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SIMULATION MODELING OF BOTTLING LINE WATER DEMAND LEVELS USING REFERENCE NETS AND STOCHASTIC MODELS

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ABSTRACT

In this paper simulation modeling of a brewery bottling line is described. Reference nets as an extended version of high level Petri nets are being used for the modeling environment and make use of external Java programming language based models. The study focuses on a bottling line used within a small-to-medium sized brewery. Machine data, flow measurements and the determination of the chemical oxygen demand from various effluent locations within the bottling line are used to build stochastic models, which are implemented into the reference net models. The resulting models are shown and a simulation experiment is compared to a real bottling process within the mentioned brewery.

1 INTRODUCTION

Sustainability is becoming a major focus in modern factories (Burkhard, Deletic, and Craig 2000, Kirby, Bartram, and Carr 2003, Gunasekaran and Spalanzani 2012). Minimizing the energy and resource demand levels while maximizing economical profits is importan for many industries using bottling lines. This research focuses on bottling lines belonging to breweries, but is also widely applicable to other industry branches.

Within breweries it is estimated that the bottling processes is responsible for about 30% of the total production costs. A 10% increase of the bottling line efficiency therefore leads to a 3% decrease of total production costs (Haider 2008). One way to enhance the efficiency is a consequent deficiency analysis. The overall demand of water in breweries averages in the range from 5 to 6 liters per produced liter of beer (Fillaudeau, Blanpain-Avet, and Daufin 2006). The total reported range varies between 3 to 11 liters. It is heavily dependent on the size of the brewery, implying a worse water to product ratio for smaller breweries (Fillaudeau, Blanpain-Avet, and Daufin 2006, Simate, Cluett, Iyuke, Musapatika, Ndlovu, Walubita, and Alvarez 2011). The specific water demand of a brewery bottling line ranges from 0.6 to 1.6 liter, leading to about 20% of the total specific water demand within a brewery. It is therefore very important to investigate the bottling process for future potential savings in the total water demand.

Due to their high water demand there is a lot of wastewater being output. 3.9 ± 1.3 liter wastewater per liter of produced beer is being discharged (Glas and Schmaus 1998). One well-known way to describe the water quality is the chemical oxygen demand (*COD*). The COD is commonly used in order to determine the amount of organic compounds in wastewater and is often involved in government regulations as one of the major wastewater parameters. The value of the COD is measured in milligrams O_2 per liter ($\frac{mg}{l}$).

The aim of this research study was to model and simulate beer bottling lines. A small-to-medium sized brewery were monitored in order to collect data. In this study the COD is also used as the major parameter for the quality estimation of the wastewater output. Therefore the CODs of wastewater at different locations within the bottling line are measured.

Several studies about bottling lines have been published. Alexander and Weckman investigated the bottling and storage operations of distillery (Alexander and Weckman 1980). Rädler used simulation modeling to optimize the efficiency of buffer and transport parts (Rädler and Weisser 2001). More literature about simulation modeling of bottling lines can be found in Voigt (2004), Hasenschwanz and Selig (2009), Bernhard and Kahe (2008). In contrast to the shown literature this study focuses on the modeling and simulation of a brewery bottling line with respect to the total water demand, wastewater output and energy demand. Reference nets are being used as the modeling tool. Reference nets are a type of high level Petri nets, that implement hierarchical modeling, a nets-within-nets formalism, timing and the Java programming language (Kummer 2002). External Java classes have been implemented in order to face the stochastic behavior of the bottling lines. Other Petri nets formalisms have already been successfully used for modeling bottling lines (Wohlgemuth and Page 2000, Mei, Yu, Cheng, and Gao , Giua, Meloni, Pilloni, and Seatzu 2002, Drighiciu and Cismaru 2013, Audry and Prunet 1995).

In what follows the bottling line under investigation and the data sampling method are explained. Furthermore the modeling approach is described. In the results section the reference net models, COD determination results and a simulation experiment compared to measurement data are shown.

2 MATERIALS AND METHODS

2.1 The Bottling Process

The underlying process of beer bottling is the same within every brewery, if no contract bottling service is being used. This also indicates the transferability of this study.

The first part of the process is the depalletizing. This is usually done with robots, which lift the beer cases from the pallet. After depalletizing the beer cases are separated from the used bottles. The cases are then cleaned and await the filled bottles. Bottles are put into a bottle washing machine, where they are rinsed and cleaned using water and a caustic solution. After the cleaning process the bottles are being inspected for waste residues or foreign bodies using optical techniques. After inspection, and removal of damaged bottles, the bottles are filled with beer in a filling system. Bottles are capped next as well as labelled using bottom and top labellers. Afterwards the labelled and filled bottles are inspected again, with respect to the volume and correct labeling. The bottles are now being put into the cleaned cases and are finally palletized again, waiting for transport to the customer (Kunze 2010).

This study is based on a bottling line from a small-to-medium sized brewery. The bottling line is distributed on two levels. The bottom level consists of the depalletizing and palletizing procedure, whereas on the second level the rest of the bottling process is realized. In Figure 1 the second level of the bottling line in question can be seen. The design and the procedure being used within this bottling line is state of the art and is implemented similarly within many breweries of this size. The typical output in such lines, given in bottles per hour, ranges from 15 to 30 thousand.

The main focus of this study lies in simulation modeling the wastewater output and water demand, with the energy demand also is being considered. Wastewater is primarily output at three locations, the

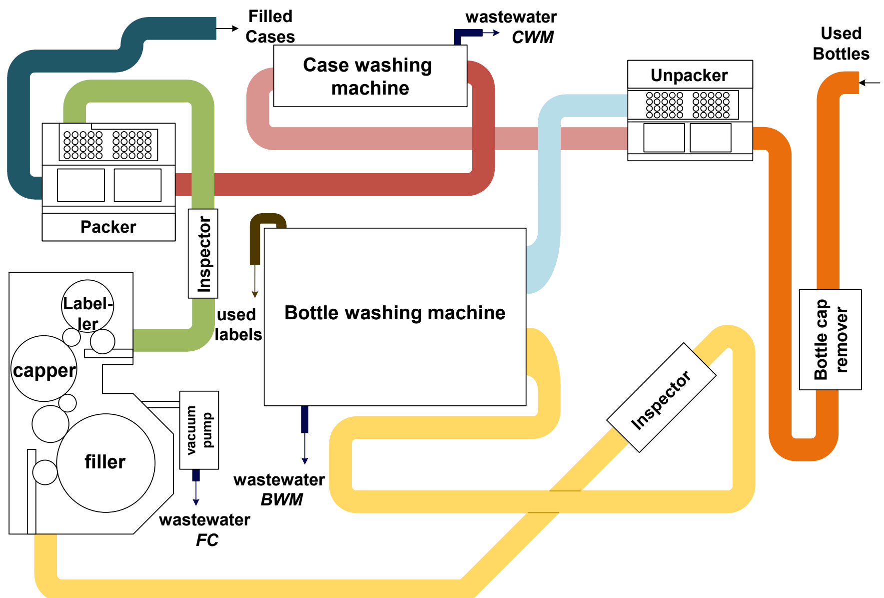


Figure 1: Layout of the bottling line under investigation. It is distributed on two levels. The upper story is shown within this figure and includes the bottle washing machine (*BWM*), the case washing machine (*CWM*) and the filler and capper (*FC*). The lower level includes the depalletizing and palletizing process steps.

bottle washing machine (*BWM*), the case washing machine (*CWM*) and at the filler and capper (*FC*). Water, needed for lubrication of the lines is neglected.

2.2 Data Sampling

In order to model the freshwater and wastewater demand levels the volume flows not being tracked with stationary flow meters have been measured using an ultrasonic flowmeter, the Proline Prosonic Flow 93T (Endress+Hauser Messtechnik GmbH & Co. KG, Weil am Rhein, Germany). This device enables retrofitting of non-invasive volume flow measurements from outside of a pipe. The freshwater (*fw*) volume flow input into the *BWM* $\dot{V}_{bwm,fw}$ is measured using the portable flowmeter. The volume of the wastewater (*ww*) output at the *CWM* was determined manually. At the filler and capper the water input for rinsing the product pipe $\dot{V}_{fc,fw,r}$ and the water needed for the vacuum pump, high pressure injectors and spray heads $\dot{V}_{fc,fw}$ is determined using the portable flowmeter. Wastewater streams at the *FC* are determined using the portable flowmeter and manually using a bucket for a volumetric determination. In Figure 2) the mass balance of the main contributors can be seen.

To determine the specific load of the wastewater being output by the contemplated process steps, cuvette tests (*LCK 314 15-150* $\frac{mg}{l}$ O_2 and *LCK 514 100-2000* $\frac{mg}{l}$ O_2, Hach-Lange GmbH, Germany) were used to determine the chemical oxygen demand. Measurements involve two milliliters of a sample, which are put into a cuvette and heated for two hours at a constant temperature of 120°C to ensure complete oxidation. The samples are than analyzed using optical absorption (*XION 500* spectrophotometer, Hach-Lange GmbH, Germany). The tests are showing a measurement inaccuracy of ± 1.5 $\frac{mg}{l}$ COD (*LCK 314*) and ± 8.7 $\frac{mg}{l}$ (*LCK514*). Samples are being diluted using a volumetric flask, if the measurement range is exceeded. A total of 110 samples have been taken and analyzed from the wastewater outputs $V_{bwm,ww}$, $V_{fc,ww}$ and $V_{vac,ww}$.

The determination of the energy demand for the filling systems involves the electrical energy demand and the amount of water vapor. Electrical energy demand for the *BWM* is calculated based on the given electric power and operating hours. Water vapor demand is determined based on measurements of the condensate volume flows. In order to estimate the total vapor amount the given pressure and temperature

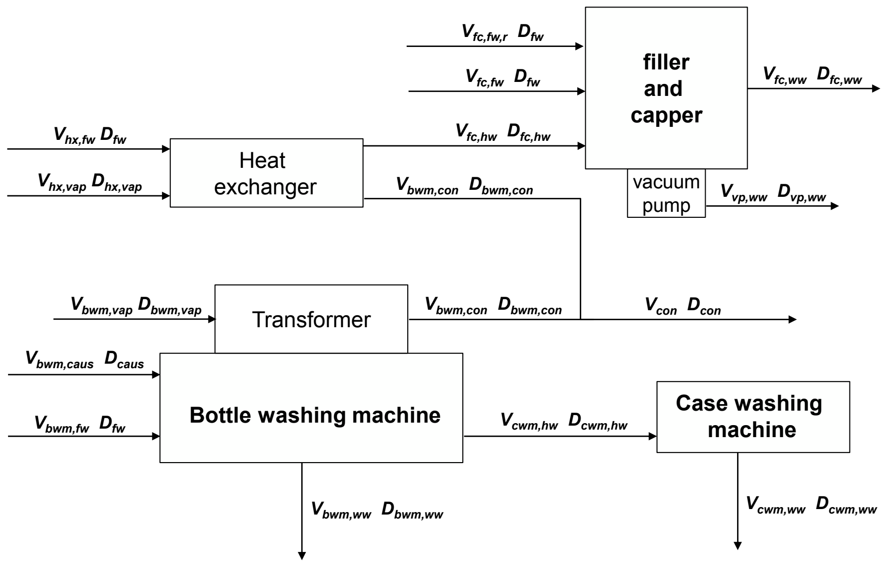


Figure 2: The mass balance flow sheet of the bottling line. With the volumes (V) and densities (D) of freshwater (*fw*), wastewater (*ww*), caustic washing solutions (*caus*), used heated water (*hw*), vapor (*vap*) and condensate flows (*con*) of the bottle washing machine (*bwm*), filler and capper (*fc*), heat exchanger (*hx*) and case washing machine (*cwm*).

are used, given as:

$$\dot{Q} = \dot{m}_{con} \times r = \dot{V}_{con} \times D_{con} \times r \tag{1}$$

With $\dot{Q}$ being the heat rate, $\dot{m}_{con}$ the mass rate of the condensate, r the enthalpy of evaporation and D_{con} the density of the condensate. In Figure 3 a measurement of the condensate volume flow is illustrated. The fluctuation is due to the fact that the condensate is transported into a vessel until a maximum fill level of it is reached, which leads to a following draining of this vessel. The apparent peaks in Figure 3 therefore depict the discharges.

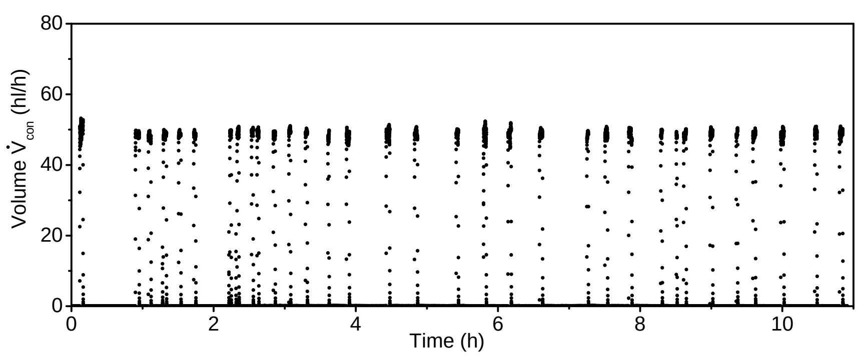


Figure 3: Volume flow of the condensate is shown in $\frac{hl}{h}$.

2.3 Reference Nets and Modeling Approach

In order do implement the discrete stochastic behaviour of bottling lines and to enable the combination of different model types based on Java programming language, Reference nets (Kummer 2002) were chosen as the modeling and simulation environment. The Reference net formalism is an high level extension to the basic Petri nets which were developed by Carl Adam Petri (Petri 1962). They introduce synchronous channels, a nets-within-nets formalism using net instances and references, a timing mechanism and many different arch types. Using reference nets, token can represent either simple black token, different data types like tuples and lists, net instances or even arbitrary objects. Reference nets also implement a Java based inscription language and plugin framework, making it possible to include external Java classes and their objects, either as tokens or static methods used within transitions. The Reference Net Workshop (*Renew*) is being used as the modeling and simulation tool within the presented research. It is developed and maintained by the Theoretical Foundations Group (Department of Informatics, University of Hamburg, Germany). Reference nets are used to model the basic logical conditions within the bottling line. To depict the stochastic behaviour, they are than further extended with external stochastic models based on the collected data. Different distributions were fitted using the software EasyFit (MathWave Technologies, Ukraine) and Matlab R2013a (The MathWorks, Inc, USA). Those stochastic models are implemented into the reference nets using Java plugins. An example of this approach can be seen in Figure 4.

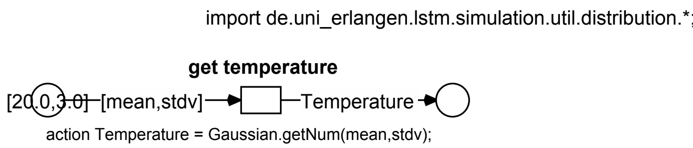


Figure 4: Example of how the implementation of stochastic models within the reference net formalism is possible. A Gaussian distribution of a daily temperature, with two parameters *mean* and standard deviation *stdv*, is implemented at the transition. Once the transition fires a sample *Temperature* from this distribution is drawn via the *action* inscription.

3 RESULTS

3.1 Bottling Line Modeling using Reference Nets

The reference net model of the bottling line consists of two levels. The first level initializes three different model scenarios at the second level (see Figure 5). Depending on the number of different types of fillings, and therefore required retooling, to be portrayed for a simulation experiment there are three unique model types. The first type implements only one filling, the second implements two different types of filling procedure involving one retooling and the third type illustrates the scenario of more than two different filling types. Each model at the second level starts with a warmup period (e.g. heating up) and ends with a shutdown phase (e.g. draining).

The second level of the reference net model consists of different parts and states of the bottling line, such as the warmup period, bottle washing machine, puffer-system, filler plus capper and the end phase of the bottling procedure. In Figure 6 the different parts of the model are shown in detail. The main objective within the second level was to model the fluctuation between the two discrete states *UP* and *DOWN* both for the bottle washing machine and the filler.

3.2 Stochastic Modeling of Water Flows and Wastewater Quality Determination

In order to determine the up and down times of the bottle washing machine the measurements of freshwater input $\dot{V}_{bwm,fw}$ are used (see Figure 8(a)). As one can see, the volume flow rate fluctuates heavily. This is due to the fact that $\dot{V}_{bwm,fw}$ is on a lower level when the washing machine is in downtime. The time between two peaks can therefore be seen as a time measurement for the up, respectively down time. Those

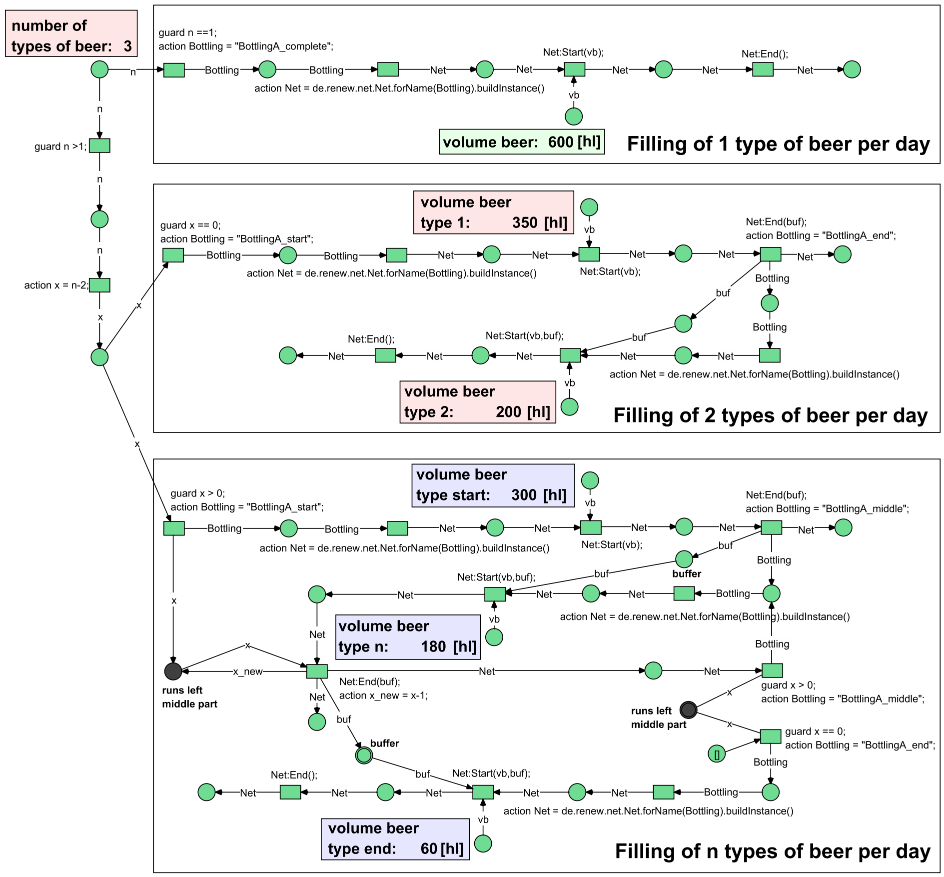


Figure 5: Main level of the reference model. Based on the user input *number of types of beer* the second level of the reference nets is initialized.

time intervals are analyzed, fitted to a Weibull distribution and implemented into the reference net model using external Java classes. The volume flow rate itself was also modeled, using distribution fitting. Two states of volume flow rate are distinguished: *uptime* and *downtime*. Volume flow rate at uptime was fitted to a Weibull distribution, whereas the volume flow rate during downtime was fitted to a generalized extreme value distribution. The case washing machine also fluctuates between two states. When inactive the hot water input $\dot{V}_{cwm,hw,down}$ was estimated as 50% of the $\dot{V}_{bwm,fw,down}$. In the event of a running case washing machine $\dot{V}_{cwm,hw,up}$ the distribution was also best described using a Weibull distribution.

The same approach, regarding the determination of up and down times, was used for the filler machine. Results of this analysis are summarized in Table 1.

As the quality of the wastewater depends on the waste being introduced via contaminated bottles into the bottle washing machine it cannot be described in a deterministic manner, as the level of pollution fluctuates heavily for each bottle. Therefore, a total of 110 samples at the previously mentioned wastewater discharge locations have been collected while the bottling process was running and analyzed regarding the chemical oxygen demand (*COD*). In Figure 7 a probability density function of the *COD* value at the wastewater discharge of the bottle washing machine can be seen. Fitting to distributions revealed a generalized extreme value distribution to describe the data best.

In Table 2, the results of the three wastewater discharge locations (bottle washing machine, case washing and vacuum pump outlet) can be seen.

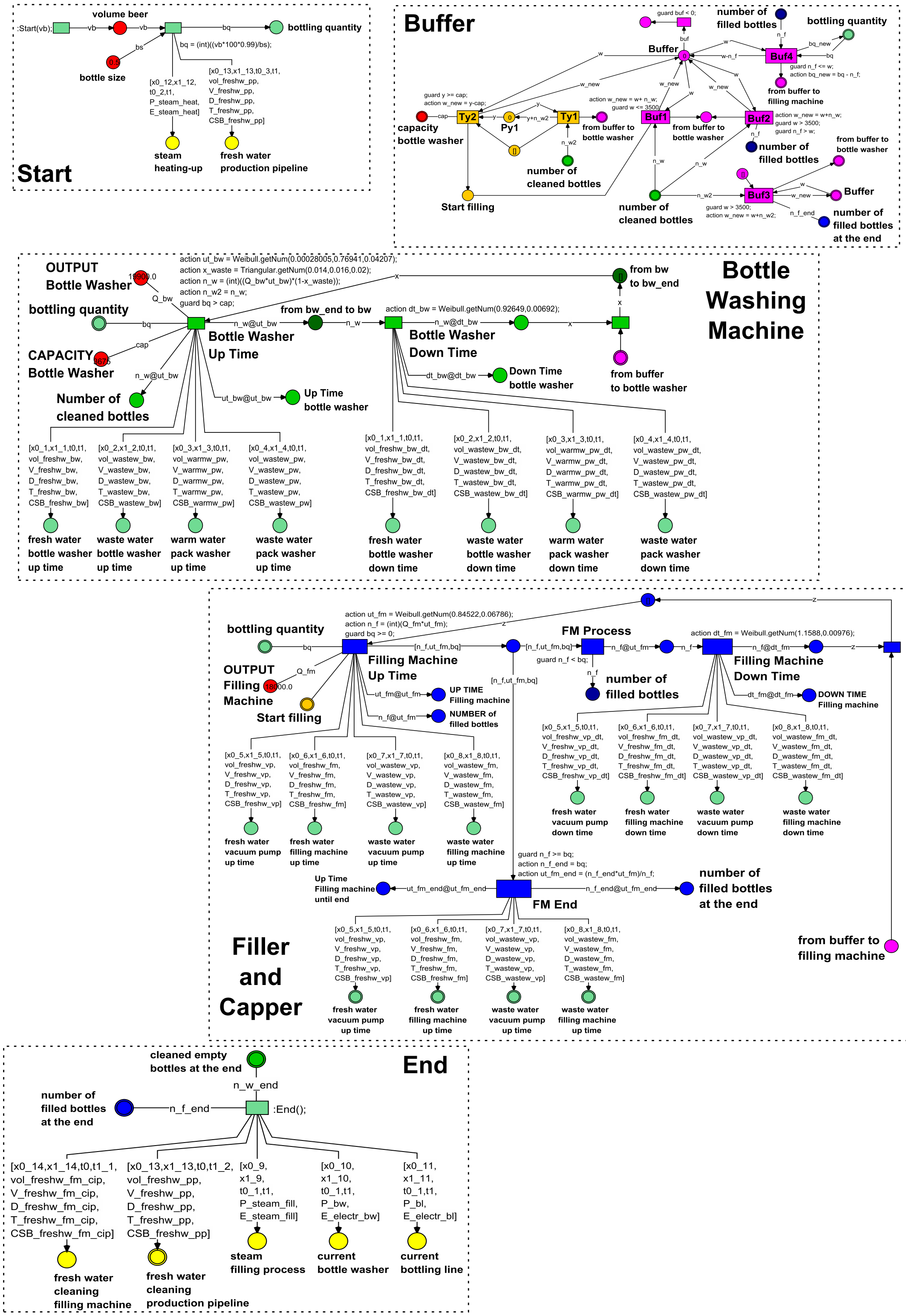


Figure 6: The second level of the reference net bottling line model. It consists of the warmup period *START*, the bottle washing machine, the filler plus capper, a buffering system and the end phase.

Table 1: List of times and water flows which were determined. Collected data of those where fitted to certain distribution, for which the parameters and sample size is given.

Type	Distribution type	Parameter			Samples (n)
$\dot{V}_{bwm,fw,up}$	Weibull	$\alpha = 4.7946$	$\beta = 40.571$	$\gamma = 12.369$	353
$\dot{V}_{bwm,fw,down}$	GEV	$k = 0.44893$	$\sigma = 1.3665$	$\mu = 4.7987$	344
$t_{bwm,up}$	Weibull	$\alpha = 0.76941$	$\beta = 0.04207$	$\gamma = 0.0$	353
$t_{bwm,down}$	Weibull	$\alpha = 0.92649$	$\beta = 0.00692$	$\gamma = 0.0$	344
$\dot{V}_{cwm,hw,up}$	Weibull	$\alpha = 14.308$	$\beta = 8.09$	$\gamma = 0.0$	17
$\dot{V}_{fc,fw,up}$	Weibull	$\alpha = 22.159$	$\beta = 17.191$	$\gamma = 0.0$	80
$\dot{V}_{fc,fw,down}$	GEV	$k = 0.08657$	$\sigma = 0.34431$	$\mu = 9.0642$	78
$t_{fc,up}$	Weibull	$\alpha = 0.84522$	$\beta = 0.06786$	$\gamma = 0.0$	80
$t_{fc,down}$	Weibull	$\alpha = 1.15580$	$\beta = 0.00976$	$\gamma = 0.0$	78

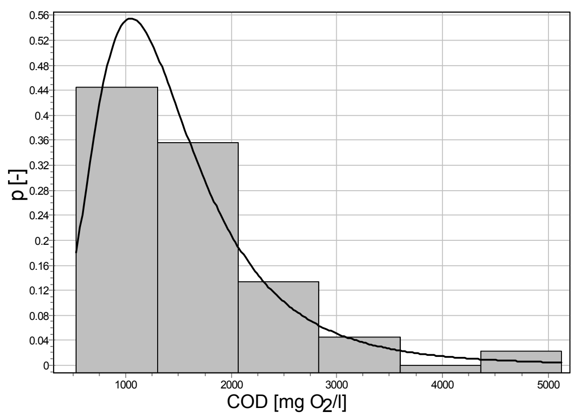


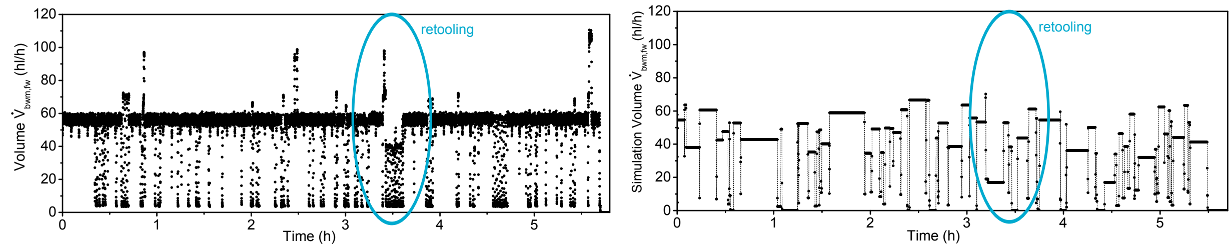
Figure 7: Probability density function of the *COD* value at the wastewater discharge of the bottle washing machine.

3.3 Simulation Results

In order to determine the validity of the simulation model, simulation results are compared to real measured data. The simulation experiment is based on the same key facts as the measured data, such as the total amount of beer to be filled and the number of beer types. In Figure 8 the simulation result of the freshwater demand of the bottling washing machine is compared to a measured trend. The measured data for the bottle washing machine, when running, varies between 50 to 60 $\frac{hl}{h}$, while the simulated flows vary between 35 to 65 $\frac{hl}{h}$. When in downtime, the bottling washing machine freshwater inflow is throttled to 5 $\frac{hl}{h}$, the simulation results in flows from 0 to 10 $\frac{hl}{h}$. The retooling due to the change of the beer type can be seen at hour 3.4 to 3.6 within the measurement and at hour 3.2 to 3.4 within the simulation.

Table 2: The chemical oxygen demand at three different locations was determined. At the bottle washing machine (*bwm*), at the case washing machine (*cwm*) and at the vacuum (*vp*) pump outlet. The measured values were fitted to certain distribution, which are given below.

Type	Distribution type	Parameter			Samples (n)
COD_{bwm}	GEV	$k = 0.16496$	$\sigma = 514.55$	$\mu = 1124.9$	45
COD_{cwm}	GEV	$k = -0.12762$	$\sigma = 114.67$	$\mu = 380.49$	14
COD_{vp}	GEV	$k = 0.69483$	$\sigma = 351.68$	$\mu = 595.06$	51

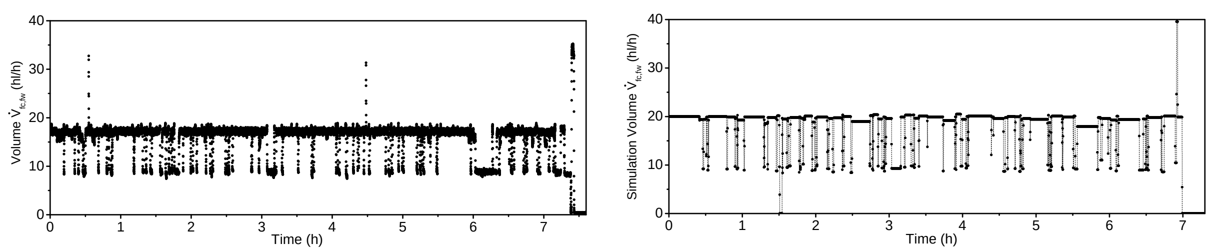


(a) Measurement of the freshwater input into the bottle washing machine.

(b) Simulated volume flows of freshwater into the bottle washing machine.

Figure 8: Comparison of simulation and measurements of the freshwater input into the bottle washing machine based on the same amount of beer and number of batches.

Furthermore the freshwater input into the filler and capper was simulated. Results can be seen in Figure 9. On the first glance it can be seen that the simulation model illustrates the real data well. The range of the measured data is between 16 to 18 $\frac{hl}{h}$ (see Figure 9(a)), whereas the simulation result varies between 17 to 20 $\frac{hl}{h}$ (see Figure 9(b)).



(a) Results of measurement for the freshwater input.

(b) Simulation results of freshwater input.

Figure 9: Comparison of simulation and measurements of the freshwater input into the filler and capper based on the same amount of beer and number of batches.

4 CONCLUSION AND NEXT STEPS

The shown simulation model of a bottling line based on real data from a small-to-medium sized brewery shows encouraging properties. It is based on an extended Petri net formalism using freely available software, which allows for easy adoption to other breweries and bottling line scenarios. The simulation results shown so far look promising. The highly stochastic discrete behaviour of a bottling line is well depicted in the continuous output flows. The simulation model increases process knowledge within the breweries due to the prediction of wastewater levels, with respect to both quality and quantity. Results of computer aided scheduling and process design studies based on this work can serve for an optimization of wastewater treatment systems. Optimization of such increases the overall economical and ecological efficiency.

Next steps involve additional collecting of validation data and the integration of the shown model into a holistic model of a brewery. This will include the brewhouse, clean-in-place systems, fermentation and maturation.

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