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Data driven stochastic modelling and simulation of cooling demand within breweries

Stefan Hubert [a,*], Thorben Helmers [b], Frauke Groß [a], Antonio Delgado [a]

[a] Department of Chemical and Biological Engineering, Faculty of Engineering, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058 Erlangen, Germany
[b] Institute of Environmental Process Engineering, University of Bremen, 28359 Bremen, Germany

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ABSTRACT

Over the last few decades the food and beverage industry has become increasingly aware of its energy and water usage. Customers are demanding an increasing level of sustainability. This is especially true within the brewery industry. The process of brewing itself is a demanding process, with respect to both energy and water requirements. To increase the knowledge about the holistic process chains, e.g. for decision making and for testing operational and procedural setups there is an evolving need for virtualisation. This paper focuses on modelling and simulation of parts within the process of brewing. The shown approach utilises reference nets as a flow-chart-like modelling environment. Models based on the Java programming language are implemented, dealing with stochastic and deterministic events. Results of eight different brew types are shown and a complete schedule with a total of 230 batches, portraying almost a year of production is being simulated.

1. Introduction

Over the last decade the will to improve process systems not only with respect to profitability but also with respect to sustainability has increased. This can be partly attributed to the Kyoto Protocol, a treaty which forces participating states to reduce carbon dioxide emissions. Moreover there are other activities like environmental management systems, for example based on ISO 14001 or Eco-Management and Audit Scheme, which enable a sustainability-oriented management policy (Simate et al., 2011; ISO, 2004; United Nations, 1997; European Commission, 2015). Studies have shown that companies which have implemented new environmental strategies are able to recover their costs quickly while improving competitiveness. This is not only due to the increasing costs of waste and energy disposal, but also due to greater penalties if environmental criteria for production are not met (Ball et al., 2009; O'Brien, 1999; Smith and Ball, 2012).

To improve complex process manufacturing systems within the food and beverage industry in terms of sustainability there is often the need to explore and test different kind of process design and process operations. But most of the time process experiments conducted with the actual system are invasive and costly, as the manufacturing processes need to be stopped for a certain period, resulting in down times with a negative impact on the profitability. The process system or design that needs to be tested may also not yet exist, which makes it impossible to experiment with. Therefore the only possibility to investigate a certain system is to model it in a physical or mathematical way. Physical models of complex process systems like breweries can be very expensive and not accurate enough if a holistic point of view is demanded. Mathematical modelling is often a valid alternative but analytical solutions in complex systems are often unfeasible, which gives rise to simulation modelling (Law, 2015).

This paper focuses on stochastic modelling and simulation of procedures within the process of brewing in small and medium sized breweries. Simulation models are needed in order to investigate the influence of operational parameters like starting time of brews and different types of brews in order to increase process knowledge, dealing with uncertainty, and to question operational policies. A holistic point of view is emphasised. Hence the models implemented into the simulation model include the brewhouse as well as wort and beer production, consisting of fermentation and maturation. The focus is laid on modelling and simulation of the energy demand of cooling systems within breweries. There are many publications dealing with energy concerns and modelling of breweries (Muster-Slawitsch et al., 2014; Fadare et al., 2010; Pennartz and Jackson, 2010; Galitsky et al., 2003; Tokos et al., 2010; Sturm et al., 2013, 2012; Muster-Slawitsch et al., 2011;

* Corresponding author at: Chair of Fluid Mechanics, Cauerstraße 4, 91058 Erlangen, Germany.
E-mail addresses: stefan.hubert@fau.de (S. Hubert), Helmers@iuv.uni-bremen.de (T. Helmers), frauke.gross@fau.de (F. Groß), antonio.delgado@fau.de (A. Delgado).

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Dumbliauskaite et al., 2010). But only a few papers are known to the authors dealing with the underlying uncertainty of the production systems within breweries (Mignon and Hermia, 1996; Goldstein et al., 1993).

There are many ways of modelling such proposals, including discrete event simulation, system dynamics and agent-based modelling. Jahangirian et al. (2010) and Mula et al. (2006) are giving comprehensive reviews of those approaches within the manufacturing environment. Also, quite a few research papers have been published about modelling within the food and beverage industry already (Georgiadis et al., 1998; Chen and Ramaswamy, 2002; de França and Meireles, 2000; Ávila and Silva, 1999).

This paper focuses on a different approach, based on a high-level Petri net formalism called Reference net (Kummer, 2002). Those are equipped with stochastic and deterministic models based on collected data and published results. Reference nets are used as a graphical modelling language and are an extended version of Petri nets (Petri, 1962). Reference nets, just like Petri nets, consist of places, transitions, arcs and tokens. In contrast to well-known standard Petri nets, the used formalism allows for tokens to reference arbitrary objects, like other nets, enabling a hierarchical modelling style. Also a timing mechanism is included and data-handling extensions like tuples and lists do exist. Furthermore a powerful inscription system implements the Java programming language, making it possible to utilise external models using custom classes and methods (Kummer, 2002).

Petri nets and high-level Petri nets, like Reference nets, have been successfully used to portray breweries, chemical processes, biopathways, energy utilisation within a steel production process, for scheduling of a sugar milling plant, water distribution networks and management workflow processes (Nagel, 2011; Theißen et al., 2011; Matsuno et al., 2003; Wang et al., 2013; Ghaeli et al., 2008; Gudiño-Mendoza et al., 2011; Luna et al., 2011; Van Der Aalst, 1996; Liu et al., 2002; Salimifard and Wright, 2001).

The aim of this paper is to show how Reference nets can be used to implement existing underlying uncertainty by combining stochastic and deterministic models. Subject of interest is the energy demand of cooling systems in regard to the heat which is dissipated. Eight different types of brew recipes and their individual process steps are implemented. Simulation experiments of single recipes are shown, as well as a simulation of a complete schedule, portraying almost a year of production and different configurations of a schedule consisting of 30 brews.

The paper is structured as follows. Section 2 describes the problem and the available data for the modelling procedure. In Section 3 the modelling approach is explained in great detail. Section 4 represents the results, both of the modelling and simulation experiments being conducted.

2. Problem description

2.1. Research objective and data basis

The presented work is based on a exemplary structure of small and medium-sized breweries (*SMB*). Production volumes of breweries of this size typically range between 20,000 and 1,000,000 hector litre beer per year according to Muster-Slawitsch et al. (2011). Data logging, compared to large scale breweries, is often incomplete here. However, there is an increasing demand for virtualisation even for small and medium-sized breweries. To stay competitive and to increase the level of sustainability as well as profitability operational and procedural changes need to be tested in before. Modelling and simulation is one way to offer such possibilities for decision making. The inconsistent data from SMBs makes this proposal quite challenging. Besides the incomplete data basis, limited budget for purchasing additional process engineering software products hampers the implementation of virtualisation tools within SMBs. The research objective of this paper is to analyse the time dependent cooling demand of a brewery using a combination of deterministic and stochastic simulation models. Only the demand site of the process is being considered within the present analysis. Therefore, influences like weather conditions as well as most equipment-based impacts are neglected.

As a foundation for this work a SMB was accompanied for a total of ten months. The first subgoal was to collect data of the considered processes. The collected information includes data about the wort production, such as original gravity, total volume after casting and process time needed within the brewhouse. Data about the beer production, in terms of fermentation and maturation processes was also collected, including temperature profiles and further details about the course of the fermentation processes, like measurements of substrate content over time. Additionally, data of the present bottling line was gathered, showing when a certain type of beer was bottled. All of the accumulated data is with respect to a total of eight different types of recipe. Table 1 lists the number of datasets of each of those items. 130 batches of fermentation data, 173 batches of brews (in terms of wort production) and 121 bottling runs were investigated. This data was used to develop stochastic models.

2.2. Cooling within the process of brewing

The process of brewing is a complex process, combining many different types of unit operations. It begins with the delivery of malt, mainly made from barley or wheat, to the brewery. The malt is being stored within silos and once a new brew is about to start it is transported to a mill, where it first gets crushed and depending on the used equipment mixed with water already. The product of this process step is called grist and is transported into a vessel, called mash tun, where it is mixed with water and heated according to a certain temperature profile. Different temperature levels are needed to activate, respectively to increase the activity of enzymes like α-amylase and β-amylase. This process step is called mashing and usually takes about two to three hours and with temperature profiles ranging between 50 and 90 °C. After mashing is finished, the so called mash needs to be separated from unsolved residues within a separation unit called lautering tun (or mash filter) and the resulting product is called first wort or wort respectively. To increase the gravity concentration, to ensure sterility and to add hops, which is necessary for the taste of the beer a boiling step is following next. After the wort is boiled another separation step follows. This step is called casting of the wort and is done in a vessel called a whirlpool. Finally the wort, now at a temperature level of about 90 °C, gets cooled down to a temperature range of about 10–20 °C, depending on the type of fermentation yeast used (*bottom-fermenting* or *top-fermenting*). After adding the yeast the fermentation is about to begin. Sugar molecules are metabolised to alcohols and carbon dioxide by the yeast cells. As the

Table 1
The data basis, including the number of different brewtypes, fermentation batch processes, wort productions (*brews*) and bottling data which were being investigated.

Item	Quantity	Data includes
Brewtypes n_{bt}	8	Recipes
Fermentation processes n_{fp}	130	Temperature profiles, substrate over time
Brews n_b	173	Original gravity, volume after casting, process times in brewhouse
Bottling n_{bo}	121	Dates and beer types of bottling