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# A New Stepless Control Concept for Multi-Lane Bottle Conveyors

**Multi-lane bottle conveyors are in use at almost all bottling plants. They are not only needed for the transportation of bottles but also for decoupling the failure sensitive machines of the plant by storing and providing bottles. This increases the overall efficiency of a plant by bridging short downtimes. These buffer conveying systems have to be controlled with regard to their filling level. State of the art is the stepwise detection of the filling level by mechanical switches, which are actuated by accumulating bottles. This leads to a stepwise control.**

**In this paper a new control concept is presented which allows controlling multi-lane conveyors stepless by monitoring the infeed and the output of the conveyor. This enables a more precise control of the conveyor sections velocities and outputs of the up- and downstream machines. No mechanical jam switches are necessary.**

**The developed control algorithm was successfully implemented and tested at an industrial scale pilot plant. Test runs showed an equal flow of bottles due to the continuous adaption of the machine outputs and conveyor sections velocities and the minimization of the conveyors dead time.**

Descriptors: conveyor control, bottling plant, buffer system

## 1 Introduction

### 1.1 Application area bottling plants

Bottling plants are a complex network of highly specialized machines. Each of them carries out a single step on the way to a saleable product. They are designed with regard to their leading machine. This is the one, where stops during operation have the most impact on product quality and plant efficiency. At most plants the filling machine is dedicated to be the leading machine. Stops during the filling process result in quality losses of the product caused by microbiological recontamination or by gas exchange of open bottles with the atmosphere. Furthermore, it is an expensive machine and oversizing should be avoided. So the filling machine is commonly laid out as the slowest machine of a plant. Standstill periods of this machine directly decrease the efficiency factor of the whole plant.

With the common bottling plants for glass bottles and cans, the filling machine is selected as the leading machine. With plants filling PET bottles the blow moulding machine might be most expensive and most delicate to run. So it may be selected as the leading machine. Thus plant design, regards to this machine.

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Figures see Appendix

In addition to the machines conveyor systems are essential parts of the network bottling plant. They perform two major tasks:

Primarily they have to assure the container conveyance between the particular machines. In order to make the machines work together, a continuous stream of production materials and intermediates has to be ensured. For this, the machines have to be connected by reliable conveying systems.

Secondly, but almost as important, the conveying systems have to decouple the individual machines. This decoupling function is necessary due to the machines failure proneness [7, 15], that is measured by their efficiency factors. While the efficiency factors of single machines have been increased over the last decades, they did not reach higher guaranteed levels than 92 to 98 % depending on the type of machine [14]. This looks fine at first glance. But if all machines are directly connected (blocked to a line), the overall plant efficiency results from the multiplication of the single machines efficiency factors (as a good approximation). For a plant consisting of ten blocked machines with the efficiency factors mentioned above the overall plant efficiency would result in a range of 42 to 82 %.

By decoupling the machines with buffer systems the overall efficiency of plants is increased significantly [3, 6, 10]. For this, their operation with an adapted filling level is vital. A filled buffer is able to provide bottles for a downstream machine during a breakdown of an upstream machine (anti-starve buffer). For an empty buffer it works the other way around. By receiving the produced bottles of an upstream machine it may bridge the breakdown of a downstream machine (anti-block buffer). To prevent unnecessary stops of the leading machine, upstream buffers have to be operated

as filled anti-starve buffers and empty anti-block buffers are needed downstream. To reestablish this state after a breakdown the upstream and downstream machines need to be able to run with higher outputs compared to leading machine as shown in figure 2 and by *Rädler* [11].

## 1.2 Conveyor control

The common buffer types used in bottling plants are multi-lane mass conveyor systems which provide storage capacity (see Fig. 1). As needed, they are able to convey bottles from one machine to another and to provide bottles during a short breakdown of an upstream machine and or receive bottles during a breakdown of a downstream machine. Depending on their storage capacity, length and maximum conveying speed they may bridge downtimes from 60 to 120 s. Because of technical and economic reasons larger capacities are hard to find in practice. *Voigt* [15] and *Cooke* [4] evinced that most downtimes of single machines are within or shorter than the buffer time range mentioned above. Working with even larger buffers would only slightly increase the plants efficiency but cause much higher costs for implementation and operation [8, 12]. As the risk of a recontamination of cleaned but open bottles stored at a buffer rises in time too, large conveyors could also cause quality problems [1].

Before a downstream buffer of a machine is completely filled up or an upstream buffer is completely empty the machine has to stop. In today's bottling plants this is triggered by mechanical actuated jam switches which are fixed at the guide rails of multi-lane conveyors. Accumulating bottles actuate the switches. So they provide a digital signal, whether the buffer area downstream to the switch is completely filled up with bottles or not. At least two switches are necessary at the conveyor infeed as well as the conveyor outlet (see Fig. 3). One is needed to trigger the stopping of the upstream respectively downstream machine and one to trigger the restart. To slow down machines stepwise long before buffers are completely filled respectively empty, additional jam switches for each speed step may be implemented. The jam switch information also is used for the stepwise control of the conveyor speeds of the particular multi-lane conveyor sections [11].

For single-lane conveyors, which are often used to connect an empty bottle inspector and a filling-machine, more precise control approaches are available. If bottles are conveyed in single-lane, light barriers may count them and detect free space between them. Counting at the infeed and outlet of a single-lane conveyor allows to calculate the filling degree of the single-lane conveyor. With the additional detection of gaps within the bottle stream, control algorithms for a precise speed control of the single-lane conveyor sections have been developed. They enable the fast and gentle closure of gaps caused by discharged bottles. But because of the low storage capacity of single-lane conveyors they cannot bridge breakdowns longer than a few seconds, depending on their length and speed.

In the presented work, a new control approach to enable stepless control of multi-lane conveyors was developed. A combination of the precise and gentle single-lane control, based on the exact calculation of the filling degree, with the long buffer times of

multi-lane conveying systems was aspired. The work is predicted on a new camera counting system for counting bottles conveyed in multi-lane [13].

In the paper, the system abstraction and modeling for control are presented. The developed control algorithm is explained in detail. Finally first experimental results are presented and discussed, which were acquired after implementing the algorithm to an industrial scale pilot plant.

## 2 Material and methods

### 2.1 Abstraction of the regarded system

The system considered in this paper is a multi-lane conveying system, frequently used in the worlds bottling plants. As the presented work considers the complete control from the infeed to the outlet of the system, the up- and downstream machines of the multi-lane conveyor had to be included into the regarded system by their output respectively input. Figure 3 shows a schematic view of the considered system.

The state variables describing the system are defined as

#### static variables:

C	buffer capacity [bottles] (maximum number of bottles in the buffering section of the conveying system)
L	minimal length of the transportation path from the infeed to the outlet [m]
$l_{in}, l_n, l_{out}$	minimal length of the transportation path from the infeed to the end of the section [m]
$v_{max}$	maximum velocity of the conveyors [m/s]
$d_0$	diameter of transported bottle [m]

#### and dynamic variables:

$t_d(t)$	minimal transportation time from the infeed to the outlet [s] (dead time of a conveyor)
B(t)	current number of middle objects in the buffer [bottles]
$v_{in}(t)$	velocity of infeed conveyor section [m/s]
$v_n(t)$	velocity of a middle conveyor section, serially numbered by n ( $n = 1, 2, 3, \dots$ ), the first section next to the infeed section is numbered by 1. (In Fig. 3, only one middle section is shown. In the paper, the control algorithm is described for this elementary case, but is generally working for all constellations with one or more middle sections.)
$v_{out}(t)$	velocity of output transportation means [m/s]
$q_{in}(t)$	object inflow [bottles/s] (output of the upstream machine)

$q_{out}(t)$  object outflow [bottles/s] (input of the downstream machine)

## 2.2 Basic requirements for the stepless control

Developing a fully functional stepless conveyor control the following purposes were served:

- The conveyor system has to fulfill its basic transportation functionality. This means, that the infeed section should be fast enough for intaking the bottles provided by the upstream machine. The output section should be fast enough to provide enough bottles for the downstream machine with a necessary jam pressure.
- The velocity of all conveyor sections should be adapted stepless to the actual situation on the conveyor (continuous closed loop control).
- Gaps within in the bottle stream should be closed before they reach the input of the downstream machine to inhibit stops.
- If the buffer or a buffer section is filled with bottles the conveyor belts should slow down to reduce the mechanical wear.

To meet these demands the transport situations occurring on the conveyor were divided into three general cases:

### Case I Continuous operation of the conveyor

During the continuous operation the number of objects on the conveyor ( $B(t)$ ) should be stabilized at a given parameter depending on the position of the conveying system within the whole plant. This could be achieved by variation of the systems inflow or outflow. With regard to the aspired continuous operation of the leading machine input, respectively output of the machine, with the further distance to the leading machine should be varied.

### Case II Tailback caused by a breakdown of a downstream machine

In case of a breakdown of the downstream machine the buffer will fill up with bottles. If so the upstream machine should be driven with regular output (output of the leading machine) as long as the buffer is filled almost completely. This is especially important with conveyors downstream to the leading machine (anti-block buffers). If machines slow down too early, this would unnecessarily decrease the plants efficiency.

As the regarded conveyor systems consist of several sections (see Fig. 3), the control concept for the tailback situation has to refer to the current state of this particular section. The velocity of the infeed section  $v_{in}(t)$  has to assure the complete intake of all bottles provided by the upstream machine. To reduce the pressure within the bottle bulk, the following sections should slow down depending on their filling degree. If a section is completely filled and the downstream machine is still not working it can be switched off. If the downstream machine starts working again, the control algorithm should switch to case I and adjust the preset number of objects on the conveyor again.

### Case III Gaps within the stream of bottles caused by a breakdown of an upstream machine

The third case to be considered is characterized by gaps within the bottle flow, caused by breakdowns of the upstream machine. This covers both small gaps because of short upstream stops and largest possible gaps that show up as completely emptied buffer sections. For the control concept the “soft” closure of the occurred gaps within the bottle stream is aspired. On the one hand a gap should be closed as fast as possible to reduce the dead time to a minimum. This increases the efficiency of the plant. On the other hand the differential velocity during closure of the gap should be not too high. Otherwise increased noise emissions and mechanical wear by the clashing bottles would occur. So a continuous control algorithm firstly has to close gaps with a high differential velocity between beginning and end of the gap. Just before the gap between two bottle bulks is closed, their streams differential velocity should be reduced.

## 2.3 The developed control algorithm

To meet the control requirements a control algorithm for the three mentioned cases was developed. Depending on the current velocity state, in- and outflow of the conveyor system, which is described by the current  $v_{in}(t)$ ,  $v_n(t)$  (for all middle sections of the conveyor),  $v_{out}(t)$ ,  $q_{in}(t)$  and  $q_{out}(t)$ , new set values for the conveyor velocities  $v_{in\_set}(t)$ ,  $v_{n\_set}(t)$  and  $v_{out\_set}(t)$  respectively  $q_{in\_set}(t)$  or  $q_{out\_set}(t)$  have to be calculated. By this the appropriate reaction on changes of the disturbance variables  $q_{in}(t)$ ,  $q_{out}(t)$  has to be assured.

### Case I Control for the continuous operation of the conveyor

Control for the continuous operation is aimed at stabilizing a given degree of filling of the conveyor system. For this, the current filling of conveyor system

$$B(t) = \int_{t_0}^t (q_{in}(\tau) - q_{out}(\tau)) d\tau$$

has to be ascertained. This is realized by continuously counting bottles at the conveyor infeed ( $\int_{t_0}^t q_{in}(\tau) d\tau$ ) and outlet ( $\int_{t_0}^t q_{out}(\tau) d\tau$ ). In practice the counting can be realized using a light barrier (single-lane transport) or the mentioned camera system for multi-lane transport.

To adjust  $B(t)$  at a preset level  $B_{set}$ , either  $q_{in\_set}(t)$  or  $q_{out\_set}(t)$  may be adapted. As anti-starve buffers located upstream to the leading machine should preferentially provide bottles,  $q_{in\_set}(t)$  should be varied. For this case  $q_{in\_set}(t)$  is calculated according to:

$$q_{in\_set}(t) = q_{out}(t) \cdot \left( \frac{B_{set}}{B(t)} \right)^p$$

So if the actual number of objects on the conveyor  $B(t)$  is lower than the preset number of objects  $B_{set}$  the upstream machine is accelerated in ratio to the downstream machine  $q_{out}(t)$ . Due to this, the number of objects on the conveyor is decreased until it reaches the preset value and the fraction  $(B_{set}/B(t))$  becomes one. The power  $p$  may be used to amplify the effect so that the aspired  $B_{set}$  is reached faster. Its value has to be determined empirically. In case of a too high number of objects on the conveyor, the upstream

machine is decelerated. Figure 4 illustrates the developed loop control for an anti-starve buffer.

For anti-block buffers downstream to the leading machine the control works in the same manner, but  $q_{out\_set}(t)$  has to be varied according to:

$$q_{out\_set}(t) = q_{in}(t) \cdot \left( \frac{B(t)}{B_{set}} \right)^p$$

In both cases the velocities of the conveyor sections are set depending on the current infeed and outflow of the buffer. The velocity of the infeed is preset in proportional correlation to according to:

$$v_{in\_set}(t) = c_{in} \cdot q_{in}(t)$$

The constant  $c_{in}$  has to be determined empirically, depending on the infeed and bottle geometry. It directly effects the width of the bottle stream which is developing at the sections input. For the calculation of the set velocity of the output section depending on the outflow the proportionality constant  $c_{out}$ , has to be determined. Additionally, a constant velocity deviation  $\Delta v_{slip}$  is added to compensate slip between bottles and conveyor belts. The velocity of the output section is calculated according to:

$$v_{out\_set}(t) = c_{out} \cdot q_{out}(t) + \Delta v_{slip}$$

The velocities of 1 to n middle sections  $v_{n\_set}$  are set to achieve the minimal velocity deviations between each section from the infeed to the output. Beginning with the first middle section 1 following the infeed section they are calculated by:

$$v_{n\_set}(t) = v_{in}(t) - n \cdot \left( \frac{v_{in}(t) - v_{out}(t)}{n + 1} \right)$$

### Case II Control for tailbacks

If a tailback occurs caused by a breakdown of the downstream machine ( $q_{out}(t) = 0$ ) bottles accumulate backwards as shown in figure 5.

For anti-starve buffers the control concept remains for case I as long as possible, remembering the last  $q_{out}(t_{tailback}) > 0$  measured just before the breakdown of the downstream machine occurred. This will continuously decrease  $q_{in\_set}(t)$  according to

$$q_{in\_set}(t) = q_{out}(t_{tailback}) \cdot \left( \frac{B_{set}}{B(t)} \right)^p$$

For anti-block buffers the  $q_{out\_set}(t)$  is calculable even though  $q_{out}(t) = 0$ . So downstream buffers continue to fill up with  $q_{in}(t)$  (given by the control of the upstream conveyor system) as long as the upstream machine is not switched off because of the complete filling of the buffer ( $B(t) = C$ ).

The velocities of the input and the middle conveyor sections are set as described for case I. As long, as the buffer is not filled completely,  $v_{out\_set}(t)$  is set according to:

$$v_{out\_set}(t) = c_{out} \cdot q_{out}(t_{tailback}) + \Delta v_{slip}$$

If the buffer is completely filled ( $B(t) = C$ ) all conveyor sections are switched off until the restart of the downstream machine. The flowchart figure 6 illustrates this control approach for tailback situations.

### Case III Control for gaps within in the stream of bottles

Breakdowns of the upstream machine cause gaps within the stream of bottles. The developed control algorithm for this case uses all sections of the conveyor to close the gaps or at least to reduce the length of the gaps before they reach the infeed of the downstream machine.

For anti-starve buffers  $q_{in\_set}(t)$  is calculable even though  $q_{in}(t) = 0$ . So the control remains for case I as the upstream machine did not restart again. It continues emptying the upstream buffer with  $q_{out}(t)$  (given by the control of the downstream conveyor system) as long as the upstream machine has not restarted again.

For anti-block buffers the control also remains for case I as long as possible, remembering the last  $q_{in}(t_{gap}) > 0$  measured just before the breakdown of the upstream machine occurred. This will continuously decrease  $q_{out\_set}(t)$  according to

$$q_{out\_set}(t) = q_{in}(t_{gap}) \cdot \left( \frac{B(t)}{B_{set}} \right)^p$$

The velocities of the output and the middle conveyor sections are set as described for case I. As long as the buffer is not empty,  $v_{in\_set}(t)$  is set according to:

$$v_{in\_set}(t) = c_{in} \cdot q_{in}(t_{gap})$$

If the upstream machine starts working again ( $q_{in}(t) > 0$ ) the positions of the last bottle before the breakdown ( $x_1(t)$ ) and the first bottle after the breakdown ( $x_2(t)$ ) is tracked. They are calculated by the passed time and the velocity of the conveyor sections. The velocity of the conveyor sections  $v(t)$  is known. It depends on the passed time and the position of the bottles. The time is clocked by two timers. Timer one  $t_1$  is started when  $q_{in}(t)$  becomes zero. Timer two  $t_2$  is started when  $q_{in}(t)$  becomes greater than zero. Thus the exact position of the bottles can be calculated according to the formulas:

$$x_{1bells}(t) = \int_0^{t_1} v(t) dt \quad \begin{cases} v(t) = v_{in}(t) & \text{if } x_1(t) < l_1 \\ v(t) = v_n(t) & \text{if } l_1 < x_1(t) < l_1 + l_2 \\ v(t) = v_{out}(t) & \text{if } l_1 + l_2 < x_1(t) < l_1 + l_2 + l_3 \end{cases}$$

$$x_2(t) = \int_0^{t_2} v(t) dt \quad \begin{cases} v(t) = v_{in}(t) & \text{if } x_2(t) < l_1 \\ v(t) = v_n(t) & \text{if } l_1 < x_2(t) < l_1 + l_2 \\ v(t) = v_{out}(t) & \text{if } l_1 + l_2 < x_2(t) < l_1 + l_2 + l_3 \end{cases}$$

By knowing the positions  $x_1(t)$  and  $x_2(t)$  the set velocity of the sections is adapted in order to reduce the length of the gap or even close it. The algorithm has to differentiate between the following three cases:

- The positions  $x_1(t) = x_{1bells}(t)$  and  $x_2(t)$  are situated on the same section (see Fig. 7). The gap cannot be closed because both bottle streams are moving with the same velocity. The velo-

city of the belts is adapted to  $q_{out\_set}(t)$  (for anti-block buffer) as described above or to  $q_{in\_set}(t)$  (for anti-starve buffer) as described at case I.

- b) The position  $x_1(t) = x_{1belts}(t)$  and  $x_2(t)$  are situated on different sections (see Fig. 8). The position  $x_2(t)$  is compared to the length  $l_{in}$  and  $l_{in} + l_n$ . The velocity of the sections is adapted according to the following rules:

$$v_{in}(t) = v_{max} \quad \text{for } x_2(t) \leq l_{in} \text{ and } x_{1belts}(t) > l_{in}$$

$$v_{in}(t) = v_n(t) = v_{max} \quad \text{for } x_2(t) \leq l_{in} + l_n \text{ and } x_1(t) > l_{in} + l_n$$

By this the rear bottle stream with position  $x_2(t)$  of the first bottle shortens the distance to the forward bottle stream with the position  $x_1(t)$  of the last bottle.

- c) The forward bottle stream entered the bulk at the end of the conveyor as can be seen in figure 9. To decide whether  $x_1(t)$  indicates the end of a moving bottle stream  $x_{1belts}(t)$  as can be seen in figure 8 or the end of the bulk  $x_{1bulk}(t)$  (see Fig. 9) the position of  $x_1(t)$  is calculated for both cases. The position  $x_1(t)$  for the bottle stream can be calculated according to  $x_{1belts}(t)$ . The position  $x_{1bulk}(t)$  for the end of the bulk can be calculated according to the following formula:

$$x_{1bulk}(t) = L - s * \left( \int_0^{t_1} q_{in}(t) dt - \int_0^{t_1+t_2} q_{out}(t) dt \right)$$

The constant  $s$  is a shape factor for bottles accumulating in a sphere packing and has to be determined for each bottle type. The first integral gives the number of bottles which entered the conveyor before the breakdown. The second integral gives the number of bottles which left the conveyor until the time of calculation. The difference of the two integrals gives the absolute number of bottles at the end of the conveyor. Multiplied by the shape factor, the position of the end of the bulk is calculated in ratio to the downstream machine. If the length is subtracted from the length of the conveyor  $L$  the position of the end of the bulk in ratio to the inlet  $x_{1bulk}(t)$  gives the needed result.

To decide which calculation of  $x_1(t)$  is the correct one, both calculations are performed and the results are compared to each other. If the position calculated by the velocity  $x_{1belts}(t)$  becomes higher than the position calculated by the end of the bulk  $x_{1bulk}(t)$  the position  $x_1(t)$  is set  $x_{1bulk}(t)$  otherwise it remains  $x_{1belts}(t)$  according to the following rules:

$$x_1(t) = x_{1belts}(t) \quad \text{for } x_{1belts}(t) < x_{1bulk}(t)$$

$$x_1(t) = x_{1bulk}(t) \quad \text{for } x_{1belts}(t) \geq x_{1bulk}(t)$$

The calculation of the positions leads to the following adaption of the velocity:

$$v_{in}(t) = v_{max} \quad \text{for } x_2(t) \leq l_{in} \text{ and } x_1(t) = x_{1bulk}(t)$$

$$v_{in}(t) = v_n(t) = v_{max} \quad \text{for } x_2(t) \leq l_{in} + l_n \text{ and } x_1(t) = x_{1bulk}(t)$$

$$v_{in}(t) = v_n(t) = v_{out}(t) = v_{max} \quad \text{for } x_2(t) \leq l_{in} + l_n + l_{out} \text{ and } x_1(t) = x_{1bulk}(t)$$

If all bottles at the end of the conveyor are bulked ( $x_1(t) = x_{1bulk}(t)$ ) the velocity of the belts  $x_2(t)$  is situated on is increased to the maximum velocity. This leads to the shortest possible dead time  $t_d(t)$  and to a possible complete closure of the gap.

The complete gap control algorithm for the described cases a), b) and c) is illustrated in figure 10.

If the upstream machine stops, timer  $I$  is started to calculate position  $x_1(t)$  and the velocity of the belts is adapted to  $q_{in\_set}(t)$  for anti-starve buffers respectively to  $q_{in}(t_{gap})$  for anti-block buffers. If the upstream machine starts working again the control decides whether the gap is longer than a critical length ( $x_1(t) - x_2(t) > l_{crit}$ ). If it is shorter the gap control is stopped, if it is longer the gap is closed, as described below.

If the bottles of the forward bottle stream left a section and the first bottle of the rear bottle stream entered the section, the velocity of the sections and all upstream sections is increased to shorten the distance between the two bottle streams. If the rear stream enters the same section, like the forward stream, the velocity is reduced again. By this constellation the length of the gap can be reduced but never can be closed completely. To close a gap completely a tailback at the end of the conveyor is necessary.

Gaps between a bottle stream being transported and a tailback are closed in the same manner. The rear bottle stream is transported with high velocity until a distance of  $l_{crit}$  to the end of the tailback is achieved. At this point the velocity of the belts is reduced to soften the impact of the bottles at the end of the bulk.

## 2.4 The entire algorithm of the stepless multi-lane conveyor control

The developed control algorithms for the mentioned cases were integrated into an entire control program for stepless control of multi-lane conveyors, as illustrated in figure 11.

To decide which control has to be used the main program monitors the infeed  $q_{in}(t)$  and the output  $q_{out}(t)$  of the conveyor. If the infeed  $q_{in}(t)$  becomes zero the gap control (case III) is used to close the appearing gap. If  $q_{in}(t)$  is not zero but  $q_{out}(t)$  becomes zero the tailback control is used (case II). If both  $q_{in}(t)$  and  $q_{out}(t)$  are different from zero the continuous control (case I) is chosen.

## 2.5 Implementation to an industrial scale pilot plant

The control algorithm was implemented and tested at a pilot plant (see Fig. 12). It is constructed as a cycle. The sections marked with (1) to (3) are controlled by the bottle inspector (3). The speed of the bottle inspector can be adapted stepless from zero to 36 000 bottles per hour. The section marked with (6) buffers the bottles when the conveyor sections marked with infeed, middle and output section are empty. The stepless control algorithm was implemented for those conveyor sections. The control algorithm was programmed in the language Instruction List and implemented at the Simatic S7-300 PLC (programmable logic control) which controls the pilot plant shown in figure 12 except the parts marked with (1) to (3).

In addition the infeed, middle and output section can be controlled by jam switches as described in the introduction. The implemented new stepless control concept does not use any jam switch signals. For counting additional sensors were installed at the inlet and the outlet of the conveyor. As the input of conveyor infeed section is single-lane, it can be monitored by a light barrier, which is connected to the PLC. By this the infeed of bottles  $q_{in}(t)$  can be monitored. The output of conveyor output section is multi-lane. As the bottles drop out of the buffer in a multi-lane bulk, they cannot be monitored by a light barrier. So the mentioned intelligent camera for counting grouped bottles is used. It is positioned above the conveyor. The passing bottles are filmed and the pictures are analyzed by the directly connected evaluation unit. Afterwards the counter value is sent to the PLC via Ethernet connection [13]. The PLC calculates the output of the conveyor  $q_{out}(t)$  by the counter values of the intelligent camera and an internal clock.

Both the control algorithm for the anti-starve and the anti-block buffer were implemented. As no machine follows the multi-lane conveyor experimental tests for the anti-block mode were not possible under reproducible conditions yet. For the anti-starve mode the conveyor output section is driven like an infeed conveyor for a machine.

### 3 Experimental results

The experiments aimed at proofing the functionality of the above described control algorithm particularly in all mentioned cases. The parameters for the test runs had to be identified in pretests first. Geometrical conditions result from measurements of the used equipment (e. g. diameter of the bottles  $d_0$ , the capacity of the conveyor  $C$  and the geometrical dimensions of the conveyor). Other conditions (e. g. the control cycle time  $dt$ , the power constant  $p$ , the maximum of  $q_{in}(t)$ ,  $q_{out}(t)$  and  $v_{max}$ ) were determined empirically during preliminary tests. The following test conditions were determined:

- $dt = 0,2$  s (integration time of the PLC for the calculation of the positions)
- power  $p = 3$
- maximum  $q_{in}(t)$  19500 bottles per hour
- $q_{out}(t)$  15000 bottles per hour
- $C = 692$  bottles
- $v_{max} = 0.31$  m/s
- $L = 10.70$  m
- $d_0 = 0.0675$  m (NRW bottles)
- $l_{in} = 5.12$  m
- $l_n = 4.37$  m

- $l_{out} = 1.21$  m
- $t_{d_{min}} = 34.5$  s (theoretically calculated minimal dead time)
- $s = 0.0169$
- $c_{in} = 1.74 * 10^{-5}$
- $c_{out} = 4.67 * 10^{-6}$
- $\Delta v_{slip} = 0.01$  m/s
- $B_{set} = 346$
- $l_{crit} = 0.1$  m

First qualitative results were achieved by careful observation of the control behavior of the new algorithm in comparison to the control using the jam switches. The stepless control program was able to run the pilot plant stable during all experiments, each with a duration of several hours. It reacted in the aspired way to all possible conveyor states.

To prove this quantitatively, the number of objects on the conveyor ( $B(t)$ ) and the speed of the upstream machine were documented over the relevant seconds of the test runs. In the following, selected results for the control behavior in the three considered control cases are presented. All results were achieved by at least five particular test runs for each case.

To evaluate the control algorithm for continuous operation (case I), the operation of the conveyor system was started with a completely empty buffer. The filling up and the stabilization of the number of objects on the conveyor ( $B(t)$ ) was monitored. Figure 13 shows the evolution of  $B(t)$  in reference to the set output of the upstream machine.

While  $B(t)$  is small the speed of the upstream machine fills the buffer with maximum  $q_{in_{set}}(t)$ . Thus  $B(t)$  rises linear at first. As it draws nearer to the set number of objects  $B_{set} = 346$   $q_{in_{set}}(t)$  is reduced continuously.  $B(t)$  is adjusted continuously and without overshooting, but with a positive deviation of about 1 %.

To evaluate the reaction of the control algorithm on short stoppages of the upstream respectively downstream machine one machine was stopped and restarted after a deviation of  $B(t)$  from its set value of about 20 %. The graphs shown at figure 14 show the readjustment of  $B(t)$  after the machine restarts.

After the breakdown at the upstream machine the gap control (case III) closed the gap and needed about 60 s to readjust  $B(t)$ . Again a continuous and stable control behavior without overshooting can be noticed. As before,  $B(t)$  is not adjusted exactly to  $B_{set}$  but with a positive deviation of about 1 %. A similar behavior can be observed for the breakdown control (case II) shown in the right figure, but the time to readjust the preset number of objects on the conveyor appears within about 100 s.

The answer to a completely empty conveyor system already was shown in figure 13. In this case the gap control (case III) was used to transport the bottles to the end of the conveyor. After the stream of bottles reached the end of the conveyor (position  $x_2(t) = L$ ), the program switched to the continuous control (case I). The preset number of bottles ( $B_{set}$ ) was adjusted after about 90 s.

To evaluate the ability of the continuous control algorithm to close gaps efficiently in general, the dead time of the conveyor system that practically showed up during the test runs was clocked. The result was a practical dead time  $t_d$  of  $35.3 \pm 0.2$  s ( $n = 5$ ,  $\alpha = 0.05$ ) that is only slightly longer than the theoretically calculated value of 34.5 s.

#### 4 Discussion and conclusions

Generally the stepless control was running within the preset parameters. It reacted in the aspired way to all situations occurring on the conveyor. The conveyor system was controlled in a stable way without oscillations during all test runs.

The achieved practical conveyor dead time of 35.3 s is only slightly higher than the theoretically achievable minimum. Thus the downstream machine is served with bottles after a longer downtime of the upstream machine almost as fast as possible. Gaps within the bottle stream are closed almost within the minimum possible time.

During the tests the actual number of objects on the conveyor ( $B(t)$ ) was increased and decreased by 20 % because of short simulated machine breakdowns. The continuous control algorithm readjusted the preset level  $B_{set}$  by modulating the outputs of the upstream machine and the velocity of the conveyor sections. The time needed for a reestablishment of the preset number of objects on the conveyor ( $B_{set}$ ) from lower filling levels was shorter than from higher ones. To explain this, the conveyors dead time has to be considered. In the best case, bottles fed into the conveyors infeed section are able to leave the conveyor after a time delay of about 35 s. Thus modulations of the input (output of the upstream machine) also show a time delay.

In all tests the preset number of bottles on the conveyor ( $B_{set}$ ) is slightly exceeded by about 1 %. This can be traced back to the fact that the output of the conveyor falls slightly below the preset level of 15 000 bottles per hour because of structural conditions of the pilot plant. As there is no machine available that would provide an exact infeed behavior at the end of the conveyor, an unavailable deviation occurs. As said before, reproducible results for the behavior of the developed control algorithm in anti-block mode could not be gained. The missing of a well-defined operating machine downstream to the test conveyor system is also the reason for this. So for further investigations the pilot plant has to be improved by technical modifications to be able to completely evaluate the developed control concept.

The first test runs proved that continuous control, according to the algorithm presented in this paper, is generally possible. The only needed input variable for the control are the in- and outflows

and the velocities of the conveyor sections. No mechanical jam switches were necessary. Using the mentioned intelligent camera for counting the concept is applicable for multi-lane conveyors with single-lane and/or multi-lane in or outlets. The benefits of this kind of control compared to the state of the art stepwise concepts are the more exact adaption of the velocity of the conveyor sections and machines to the actual system situation and the almost minimum achieved buffer dead time. These benefits lead to lower mechanical wear of the plant and the bottles and high plant efficiencies. Additionally a lowering of the noise emission caused by clashing bottles could be noticed during testing which has to be investigated in further studies.

#### 5 References

1. Back, W.: Sekundärkontaminationen im Abfüllbereich. BRAUWELT **134** (1994), pp. 686-690 and 692-695.
2. Berg, F.: Technische Flaschenkeller-Betriebskontrolle, BRAUWELT, **108** (1968), pp. 833-838.
3. Buzacott, J. A.: Automatic Transfer Lines with Buffer stocks, International Journal of Production Research, **5** (1967), no. 3, pp. 183-200.
4. Cooke, R. M.; Bosma, A. and Härte, F.: A partial model of Heineken's bottle filling line with dependent failures, European Journal of Operational Research, **164** (2005), pp. 491-504.
5. Deutscher Brauerbund: Mediendatenbank, <http://www.brauer-bund.de/index.php?keyword=&searchtype=keyword&id=167&pos=61&cat=Brautechnik>, April 2010.
6. Jafari, M. A. and Shanthikumar, J. G.: Determination of Optimal Buffer Storage Capacities and Optimal Allocation in Multistage Automatic Transfer Lines, IIE Transactions, **21** (1989), no. 2, pp. 130-135.
7. Kather, A.: Fehlerlokalisierung in verketteten Produktionslinien am Beispiel von Lebensmittelverpackungsanlagen doctoral thesis, TU München, 2009.
8. Kay, E.: Buffer stocks in automatic transfer lines, International Journal of Production Research, **10** (1972), no. 2, pp. 155-165.
9. Manning, H.: Computer Modeling of Packaging Lines, MBAA Technical Quarterly, **17** (1980), no. 4, pp. 177-183.
10. Okamura, K. and Yamashima, H.: Analysis of the Effect of Buffer Storage Capacity in Transfer Line Systems, IIE Transactions, **9** (1977), no. 2, pp. 127-135.
11. Rädler, T.: Modellierung und Simulation von Abfülllinien, doctoral thesis, TU München, 1999.
12. Sörensen, K. and Janssens, G. K.: Buffer allocation and required availability in a transfer line with unreliable machines, International Journal of Production Economics, **74** (2001), pp. 163-173.
13. Sorgatz, A.: Entwicklung eines Sensorsystems zur Behälterzählung im Pulk, BRAUWELT, **149** (2009), pp. 692-695.
14. Struss, P.; Kather A.; Schneider, D. and Voigt, T.: A Compositional Mathematical Model of Machines Transporting Rigid Objects, Proc. 18<sup>th</sup> European Conference on artificial Intelligence, 2008, pp. 184-188
15. Voigt, T.: Neue Methoden für den Einsatz der Informationstechnologie bei Getränkeabfüllanlagen, doctoral thesis, TU München, 2004

Appendix



Fig. 1 Bottling Plants for returnable glass bottles with multi lane conveyors [5]

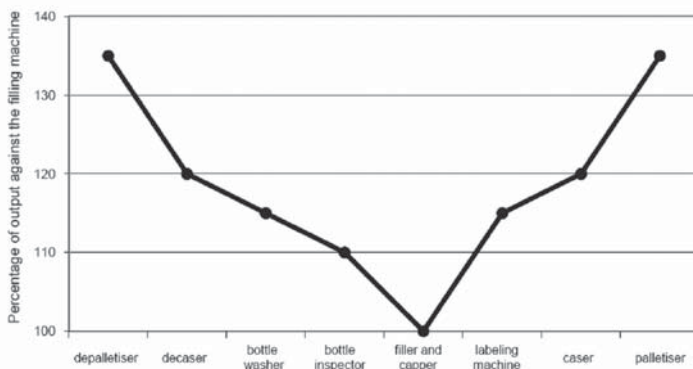


Fig. 2 V-Graph showing the grading of the speed of machines in a bottling plant with the blocked filler and capper as leading machine [2]

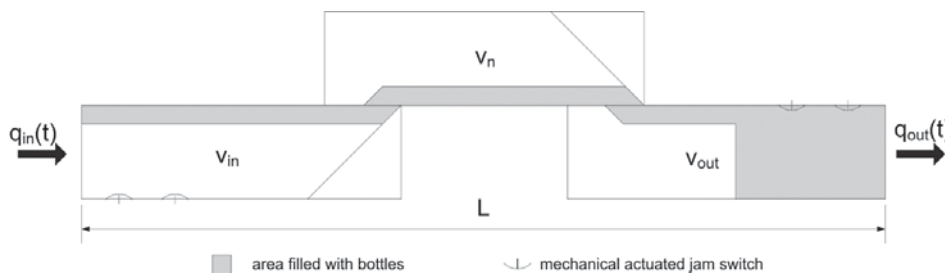


Fig. 3 Schematic view of the considered conveying system with one middle mass conveyor section

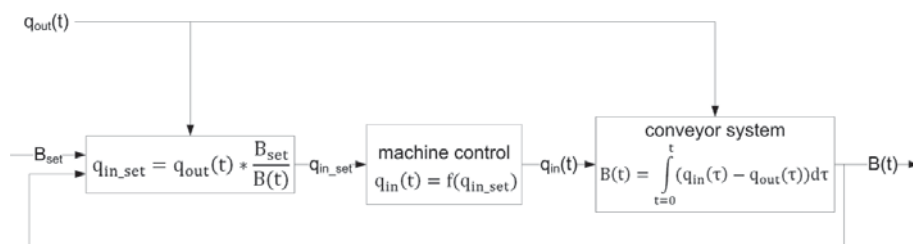


Fig. 4 Control loop for the continuous operation of anti-starve conveyors

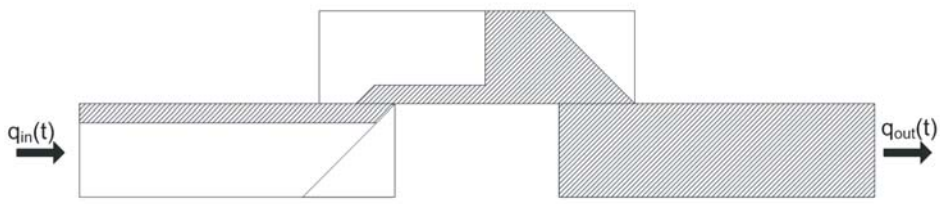


Fig. 5 Tailback situation on a conveyor

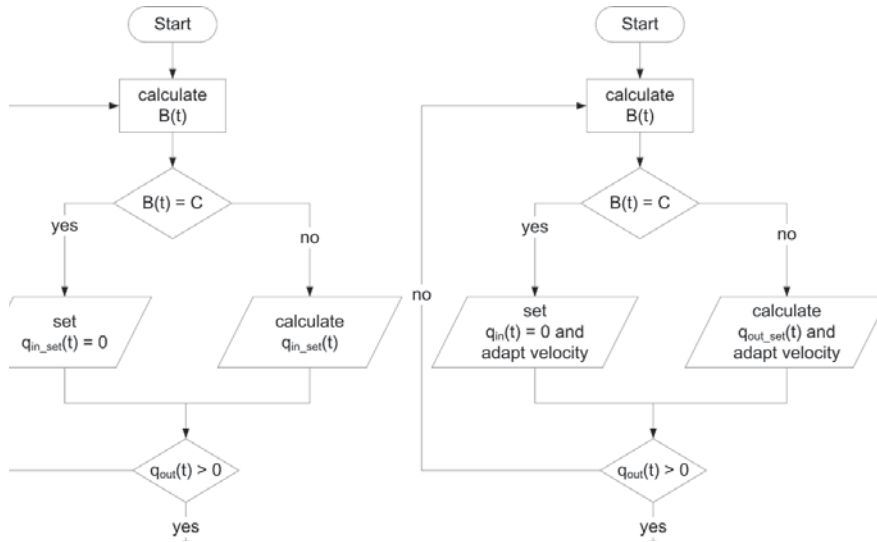


Fig. 6 Flowchart of the control algorithm for the tailback control of anti-starve buffers on the left and tailback control for anti-block buffers on the right

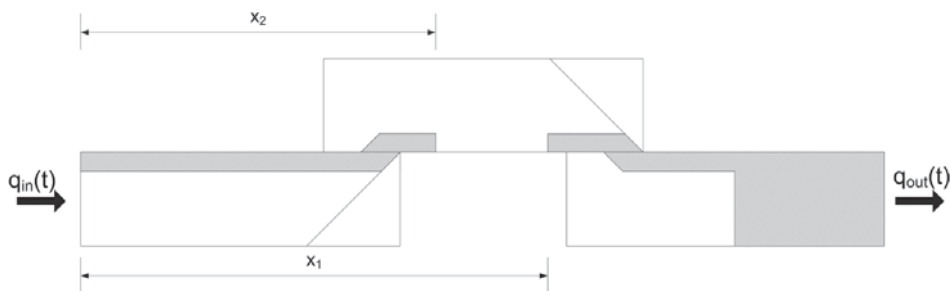


Fig. 7 The end of the forward bottle stream and the beginning of the rear bottle stream are situated on the same section

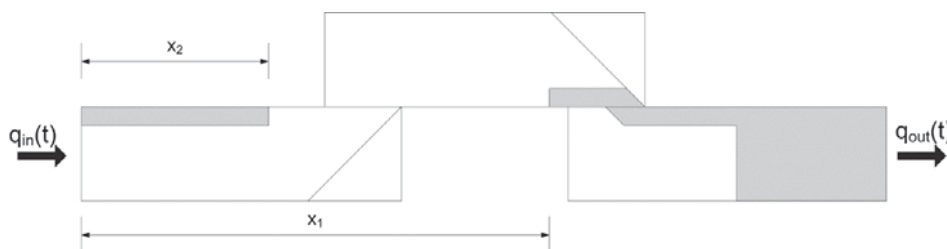


Fig. 8 The end of the forward bottle stream and the beginning of the rear bottle stream are situated on different sections

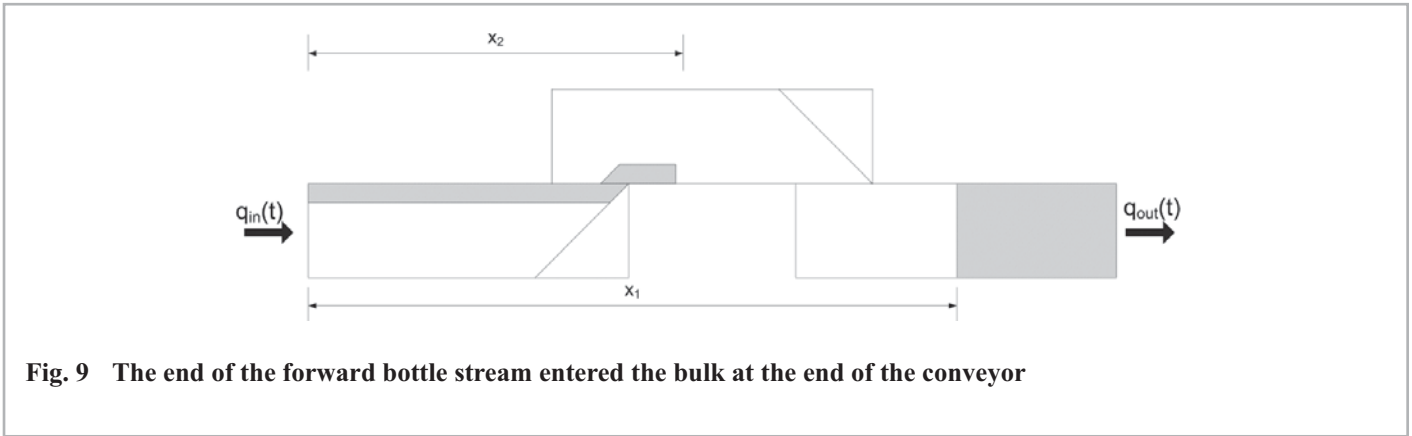


Fig. 9 The end of the forward bottle stream entered the bulk at the end of the conveyor

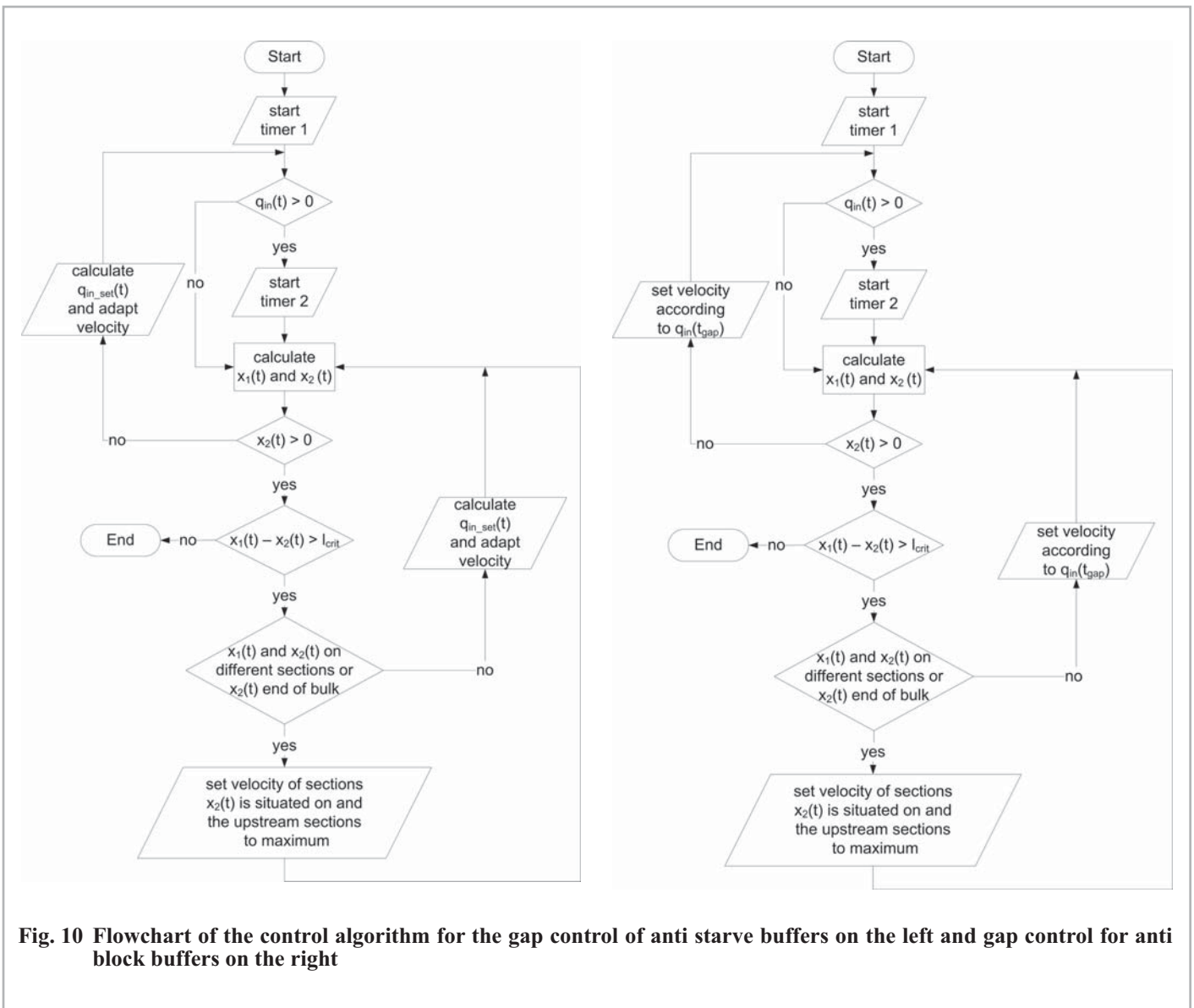


Fig. 10 Flowchart of the control algorithm for the gap control of anti starve buffers on the left and gap control for anti block buffers on the right

