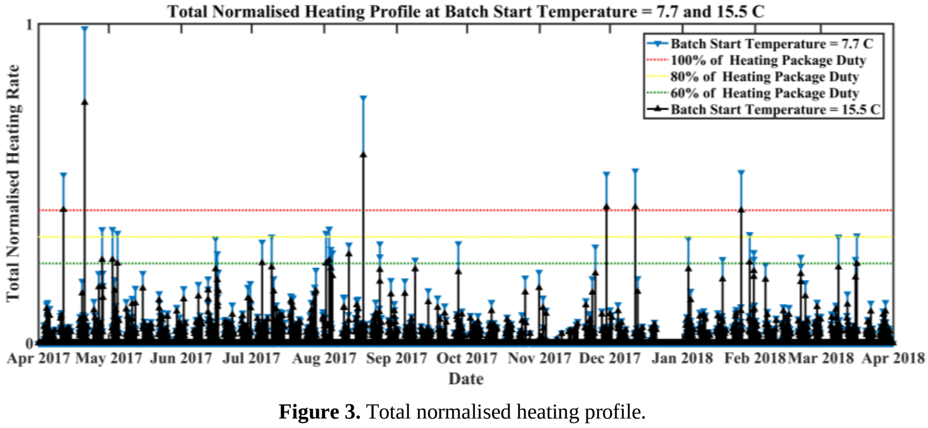
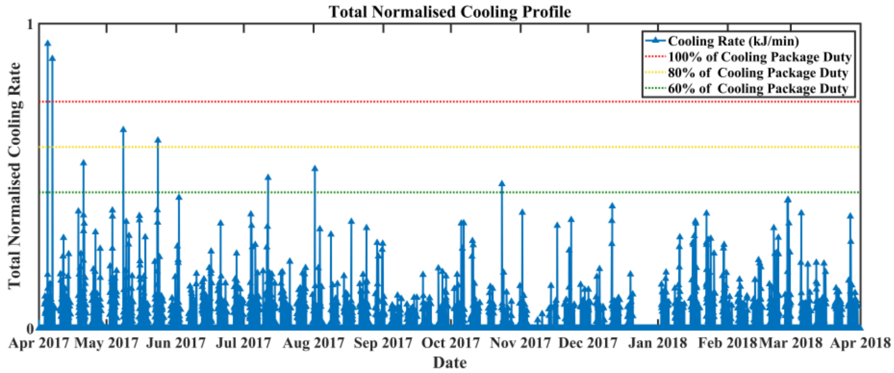


Figure 3. Total normalised heating profile.

As shown in Figure 4, there are two cases when the cooling demands exceeded the maximum capacity of the cooling supply packages. This took place when 6 batches were manufactured at the same day. There are four cases when the cooling demand exceeded the 60 percent (%) line and only two cases surpassed the 80 percent (%) line. From these points, it is obvious that heating supply system has more constraints than the cooling supply system as the latter has a much less number of cases above the 60 percent (%) line.

There are a number of reasons for exceeding the normal operating duty of the energy or utility supply packages. Most of these reasons revolve around the production schedule as the more batches being manufactured at the same time, the greater the utility requirements. In addition, the size of the batch has a great effect on the required heating or cooling rates as larger batches require longer time to heat and cool. So, an efficient production schedule can be defined as the schedule which minimises or avoids overlap between heating or cooling stages of batches being manufactured in parallel. When the heating rate exceeds the normal duty of the heating supply, it is more probable that the gas booster will operate to overcome the high heating demand resulting in higher gas consumption. If the cooling demand surpasses the normal operating duty, the refrigeration package which supplies the cooling water shall work with a higher electrical load.



4. Conclusion

Batch manufacturing is a favourable production technique in the case of low-volume and high value-added products. In most cases, batch manufacturing facilities have shared utilities which provide the manufacturing system with the required utility such as heating or cooling water. Manufacturing of more than one batch at the same time can lead to less production throughputs and higher manufacturing cycle time. This happens in cases where there are limited shared utilities. In this work, data is converted from manually recorded batch records into a digital format to analyse the data to identify the constraints in the utility supply system. By calculating the total heating and cooling rates at each minute for the studied period, it is shown that heating and cooling rates were within the normal operating range of their supply packages in most cases. However, on days of high production demand, heating and cooling demands exceeded the normal operating duties of the packages. This can lead to higher fuel gas consumption being burned in the gas-fired boiler and higher electrical load by the refrigeration package. Moreover, it is shown that the heating supply has more constraints than the cooling supply system as the former has many cases exceeding the 60 percent (%) line compared to the latter. By using the proposed methodology, the cases of high energy demand are identified. Those production situations that require higher than normal heating and cooling demands can then be scheduled in such a manner as to minimise the overall energy consumption.

Acknowledgements

The North West Centre for Advanced Manufacturing (NW CAM) project is supported by the European Unions INTERREG VA Programme, managed by the Special EU Programmes Body (SEUPB). The views and opinions in this document do not necessarily reflect those of the European Commission or the Special EU Programmes Body (SEUPB). If you would like further information about NW CAM please contact the lead partner, Catalyst Inc, for details.

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