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Accuracy Verification of Continuous Juice Blending Process Using Simulation

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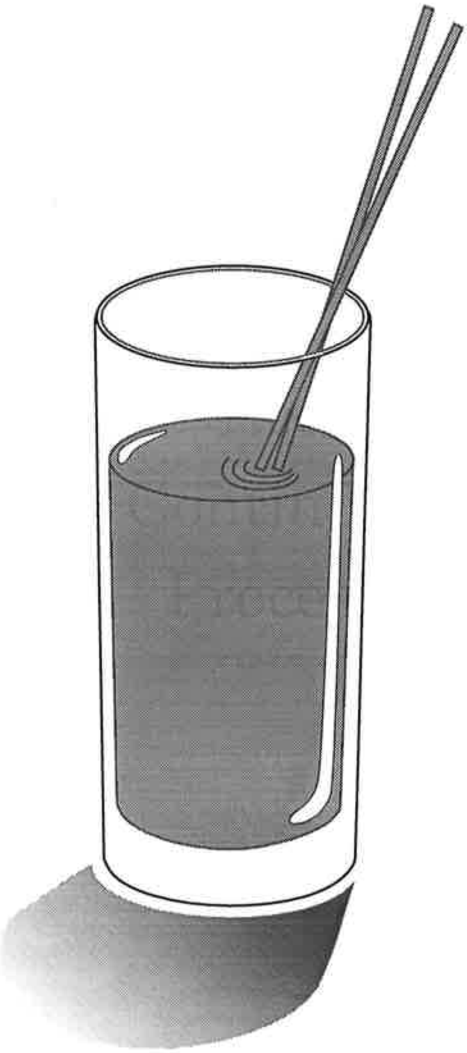

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Abstract

This report evaluates a new type of equipment (Tetra Alblend) for producing different kinds of fruit beverages. The equipment consists of a number of pumps, valves, compartments and mixers and blends up to six components to get the perfect customer's beverage. The equipment is represented in the object oriented modelling language Omola. To establish the accuracy of its performance it is also simulated in Omsim and submitted to various predictable disturbances. The accuracy is defined as the standard deviation of juice concentration.

The report includes background on the processes involved and how the models are built. The models are validated against tests done on the real Tetra Alblend plant. Experiments with production capacities and blending accuracy are also analysed in order to predict the performance of the Tetra Alblend and suggest improvements.

Key words
Process modelling, dynamic simulation, object oriented modelling, continuous juice production, oBrix.

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1. Introduction

Consumption and production of fruit beverages is a constantly growing market. To satisfy the increasing demand of fruit juices, the industrialised world imports large quantities of fruit juice concentrate. Tetra Pak Processing Systems AB is one of the major players on the world market of equipment for producing beverages.

Conventional juice production is done by blending concentrate and water in batches and then pumping each batch to pasteurisation and filling. The Tetra Alblend introduces a new and more efficient concept in this business. By blending the beverage continuously (in-line) it is possible to achieve higher accuracy, better adjustment to production rate and more space efficiency.

One of the most important features of the Alblend is the accuracy of juice concentration. The concentration is measured in Brix (°Bx) which is related to the refraction index of the fluid. To be able to guarantee Brix accuracy it is necessary to observe the plant during time-consuming test series. Computer simulations is a very good tool for carrying out these tests in less time and with more variations.

This report includes simulations of a simplified model of the Tetra Alblend. The model is implemented in the object oriented modelling language Omola and includes both the continuous-time as well as the discrete-time processes of the machine. The simulations carried out on the validated model are analysed to tell a little more about the abilities of the real Tetra Alblend and in some aspects suggest improvements of control properties.

2. Purpose

This project will evaluate the performance of the Tetra Alblend blending module in the aspect of Brix accuracy in its final product. The Omola models and the simulations in OmSim are to be analysed statistically to obtain a standard deviation in product Brix during a number of predictable disturbances. The specification for the Alblend is ±0.1°Bx in standard deviation of blended product. The simulations of the model are also to be regarded as a tool for predicting the production limitations of the Alblend.

If the Omola models also are proven to be a good representation in other aspects than Brix control, the simulations could also be used to improve the performance of the Tetra Alblend in these aspects.

3. Tetra Alblend

3.1 Background

The Tetra Alblend is a system for producing various kinds of high acid fruit beverages basically by mixing concentrate with water. It is an in-line system which means that it mixes the components continuously, and that the production rate is adapted to the succeeding pasteurisation and filling modules.

The restrictions, when making juices out of concentrate and water, differ from country to country, but normally includes a legal demand of a minimum content of concentrate. Of course, it is impossible to analyse the amounts of all the ingredients and the sugar concentration is therefore used as a simplified test parameter. Sugar concentration is specified in the unit Brix which is the calculated concentration of sugar based upon the measured refraction index (Brix is the short form of the German word "Brechungsindex").

$$1°\text{Bx} \approx 1\% \text{ sugar solution}$$

To be able to guarantee the Brix level of the product the Alblend has been put through extensive tests during the autumn of 1995. The Brix level has been observed during production with a number of predictable disturbances, such as various production rates and variations in concentrate Brix.

3.2 Working principle

To be able to secure the Brix level of the beverage, the blending takes place in two steps.

1. In the first step mixing is controlled by the measured flow rates without any feedback. The product is slightly overmixed with concentrate to make further dilution in step 2 possible.
2. In the second step feedback, with respect to Brix level, is included by measuring the Brix level and then diluting with further water.

Furthermore, the product Brix level is smoothened out in the buffer tank which holds 1000 l and is constantly stirred.

During regular production the total flow rate in the machine is controlled by the level in the buffer tank. The production rate may then change slowly even though the production demand from the subsequent pasteurisers may change rapidly.

3.3 Standard design

The base module of the Alblend consists principally of the following units.

- a water unit
- a concentrate unit
- a blending unit
- a buffer tank unit.

A unit for reclaim products can also be connected. This unit takes care of product that is either out of Brix range or wasted somewhere along the succeeding production line. The reclaim unit is optional but is included in this analysis.

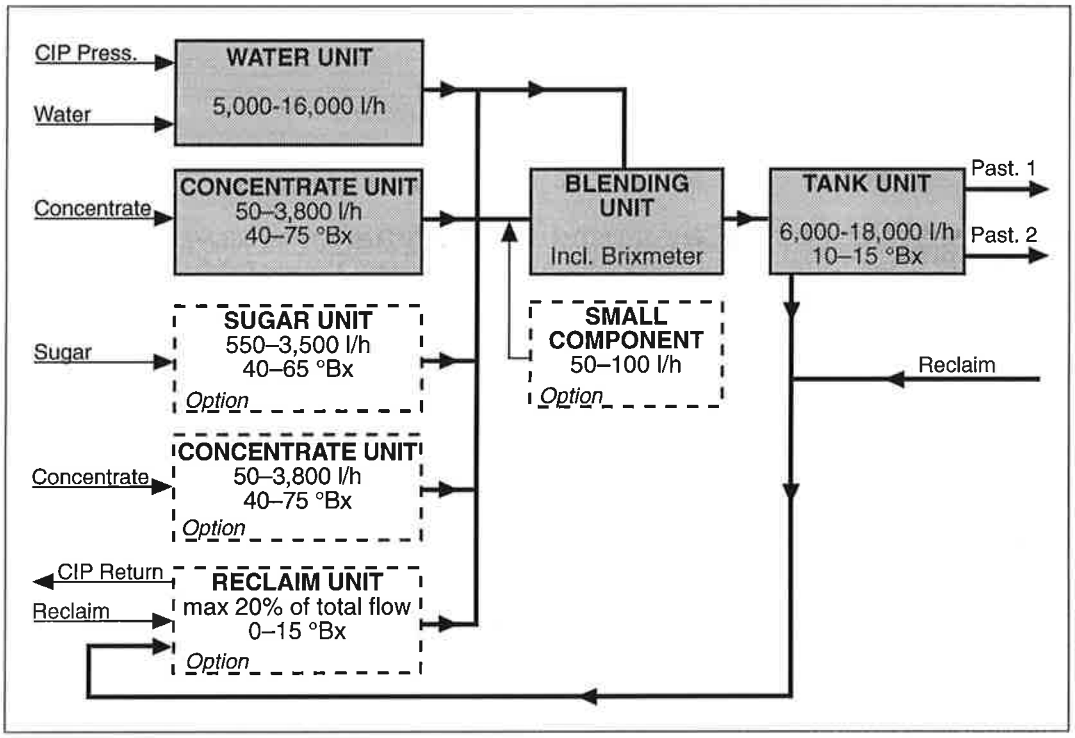


Figure 3.1 Tetra Alblend with all its units as sketched by Tetra Pak Processing Systems.

As seen in Figure 3.1 the Tetra Alblend is designed to match the following demands.

Medium	**Flow range**	**Brix range**
Water	5 000–16 000 l/h	—
Concentrate	50–3 800 l/h	40–75 °Bx
Reclaim	max. 20% of total flow	0–15 °Bx
Sugar	550–3 500 l/h	40–65 °Bx
Concentrate 2	50–3 800 l/h	40–75 °Bx
Small component	50–100 l/h	—
Final product	6 000–18 000 l/h	10–15 °Bx

Other optional units that are available are those for in-line blending of sugar solutions, further concentrate, small components (e.g. aromas, vitamins) but these units are left out of this project. The standard units of the Tetra Alblend are more carefully described in the sections below.

3.3.1 The water unit

The water unit is the main unit in the Alblend system and includes the following components. The water flow rate sets the flow rates of the other units by ratios specified in the recipe.

- Centrifugal pump (M10)
- Balance tank (BT1)
- Flow transmitter (FT1)
- Flow controller (FC1)
- Speed controller (SC1)

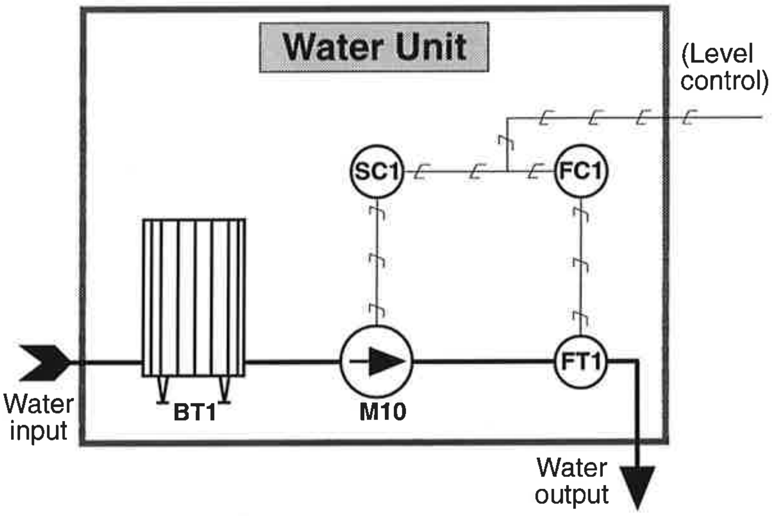


Figure 3.2 The Alblend water unit

During start up procedures the water unit runs at a constant flow rate. When the tank of the buffer tank unit is half full the water unit is switched over to automatic level control. The balance tank, BT1, secures constant pressure and water flow to the inlet of the water pump.

3.3.2 The concentrate unit

The concentrate unit runs at various flow rates, specified by a ratio of the water flow rate. The two mono pumps (positive displacement pumps) have different flow ranges. Due to inaccuracy in the large pump, a smaller pump is needed to smooth out the flow rate changes.

The concentrate unit includes the following components.

- Mono pump (M20A)
- Mono pump (M20B)
- Balance tank (BT2)

- Flow transmitter (FT2)
- Flow controller (FC2)
- Speed controller (SC2A)
- Speed controller (SC2B)

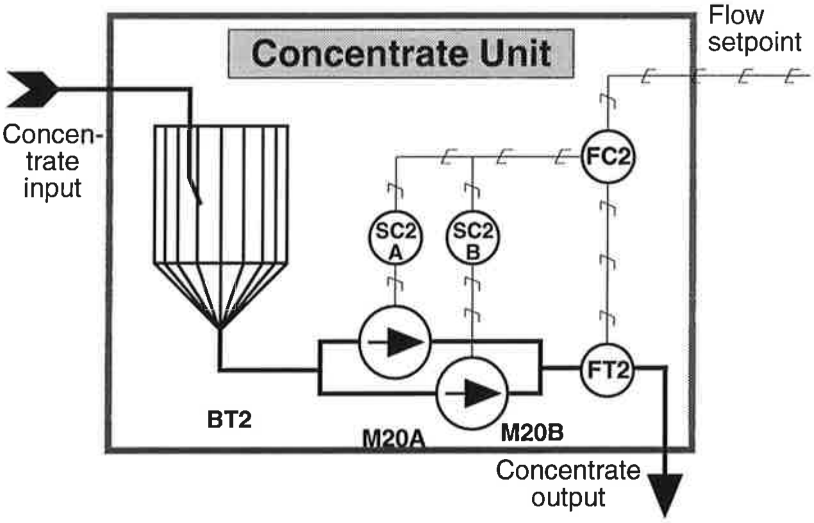


Figure 3.3 The concentrate unit.

3.3.3 The reclaim unit

Reclaim includes product that has not made it through the complete production line. This could be due to rinsing of concentrate tanks or production stops in pasteurisers or fillers. The reclaim unit consists of the following components.

- Centrifugal pump (M40)
- Reclaim buffer tank (BT4)
- Flow transmitter (FT4)
- Flow controller (FC4)
- Speed controller (SC4)

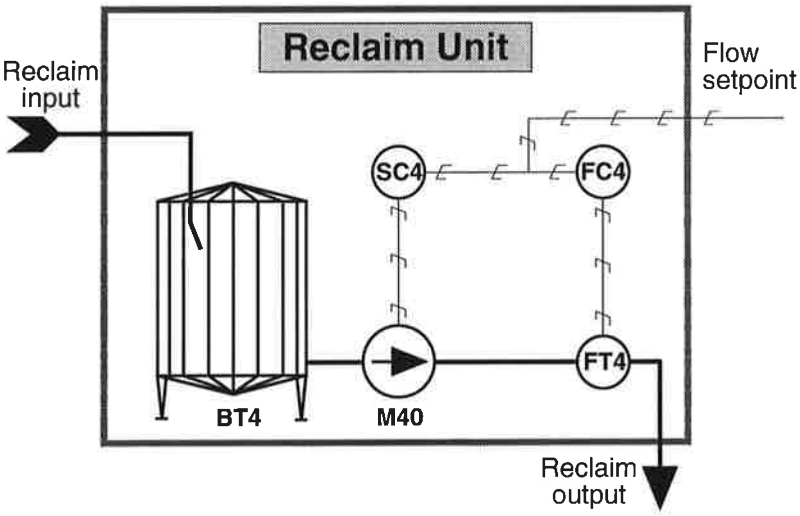


Figure 3.4 The reclaim unit

The reclaim flow rate, like in the concentrate unit, varies with the water flow rate. Furthermore, the flow rate depends on the level in the reclaim buffer tank. Since this tank sometimes is empty there is additional logic to control when to mix in reclaim or not. The unit is, as mentioned earlier, optional in the Alblend design, but is included in this project due to the discrete control logic which implies discontinuous features and disturbances in a Brix aspect.

3.3.4 The blending unit

The blending unit define the Brix feedback process. It consists of the following components.

- Static mixer.
- Brix transmitter. (BxT)
- Brix controller. (BxC)
- Constant pressure module. (CPM)
- Control valve. (V60)
- Flow transmitter. (FT6)

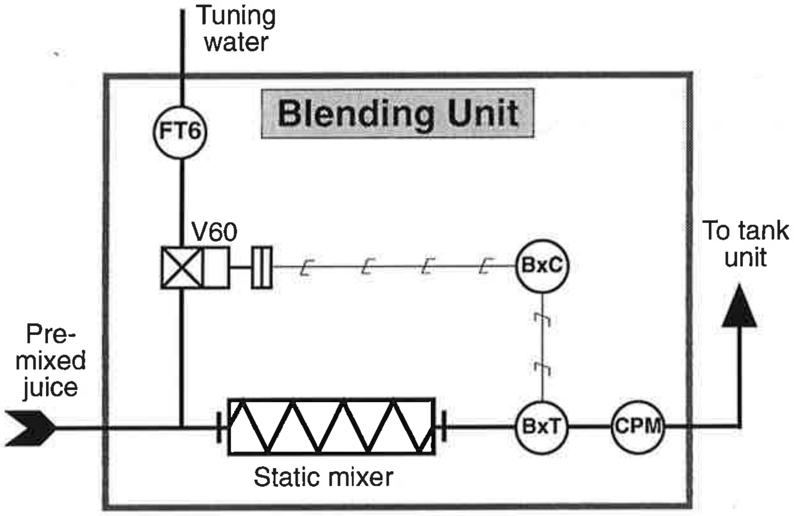


Figure 3.5 The Blending unit.

The premixed juice is thoroughly blended in the Static mixer before entering the Brixmeter, BxT. The Constant pressure module, CPM, makes sure that the pressure in the blending unit is constant. This is done not to affect the Brix measurement. The flow transmitter, FT6, is only used for supervision purposes.

3.3.5 The buffer tank unit

The buffer tank unit is the last stop for the blended product before its being shipped on to the next machine in the production line. It consists of the following components.

- Buffer tank. (BT7)
- Centrifugal pump. (M70)
- Level transmitter. (LT7)
- Level controller. (LC7)

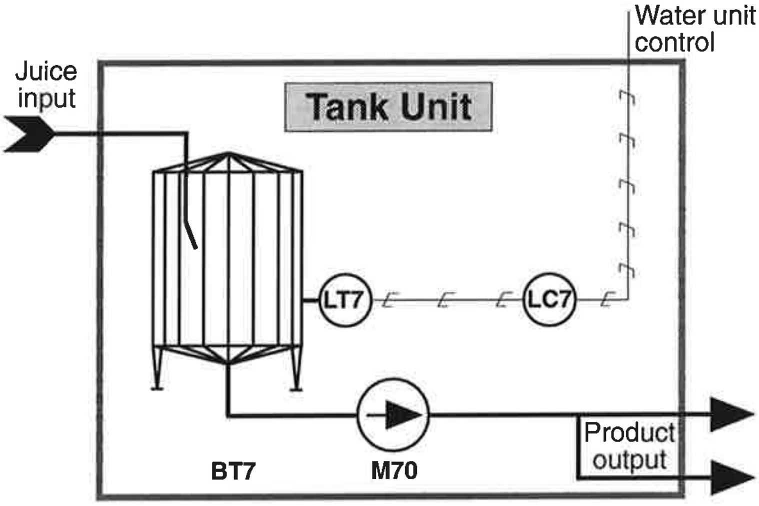


Figure 3.6 The Buffer tank unit.

The buffer tank holds 1000 l of blended product. During regular production the level in this tank controls the total product flow rate in the Tetra Alblend. The level setpoint also varies with the total flow rate to increase the buffer capacity of the tank.

4. The Alblend Omola model

4.1 Backgrounds on Omola and OmSim

Omola is an object oriented modelling language developed at the Department of Automatic Control, Lund Institute of Technology. OmSim is the interactive environment for defining and simulating the models made in Omola. In this environment it is also possible to edit the models graphically. This tool is used to create the OmSim images in this report. OmSim runs on Sun and HP workstations and is not a commercial software.

4.1.1 Object orientation

The models are called classes in the Omola language. Due to the object orientation the classes are made from superclasses which gives them a parent-child relation. The class inherits the features of its superclass. The components with their interconnections and all of their superclasses compose the database with which we work. A number of unit directories such as FlowUnitLib and CompartmentLib contain the classes and form the new database AlblendDb.

4.1.2 Continuous and discrete time systems

As most systems in reality, the Tetra Alblend consists of both continuous- and discrete-time processes. Apart from most simulation software Omola and OmSim are able to handle both kinds of processes in combination. Although discrete events may cause discontinuity problems, this makes it possible to simulate systems in a greater context.

4.2 General structure of the Alblend model

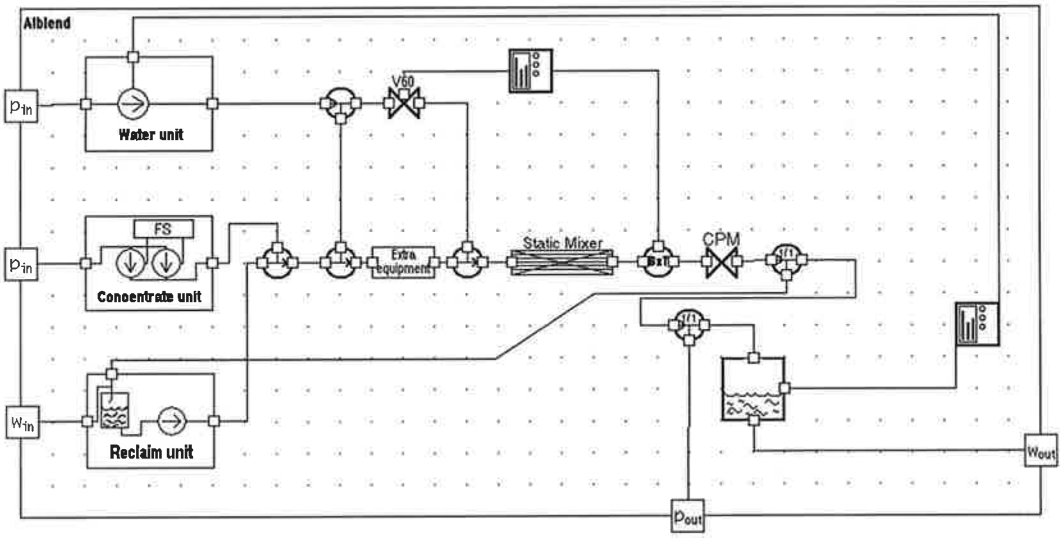


Figure 4.1 The full Omola model of Tetra Alblend.

The full model of the Tetra Alblend is based upon the flow chart designed by Tetra Pak. The model has been divided into units as described in Figure 3.1. The "blending unit" and the "buffer tank unit", however, has not been modelled as a unit for visual reasons.

Most of the symbols in the model speak for themselves but some of them may need further explanation.

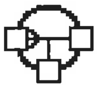
The **V60** is the valve that controls the fine tuning of water in the Brix feedback process.

The **Brix transmitter** is in fact a refractometer that registers refraction index, but it is set to return the Brix value

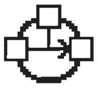
The **Static mixer** mixes the product before Brix measurement

The **Constant Pressure Module** keeps the pressure on the inlet side constant.

The **Two way valve** directs the product one of two ways.



The **Flow split** divides one flow into two.



The **Flow junction** joins two flows into one

The **Extra equipment** represents the tubes, bends and junctions in the Alblend.

As shown in figure 4.1, the Omola model of the Alblend consists of the four standard units of the Tetra Alblend, i.e., the water unit, the concentrate unit, the blending unit and the buffer tank unit. In addition, the model also includes the reclaim unit. This is partly because the mixing of reclaim products into the juice may interfere with the Brix accuracy, but also because the reclaim unit is considered to be a common addition to the standard design.

4.2.1 The water unit

The Water unit model is in some aspects a simplification of the real water unit. The balance tank, BT1 in Figure 3.2, is excluded since constant pressure and supply of water is provided by the computer and does not influence the simulation performance. The flow transmitter, FT1, and the speed controller, SC1, is included in the centrifugal pump model, which is further described in section 4.3.1.

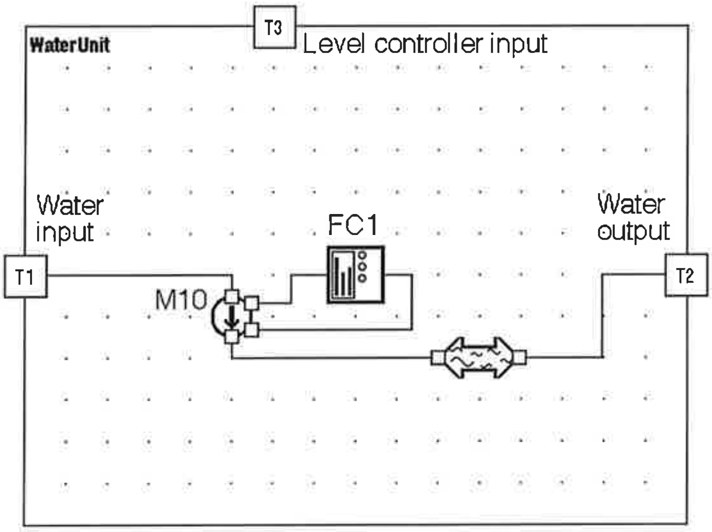


Figure 4.2 The Omola model of the water unit.

The flow controller is only used during the start-up procedure. When the water unit runs in continuous production, the flow controller is switched over to level control. The signal from the level controller enters the water unit through the terminal T3. The terminals T1 and T2 are flow terminals, used to connect the water unit to the other units.

4.2.2 The concentrate unit

The concentrate unit maintains a steady concentrate flow rate, specified as the juice recipe ratio of the water flow rate. As in the water unit, the balance tank, BT2 in Figure 3.3, is excluded from the model. The flow transmitter, FT2, is included in the flow junction, and the flow and speed controllers, SC2A, SC2B and FC2, are included in the FlowSupervisor.

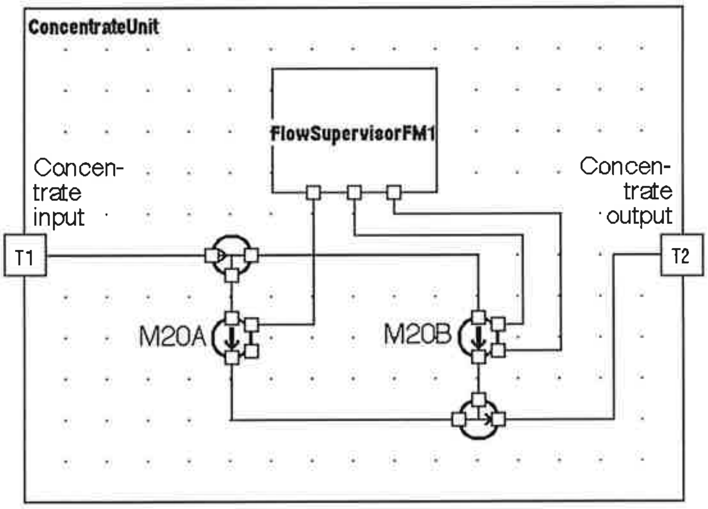


Figure 4.3 The Omola model of the concentrate unit.

The FlowSupervisor takes care of the total flow out of the concentrate unit, which means controlling the up and down shifts of the large pump when the small pump reaches one of its flow range limits. Between these shifts the FlowSupervisor also controls the flow rate of the small pump by using a the PID-controller, FC2. The model of the FlowSupervisor is further described in section 4.2.3.

4.2.3 The reclaim unit

The reclaim unit includes the reclaim balance tank, BT4, the pump, M40, and the flow controller, FC4. The speed controller, SC4, and the flow transmitter, FT4, in Figure 3.4, is included in the pump model. With reclaim we mean the product that is either out of range in the blending process and therefore re-routed, or in other ways wasted product, somewhere along the production line, that still is usable. The waste product enters the unit through the terminal T3, which is externally connected to the Buffer tank unit.

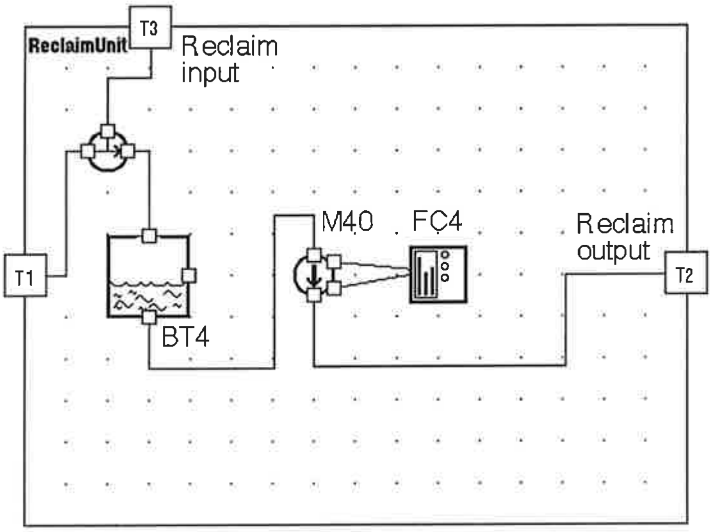


Figure 4.4 The Omola model of the reclaim unit.

Since the supply of reclaim is very unpredictable the reclaim unit must operate under a set of logical conditions.

1. When the reclaim tank level is below 2% the reclaim unit is shut off.
2. When the reclaim tank level rises above 2% of the maximum level, reclaim is being mixed into the product with a rate of 100 l/h. (Min. reclaim)
3. When the reclaim tank level rises above 10% of the maximum level, the reclaim flow rate is ramped up during 7 minutes to a flow rate set by a ratio of the water flow. (Max. reclaim)

The state where the reclaim unit is shut off is not implemented. It may seem like a simple thing to do but has proven to be quite difficult to find a model valid for zero flow as well as for non-zero. Therefore the reclaim unit in the Omola model runs only with the conditions 2 and 3 above. A reclaim flow of 100 l/h (Min. reclaim) into the reclaim tank is provided to make sure the level never goes below 2% of the maximum level.

4.2.4 The blending unit

This unit constitutes the Brix feedback process in the Tetra Alblend. The Brix level is adjusted just by adding water to the pre-mixed product.

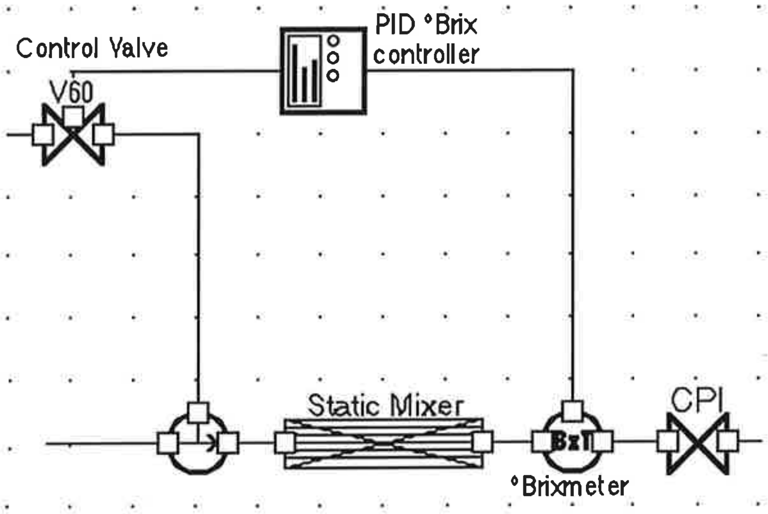


Figure 4.5 The Omola model of the Blending Unit.

To be able to adjust the Brix level just by adding water through the control valve the ratio by which the concentrate unit runs has to be higher than the concentration wanted in the final product. The flow setpoint of the concentrate unit is therefore 4.5% higher than specified in the recipe. The Static Mixer is merely a tube with fixed propellers, helping the concentrate to diffuse in the water before the Brix measurement. The CPM keeps the pressure constant on its inlet side to assure good Brix measurements.

4.2.5 The buffer tank unit

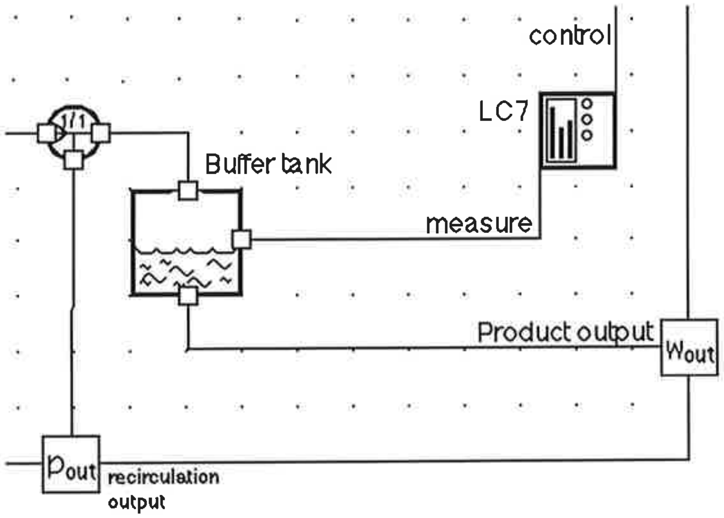


Figure 4.6 The Omola model of the Buffer tank unit.

The buffer tank unit is the final stop for the product before leaving the Alblend module. It includes the buffer tank and a PID-controller for level control. The tank holds 1000 l and its content is constantly stirred to even out fluctuations in product Brix. When the Tetra Alblend runs in production mode the PID-controller maintains the buffer tank level by controlling the water unit flow rate. During start-up procedures this PID-controller is shut off.

To fully utilise the buffer capacity of the buffer tank, the setpoint for the tank level is high when production rate is low and vice versa as shown in Figure 4.7. (Since production rate is more likely to increase rapidly when it is low, the level of product needs to be high in order to avoid a production failure by running dry.)

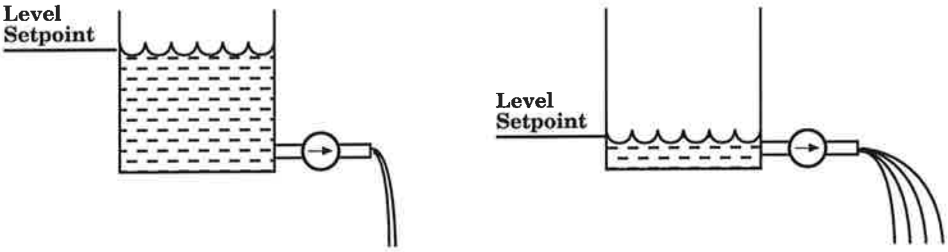


Figure 4.7 a) Low production rate – high buffer tank level. b) High production rate – low buffer tank level.

The buffer tank level is a function of the total flow rate out of the tank.

$$L = L(Q_{tot})$$

Since there is no flow transmitter in the Alblend that can measure the actual total flow rate in the Alblend, i.e. the flow out of the buffer tank, the total flow rate has to be estimated mathematically. This is done by filtering the measured flow rate into the buffer tank through a filter of first order. In reality this is done with the discrete algorithm

$$Q_{tot}(t+T) = k_1 \cdot Q_{in}(t+T) + k_2 \cdot Q_{tot}(t)$$

where Q_{tot} = Calculated flow rate out of buffer tank
Q_{in} = Measured flow rate into buffer tank
$k_1 = 1 - e^{-T/T_0}$
$k_2 = 1 - k_1$
T = Sample time
T_0 = Time constant

This algorithm is, due to limitations in the Alblend PLC, executed only every 5th second. This sample period is, however, several times smaller than the time constant for this process, which makes the discrete algorithm almost equal to the continuous algorithm. Since a continuous filter is much more conveniently implemented in OmSim and also more efficient in simulations, this is what is done.

$$Q_{tot}(t) = Q_{in}(t) - \frac{1}{T_0} Q'_{tot}(t) \qquad \text{where} \qquad Q'_{tot} = \frac{dQ_{tot}}{dt}$$

4.3 Modelling details

All of the components in the Alblend are modelled from the data sheets of each component. In most cases this does not imply any difficulties. A few of the components, however, needed more careful modelling.

4.3.1 The centrifugal pump

The centrifugal pump is a non-ideal pump in a speed-flow rate sense. Since the pump leaks some of the fluid backwards, the flow rate is also dependent on the pressure over the pump. These characteristics are available in the data sheets as two-dimensional pump charts for specific speeds. The centrifugal pump is used in the water and in the reclaim unit.

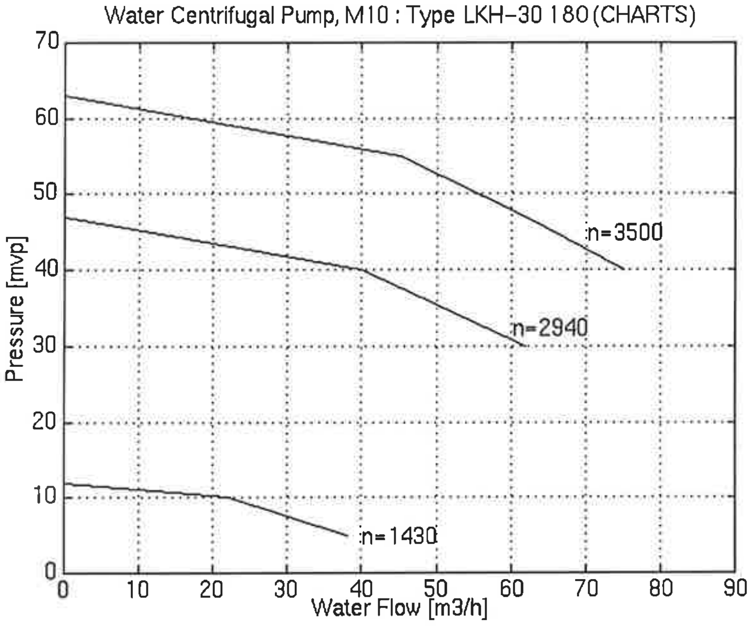


Figure 4.8 The flow-pressure charts for the centrifugal pumps at three different speeds.

To get a model of the pump continuous in time, a mathematical expression has to be found that gives the flow rate as an expression of pressure and speed.

$$Q = Q(H,n); \quad H \geq 0, \; n \geq 0$$

To find the complete mathematical expression of the pump characteristics the expression for the flow rate at a fixed speed is established.

$$Q = Q(H); \quad n = n_{\max}$$

Physically the relation between the flow rate and the pressure is,

$$Q(H) = k_1 \cdot \sqrt{H} + k_2 \;\Leftrightarrow\; H(Q) = c_1 \cdot Q^2 + c_2$$

Since the $H(Q)$ has its maximum at $Q = 0$ the first order coefficient in the $H(Q)$ effort is zero. The constants c_1 and c_2 are established in Matlab in a least-square sense and the expression is then converted back to $Q(H)$ since Q is the wanted quantity.

This expression is then scaled with the assumption that the pump characteristics are linear in speed. Thus a linear expression of H in n is pursued. In Figure 4.9 a we see that the limits of the pump characteristics are lines in the pressure-speed plane. These limits intersect in a point $p_0 = (n_0, H_0)$. In Figure 4.9 b p_0 is used to convert an arbitrary point $p = (n, H)$ to a point $p^* = (p^*, H^*)$ on the line $n = n^* = n_{\max}$.

$$H^* = \frac{H - H_0}{n - n_0} \cdot (n^* - n) + H$$

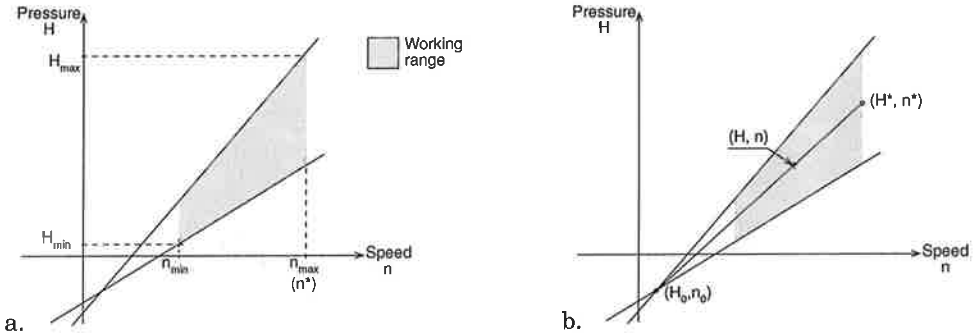


Figure 4.9 The continuous pump characteristics projected in the pressure-speed plane.

$H*$ is then used in the expression,

$$Q^* = Q(H^*) = k_1 \cdot \sqrt{H^*} + k_2$$

Q^* represents a flow rate at $n = n_{\max}$ and is therefore too large.

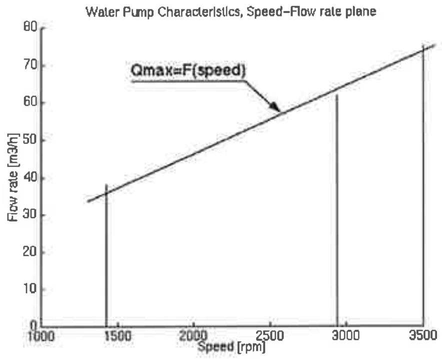


Figure 4.10 The continuous pump characteristics projected in the flow rate-speed plane.

Hence it must be scaled to represent the flow rate at the speed n. As seen in Figure 4.10 $Q_{\max}$ is linear in n The expression is,

$$Q_{\max}(n) = a_1 n + a_2$$

The final expression of the centrifugal pump flow rate at any speed or pressure is thus as follows and is shown in Figure 4.11 plotted for the water pump.

$$Q(H,n) = \frac{Q_{\max}(n)}{Q_{\max}(n^*)} \cdot \left(k_1 \sqrt{H^*(H,n)} + k_2 \right)$$

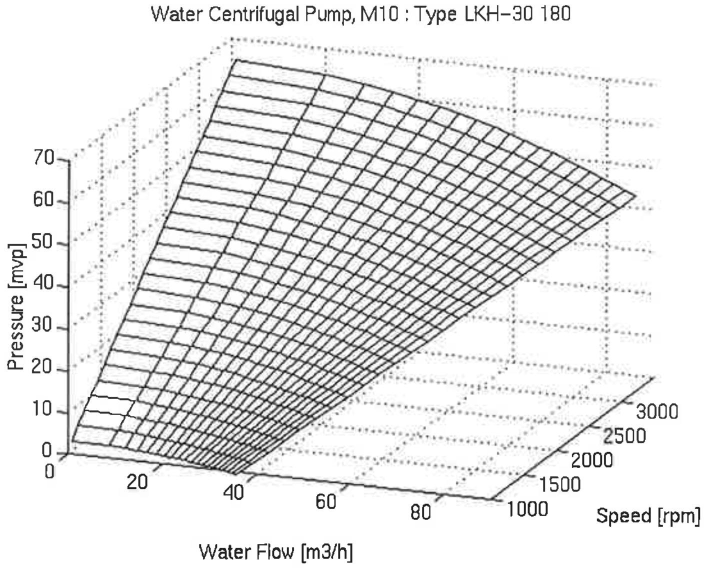


Figure 4.11 The centrifugal pump characteristic surface.

4.2.2 The pressure chart

The pressure chart was provided by Tetra Pak. It is a prediction of what the pressures in different places of the Alblend will be, based on component data. Even if this chart is not made from actual pressure measurements made on the Alblend it is necessary to adjust the loss factors of the affected components. The pressures in the chart are given in bar (= 10^5 Pa).

Total flow rate	p_3	Extra equip. Δp	p_2	Static Mixer Δp	p_1	BxT Δp	CPM p, Δp	Buffer tank, p_0
20 000 l/h	6,8	3,0	3,1	1,0	2,1	0,3	1,8	0
15 000 l/h	3,55	1,25	2,3	0,4	1,9	0,1	1,8	0
10 000 l/h	2,7	0,6	2,1	0,2	1,9	0,1	1,8	0
5 000 l/h	2,25	0,25	2,0	0,1	1,9	0,1	1,8	0

The pressure drop over these components can be described as a loss factor.

$$z_{loss} = \frac{A^2 \Delta p}{Q^2 \rho};$$

where

A = Area of cross section
Δp = Pressure drop
Q = Flow rate
ρ = Medium density

For most of the components the loss factor, z_{loss}, could easily be expressed.

$$z_{loss} = b_1Q^2 + b_2Q + b_3$$

By altering the constants in this expression it was possible to achieve the pressure drops over each component to make the model pressures match the pressure chart.

4.2.3 The FlowSupervisor

The FlowSupervisor is the submodel of the Concentrate unit that controls the total flow rate of the two separate mono pumps. They cover different flow ranges.

Pump M20A: 40–470 l/h
Pump M20B: 370–3200 l/h

The control signals to both of the pumps are discrete. For the large pump this means that the resolution is too low. The steps in flow rate will be too large. Therefore the small pump is continuously controlled by a PID-controller. However, when the small pump reaches one of its limits, the large pump is shifted either up or down. When the large pump is shifted up or down the small pump is subsequently adjusted to maintain a smooth total flow. This process proved to be a bit difficult to control. One step of the large pump is equal to 80 l/h which is well within the flow range of the small pump. This means that there are many possible combinations of the pumps to achieve a specific flow rate. Therefore the discontinuities caused a very bumpy and unpredictable flow.

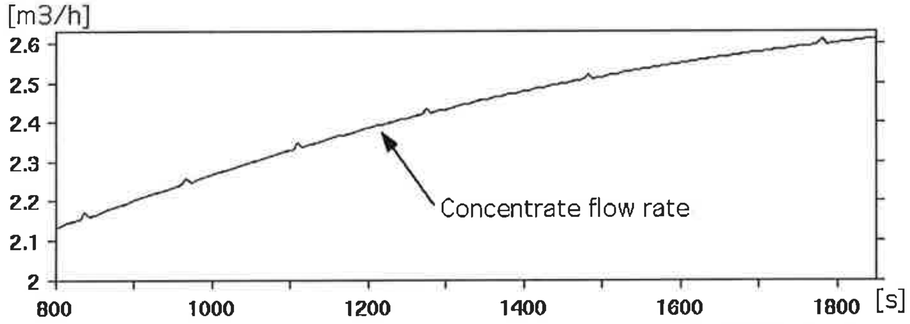


Figure 4.12 The discontinuities in concentrate flow rate as a result of shifts in the FlowSupervisor.

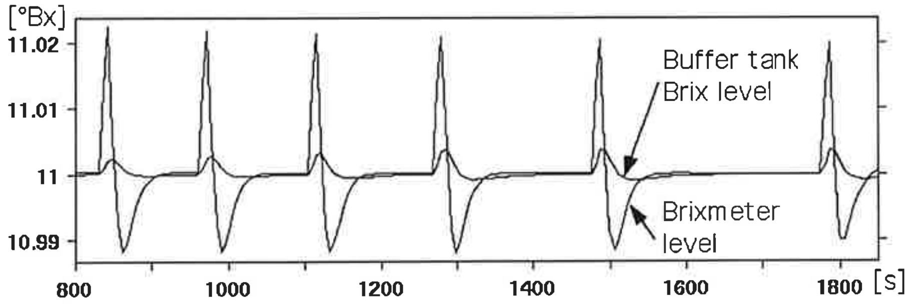


Figure 4.13 Disturbances in the Brix level as a consequence of the discontinuities in Figure 4.12.

The unit still does not respond very well to step changes of the flow rate setpoint, but works well with a ramped setpoint which is how the Tetra Alblend works in reality. This discontinuous behaviour is shown in Figure 4.12 and 4.13 during a step change of total production. As a result of the discontinuities in concentrate flow rate, the Brix level is affected. The changes are acceptably small and occur almost simultaneously with the flow rate bumps.

It is interesting to note that the concentrate unit runs smoother during a ramp up than a ramp down in flow rate. This is in fact the way it works in reality too. No efforts have been made to establish why this phenomenon appears.

4.2.4 Estimated dynamics

The computer simulations needs also to be adjusted in the aspect of time dynamics. In some of the processes, such as the pump processes and the Brix controlling process, the time constants and the steady state gain has been supplied by measurements made by Tetra Pak. In these cases the dynamic data have just been included in the model. For some processes it has been necessary to make experienced guesses with assistance from Tetra Pak.

Another aspect of time in the Alblend is the constant volume contained in the machine. A total amount of 40 l has therefore been included in the models divided between the different components. This volume causes a delay in concentration along the product flow of the machine.

4.3 Degree of implementation

A model can never describe the reality exactly. Therefore it is necessary to define a degree to which the implementation is brought. In this project it has been difficult to establish which features to implement and which to neglect before observing the actual performance of the models. This section describes some of those features.

4.3.1 Distortion

The two major predictable disturbances on the Alblend system are step changes in total production rate and in the concentrate Brix level. Depending on whether the production line runs with one or two pasteurisers the production could change from a very small flow rate to a large one in a very short time. Also the small changes in the concentrate Brix can affect the quality of the final product. The influences of these step changes are possible to observe in the simulations.

In reality there is of course always some kind of distortion involved in every process. The most significant distortion in the Alblend is caused by the diffusion of juice concentrate in water. It takes more time for the concentrate to mix with the water, than it takes for the product to travel from the mixing point to the Brix transmitter. By the time the product leaves the buffer tank, these variations have levelled out. This type of distortion could be modelled as concentration variations at the mixing point and is one way of making the models more realistic, but is left out of the models at present. It is questionable, however, if they influence the Brix accuracy of the final product.

Other types of distortions are variations of the Brix level in the products that is brought to the reclaim tank from other modules in the production line. This reclaim product enters the tank through the w_{in} terminal in Figure 4.1. This kind of disturbance has not been implemented in the model since there is no good prediction of its behaviour.

4.3.2 Circulation

To be able to maintain a stable production even though another machine in the production line stops, the Tetra Alblend is equipped with recirculation routines. The fluids are then recirculated within the units through the balance tank of each unit. This allows the pumps to run as usual during the production stop and makes the restart of the production smoother. When the Alblend goes into recirculation, the control signals to all the pumps are frozen. In the model the recirculation routine is implemented by sending the product to a waste terminal instead of sending it to the buffer tank. This is no problem since cyber juice nowadays is virtually free.

4.4 Performance

There are mainly two different kinds of simulations. The continuous production and the start-up procedure. The circumstances for these cases need some further explanation.

4.4.1 Continuous production

One of the simulations starts directly in the state of continuous production. The important states are set as follows:

Total flow rate : 12 000 l/h
Concentrate Brix : 65.0 °Bx
Product Brix : 11.0 °Bx
Buffer tank level : 0.5 m
Reclaim flow rate : 100 l/h

From this state it is possible to make step changes in all of these variables. The most realistic changes are changes in total flow rate and concentrate Brix.

4.4.2 Start-up procedure

When simulating the start-up procedure the buffer tank is initially empty. The juice output at terminal $w_{out}=0$ and the total flow rate is held constant. This causes the buffer tank level to rise until it reaches production level, which is when the tank is half full. The important states for the start-up procedure are set as follows:

Total flow rate : 7 000 l/h
Concentrate Brix : 65.0 °Bx
Product Brix : 11.0 °Bx
Buffer tank level : 0 m
Reclaim flow rate : 100 l/h

The start-up procedure not only fulfills the purpose of filling the buffer tank. It also allows the Brix control to stabilise. During the filling of the buffer tank the water pump is controlled by the flow controller included in the water unit. Meanwhile the level controller tracks the flow controller in order to achieve a bumpless change-over to level control. The change-over takes place when the buffer tank is half full.

4.4.3 Reclaim circulation

If the product, after being measured in the Brix transmitter, is found to be out of range (±0.3 °Bx), the first two-way valve redirects the product flow to the reclaim unit buffer tank. This is done not to affect the Brix level in the buffer tank beyond control and that is why it is implemented in the models as well.

4.5 Omola qualities

Omola is a very good tool for modelling systems with both continuous- and discrete-time processes. This fact reduces the need for simplifications when creating a simulation model. The model will then, of course, include a larger number of variables, but since derivatives does not have to be expressed explicitly, implementation of a large system is easy to make.

The initializer helps to solve the equation system when starting a simulation and every time a discrete event, that implies discontinuities, occurs in the simulation. It is, however, sometimes necessary to supply the simulator with initial values for some of the variables, in order to help the initializer to converge.

In a tutorial sense the Omola and OmSim documentation could have had more to offer. Since the software is developed continuously it is difficult to know when a problem occurs due to a software bug or a modelling mistake. A more extensive tutorial manual would help to avoid these problems. Considering Omola and OmSim not being commercial software, the demands for support and documentation is of course an issue of less priority.

5. Verifying the models

5.1 Significant variables

When verifying the Omola models with the real Alblend machine it is important to consider which variables are the most significant. In the Tetra Alblend the most important variables are also very easy to observe. In this test the water and concentrate flow rates, the buffer tank level and the Brix levels are observed.

5.2 Comparing tests with simulations

During Tetra Pak´s tests of the real Alblend plant, a lot of time has been spent on tuning and modifications. It has therefore been difficult to obtain results from proper tests suited for comparison with a theoretic model. The results from one test have provided sufficient datasets for identification of the processes. This will, however, not be enough to also validate the model.

5.2.1 Control algorithms

The data from the test made it possible to check the control algorithms in the model. The controller of the model was given the measuring signal from the test and the simulated control signal was then compared with the control signal from the test. Figure 5.1 shows how the control signals differ when using the same control parameters, K=0.4; T_i=400 s. The controllers used in the simulation have therefore been adjusted to match the ones used in the machine. The new parameters are K=0.2; T_i=260 s.

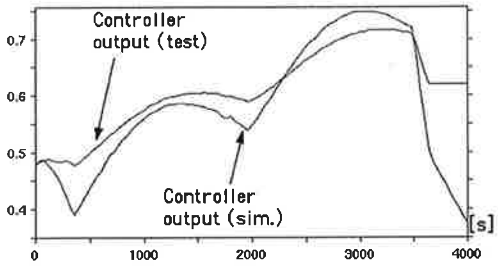


Figure 5.1 Simulated controller with given parameters, K=0.4 and T_i=400 s.

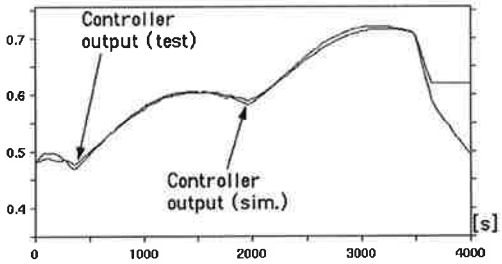


Figure 5.2 Simulated controller with identified parameters, K=0.2 and T_i=260 s.

Solving the problem this way, of course, excludes the possibility to draw any conclusions about improved controller parameters. To retain this possibility it is necessary to fully analyse the differences in algorithms for the PI- and PID-controllers. Lack of time has prevented me from doing so in this project.

5.2.2 The full production test

The perfect test, from a simulation point of view, includes step changes of total flow rate without unknown interferences. Between the step changes the machine should also be allowed to stabilize. This kind of test, however, takes too much time. The maximum time for a test is limited by the test compartments which holds the volume of about 1 hours test. Therefore the tests obtained always include the start-up procedure, which consequently has made it necessary to implement the model to run both in start-up mode as well as in continuous production mode.

This test is performed with orange concentrate of 65 °Bx and the blended product is 11 °Bx juice. It includes a start-up procedure, a step-change in total flow rate and finally, a production stop. The test sequence follows below.

Step	**Time**	**Flow rate**	**Control**
1. Start-up procedure	0 seconds	7 000 l/h	Flow rate control
2. Production 1	380 seconds	10 100 l/h	Level control
3. Production 2	1952 seconds	13 500 l/h	Level control
4. Production stop	3684 seconds	0 l/h	Frozen control signals

As seen in Figure 5.3 the simulation of the Omola model is very similar to the test on the real Alblend machine. The peaks in the buffer tank level plot are the result of the man made step changes of product flow rate and are therefore matched to occur simultaneously. It is, however, noticeable that the flow rates differ somewhat (Figure 5.4). This implies that there could be unknown dynamic properties in the water unit or in the water pump that have not been implemented.

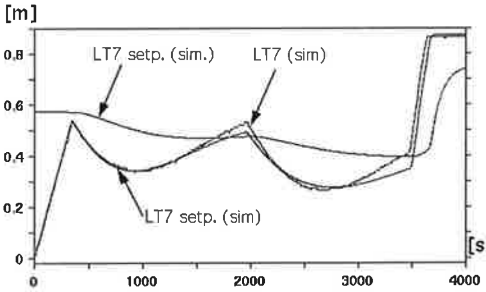


Figure 5.3 The buffer tank level.

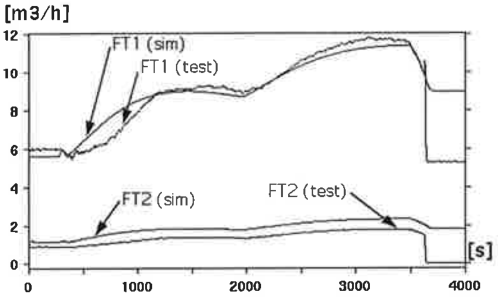


Figure 5.4 The water and concentrate flow rates.

The differences in Brix level are more significant, especially in the Brixmeter as shown in Figures 5.5 and 5.6. This implies that there are disturbances of some kind in the machine, not included in the model. The phenomenon could be related to irregularities in the blended product, as mentioned in section 4.3.1. The simulated Brix level in the buffer tank, which is more relevant, resembles the reality more. This depends, of course, on the large volume of the buffer tank, but also on the time that concentrate has been allowed to diffuse in water.

Since the simulated Brix levels are much smoother than in the test, it is difficult to draw any conclusions about the Brix accuracy of the machine. To be able to make any form of comparison of the Brix level results in the simulation and the real test, the plotted graphs are stored and later analysed in Matlab.

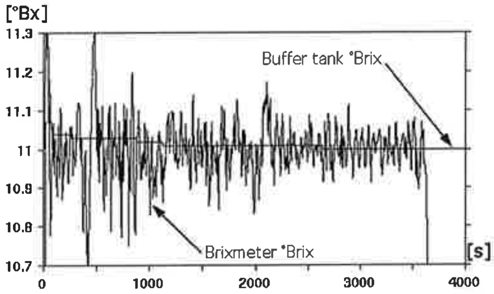


Figure 5.5 The Brix levels in the Tetra Pak test.

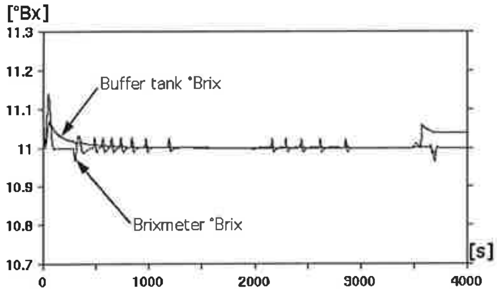


Figure 5.6 The simulated Brix levels.

The simulated tuning valve stroke lacks distortion for the same reasons as the Brix level. It does, however, have about the same mean stroke as in the Tetra Pak test, as seen in Figure 5.7 and 5.8.

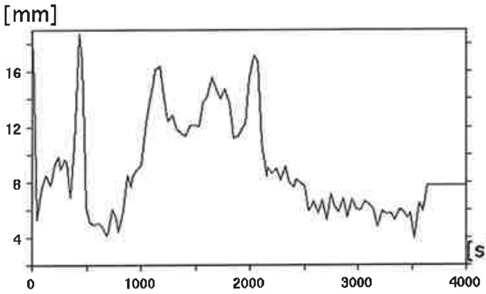


Figure 5.7 The tuning valve stroke in the test.

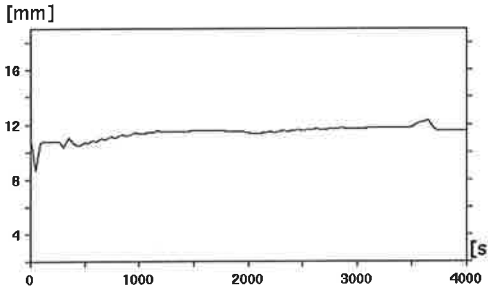


Figure 5.8 The simulated tuning valve stroke.

5.3 Validation

The test results provided by Tetra Pak represent a test of the Tetra Alblend that is to be considered as very significant for its normal operational conditions. There is, however, only this one test available for validation. A proper validation procedure would require two or more sets of data from tests carried out on the machine. However, since the simulation resembles the test very well the Omola model of the Tetra Alblend must be considered to be a rather good representation of the real machine concerning the important features such as flow rates, tank levels and Brix level.

6. Experiments on the models

The validated Omola model is a very good tool for observing the Tetra Alblend during a number of different production cases. This chapter presents some representative experiments made on the model.

6.1 Responses to steps in production rate

A sudden change of total flow rate in the Tetra Alblend blending module is a very common production disturbance. The flow rate in the Alblend is a consequence of how the rest of the production line performs. If, for instance, production in a second line is started, the total flow rate could be more than doubled in a very short time. This is why it is interesting to see how the Tetra Alblend responds to this kind of disturbance.

The test is done during continuous production mode and the total flow rate is controlled by the level controller, LC7, in the buffer tank unit. Before the step change all states are stationary .

State	**Before change**	**After change**
Total flow rate	: 12 000 l/h	15 000 l/h
Concentrate Brix	: 65.0 °Bx	65.0 °Bx
Product Brix	: 11.0 °Bx	11.0 °Bx
Buffer tank level	: 0.44 m	0.37 m
Reclaim flow rate	: 100 l/h	100 l/h

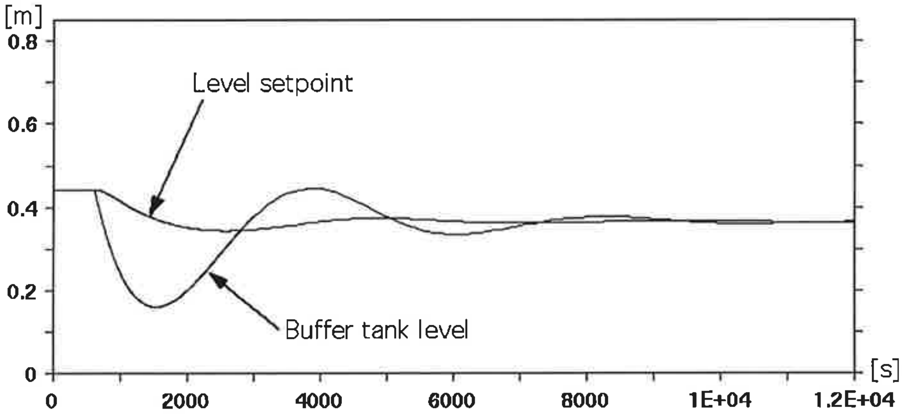


Figure 6.1 The simulated buffer tank level response of a step change in production rate.

The flow rate increases from 12 000 l/h to 15 000 l/h 600 seconds after the simulation is started. As seen in Figure 6.1 it takes a rather long time before the buffer tank level has assumed its new setpoint. The minimum level in the buffer tank is also dangerously low and it will be difficult to do a larger step in production rate, for instance from 12 000 l/h to 18 000 l/h, without the buffer tank running dry.

Notice that the setpoint also varies in time. This is due to the "circle relation" in the generation of the level setpoint. As described in Section 4.2.5, the level setpoint is based on the flow rate out of the buffer tank. Since there is no flow transmitter to measure this flow rate, the flow rate into the buffer is filtered to estimate the output flow rate.

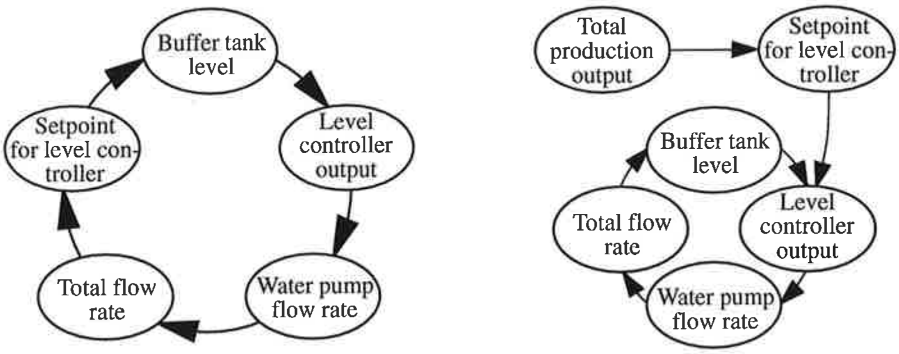


Figure 6.2 Two ways to implement the buffer tank level process with setpoint generation.

Thus, the level controller, controls the flow rate into the buffer tank which in its turn affects the setpoint for the controller. This implementation might not seem to be very robust but since the tank process is much slower than the controller process, the closed loop remains stable. The implementation where the level process and the setpoint process are separated, furthermore, needs an extra flow transmitter to work.

The water and concentrate flow rates behave rather properly during the production step change. As seen in Figure 6.3, the flow rates stabilise just as slow as the buffer tank level, but the amplitude of the oscillations are not at all as critical.

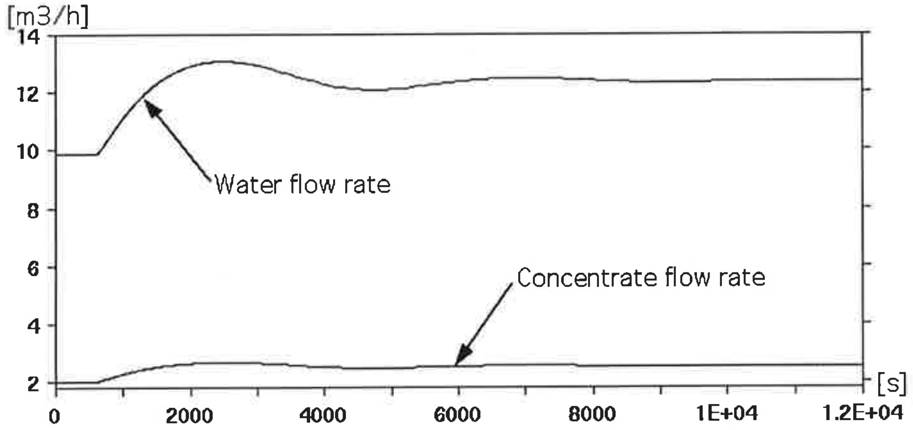


Figure 6.3 The simulated water and concentrate flow rate response of a step change in production rate.

The most important property to observe during the production step change is of course the Brix level which is, as shown in Figure 6.4, well within the accuracy limits.

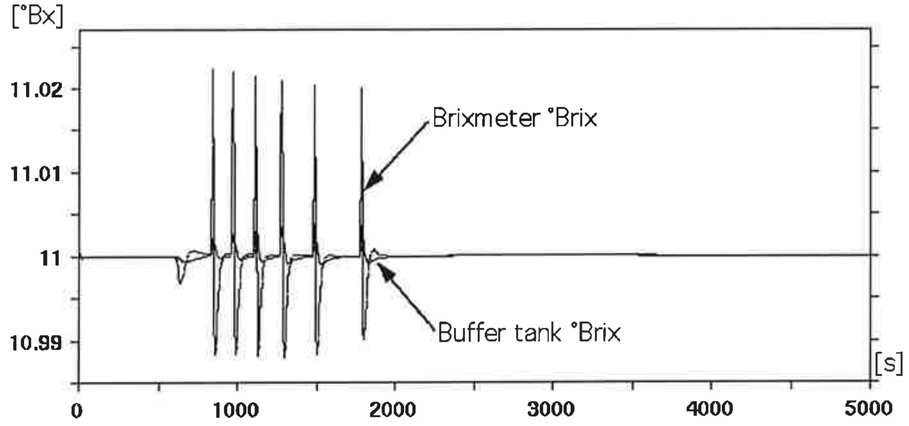


Figure 6.4 The simulated Brix level response of a step change in production rate.

6.2 Responses to steps in concentrate Brix

During production a sudden change of Brix in the concentrate could occur. The reasons for this phenomenon are many and therefore not further expounded. The disturbances appear, however, most likely as step changes of rather long duration. It is thus relevant to observe the Tetra Alblend during such a disturbance in concentrate Brix. As in the experiment in Section 6.1, this simulation is done during continuous production. The states before and after the disturbance is presented below.

State	**Before change**	**After change**
Total flow rate	: 12 000 l/h	12 000 l/h
Concentrate Brix	: 65.0 °Bx	63.0 °Bx
Product Brix	: 11.0 °Bx	11.0 °Bx
Buffer tank level	: 0.44 m	0.44 m
Reclaim flow rate	: 100 l/h	100 l/h

The buffer tank level is not primarily affected by a change in concentrate Brix and, as shown in Figure 6.5, the flow rates adjust very quickly to the new circumstances. The plot of the buffer tank level is therefore excluded.

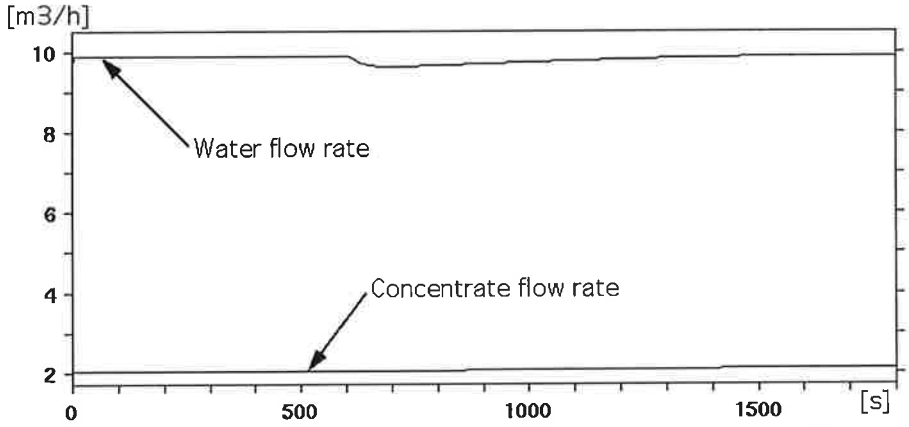


Figure 6.5 The simulated flow rate response of a step change in concentrate Brix.

Since the concentrate suddenly has a lower Brix level, relatively more concentrate must be added to the water to maintain the wanted product. This must be done without changing the recipe. As seen in Figure 6.5, the water flow rate decreases at first due to a decresing tuning water flow. The water flow rate then slowly increases again to maintain a constant total flow rate and buffer tank level.

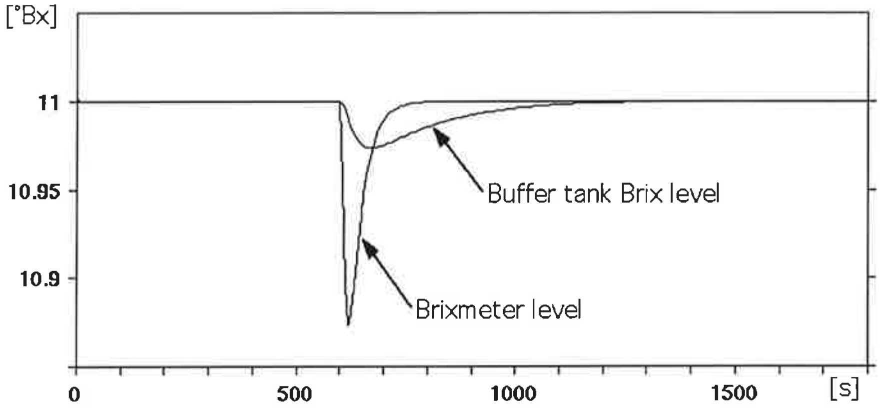


Figure 6.6 The simulated Brix level response of a step change in concentrate Brix.

The Brix levels are, of course, affected but does not exceed the accuracy limits (±0.3 °Bx in the Brixmeter and ±0.1 °Bx in the buffer tank) and return to the set-point in about 150 seconds in the Brixmeter and in about 500 seconds in the buffer tank.

6.3 Improving the buffer tank level control

Since the control algorithms in the model differ from the ones in the Tetra Alblend, it is impossible to establish improved parameters for the buffer tank level control. It is, however, possible to establish the fact that it is possible to improve the level control.

The speed, ω, of the closed loop system, including the tank process controlled by a PI-controller, is related to the control parameters as,

$$\omega \sim \sqrt{\frac{K}{T_i}}$$

and the damping ability of the system, ς, is related as,

$$\varsigma \sim \sqrt{K \cdot T_i}$$

Increasing K and T_i the same relative amount, results in maintained speed and improved damping of the buffer tank level process. As seen in Figure 6.7-6.9 the improved parameters establish the fact that it is possible to achieve better level control without significantly more distortion in the Brix level.

Furthermore, it is possible to refine the filter, with which the flow rate out of the buffer tank is estimated. By choosing the filter time constant, T_f, the same as the integrating time of the PI-controller, one of the zeros in the level process transfer function is cancelled. This reduces the influence of the setpoint generation in the process and improves the control further. The parameters for the buffer tank level process in this experiment are set as follows:

$$K = 0.9$$
$$T_i = 900 \text{ seconds.}$$
$$T_f = 900 \text{ seconds.}$$

The experiment is carried out as in Section 6.1, i.e. as a step change of production rate. The step change occurs 600 seconds after the simulation is started and the states before and after are the same as in Section 6.1.

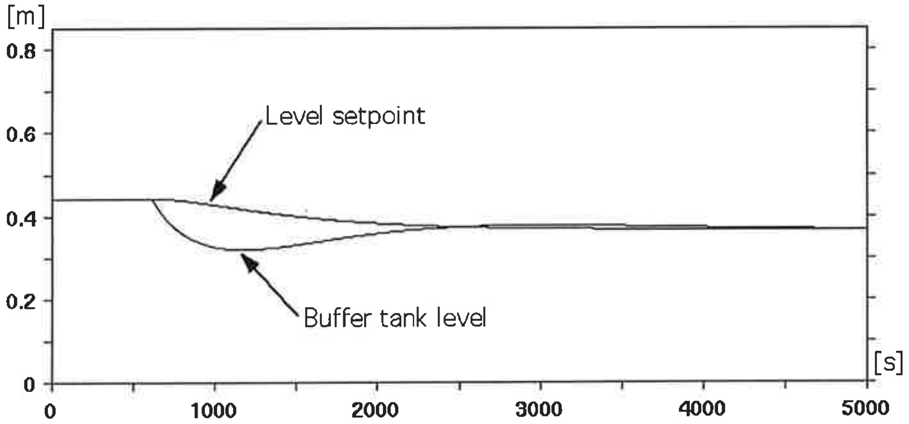


Figure 6.7 The buffer tank level during a step change in production rate, simulated with improved control parameters.

As seen in Figure 6.7 the buffer tank level clearly reaches its setpoint faster than in the simulation with the original control parameters. The process becomes approximately four times faster than before. The water and concentrate flow rates are, of course, improved to the same degree.

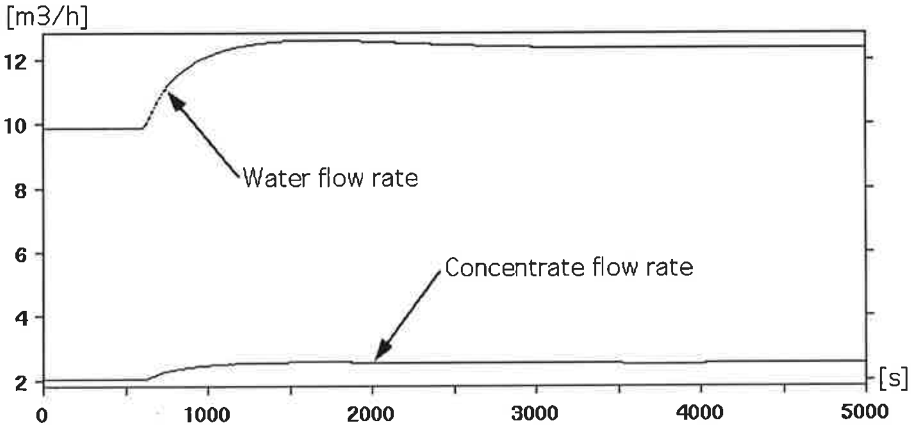


Figure 6.8 The flow rates during a step change in production rate, simulated with improved control parameters.

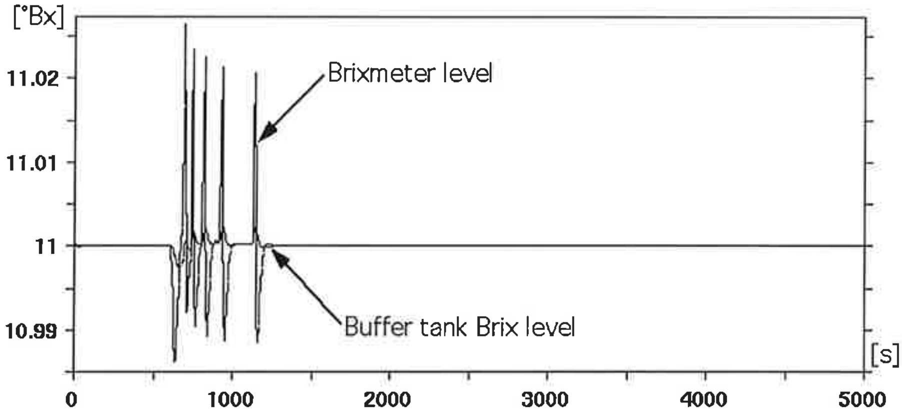


Figure 6.9 The Brix levels during a step change in production rate, simulated with improved control parameters.

Although the tank level process is four times faster, the Brix level process does not suffer any significant deterioration. The distortion due to the discontinuities in the Concentrate unit are virtually the same. This is because the Brix level process is approximately 100 times faster than the tank process.

7. Analysing the experiments

7.1 Conditions of accuracy

To be able to forecast the worst possible accuracy of the Tetra Alblend, it is necessary to know more about the disturbances that obviously are not implemented in the models. Furthermore, it is necessary to validate the models more carefully. Another set of data from a test, similar to the test analysed in Chapter 5, would be sufficient, but two or three tests are preferable.

Since the Brix level in the buffer tank is not measured but estimated mathematically in the Tetra Alblend, it is desirable to do laboratory tests to verify the estimation algorithm. After that it is relevant to verify the simulated Brix level in the buffer tank. An alternative to the present implementation of the Brix control, is to let the estimated Brix value in the buffer tank be the input to the Brix controller instead of the Brixmeter value. This would improve the possibilities to assure the right Brix level in the final product.

The conditions of accuracy in the Tetra Alblend is:

In the Brixmeter:	±0.3 °Bx
In the buffer tank:	±0.1 °Bx

A condition of accuracy must be defined as the standard deviation of blended product under specified circumstances. Therefore the permitted variations in input parameters, such as concentrate Brix and production capacity, must be defined. These permitted variations could also be defined backwards by using simulations.

7.2 Conditions of production capacity

The simulations can be used to evaluate the capacity limits of the Tetra Alblend. Static limitations, such as maximum production rate, are easy to calculate manually. It is more difficult to evaluate the dynamic limitations. The most interesting dynamic property to observe is the buffer capacity of the buffer tank. This depends of course on how good the level control is and how large the tank is.

As shown in Section 6.1, the buffer capacity is almost fully utilised at a reasonably small change in production rate. Section 6.3 shows, however, that it is possible to refine the level control and make it faster. This leaves the possibility to use a smaller buffer tank and thereby save space and money.

8. Suggestions to go further

8.1 Further modelling

The Omola model of the Tetra Alblend machine can always be improved. Some improvements will, however, not be relevant when looking at the basic performance of the Alblend. In an extension of this project some features seem more important to proceed with:

Random distortion always occurs at the mixing point, where the concentrate blends with the water. To implement this distortion it is necessary to establish a reasonable behaviour of such distortion. It is, however, uncertain if this distortion will affect the Brix level of the final product that leaves the buffer tank.

Quantazation of all the digital signals in the Alblend. Most of the digital signals in the Alblend have an 8-bit resolution and this could certainly affect the Brix control process in an unfavourable way.

Analysing the control algorithms is a critical point before being able to make further conclusions about the Tetra Alblend. To be able to suggest better parameters for the controller, for instance, this is a necessary condition.

8.2 Configuring the Alblend

The Alblend is designed to produce 6 000 – 18 000 l/h blended product of 10 – 15 °Bx. It is of course possible to replace certain parts of the machine, such as pumps and valves, to alter these features. With the OmSim simulations of the Alblend it is possible to easily evaluate a new configuration of pumps and valves. The results of these evaluations could then be presented in an Excel sheet. This was originally a request from Tetra Pak, but has, due to extensive modelling, not been pursued.

8.3 Analysing the production limits

The OmSim simulations could be used to analyse the flow rate and Brix limitations of the Alblend. If a customer's request includes features not within the standard Alblend specification, simulations could easily show which unit or component to modify. The handling of these problems would probably be easier in, for instance, an Excel sheet, but to obtain the static and dynamic estimations to design such a sheet, simulations are necessary.

An example

The standard Tetra Alblend is designed to produce 12 000–18 000 l/h juice of 10–15 °Bx. A customer might want to produce a juice concentrate of 35 °Bx at a capacity of 5 000–10 000 l/h instead of the standard ready-to-drink juice. This change in specification implies the need for a concentrate unit with higher capacity. Furthermore, the water unit as well as the buffer tank capacity can probably be reduced. The performance of the new Alblend configuration is easily implemented and tested in the OmSim environment.

8.4 Modelling other Tetra Pak modules

Since many models already are implemented in the Omola modelling language, it is reasonable to believe that only a small effort is needed to complete the model libraries to also cover the other processing modules of Tetra Pak Processing Systems. For instance, heat exchangers are already implemented and tested, and are ready to be adapted for the simulation of a pasteurisation module. Since Omola is object oriented it is convenient to prepare modelling of other Tetra Pak modules by creating models of the Tetra Pak standard components.

8.5 Converting Omola to Dymola

The Omola and OmSim simulation software is non-commercial and developed for Sun and HP workstations. There are, however, alternatives for PC-users to explore the possibilities of continuous and discrete time simulations. Dymola is a commercial software system developed for PC. Its structure is similar since the origin is the same. It is therefore easy to convert the Omola models to Dymola if Tetra Pak is interested in developing their competence in the dynamic simulation area.

8.6 Further evaluation of accuracy properties

The original goal to establish the °Brix accuracy of the Tetra Alblend has not been fulfilled in this project. To be able to do so it is necessary to identify more properties of its performance. Given the models, built in this project, it is possible to further analyse the °Brix accuracy concept. These simulations need, however, additional and more thorough test results from the Tetra Alblend. For instance it would be possible to analyse the buffer tank influence on the °Brix accuracy at different buffer tank levels.

9. Conclusions

9.1 Model validation

Due to modifications and tuning during the testing of the Tetra Alblend it has been difficult to obtain sufficient test data to validate the model. The Omola models have been matched to one set of data, but to properly validate the models, one or two additional datasets are needed. The first set of data was, however, very close to the theoretical model and this implies that the model is accurate.

9.2 Brix accuracy

The simulations show that Brix accuracy of the product that leaves the Tetra Alblend is well within the specified limits. It is, however, difficult to draw conclusions from this since the models are more accurate than the Tetra Alblend in reality. To establish possible differences it is necessary to compare laboratory tests of produced juice with the analysis of simulated juice.

9.3 Buffer tank level control

It is possible to achieve better control of the buffer tank level process. Exactly which control parameters to choose is uncertain. To be able to do that it is necessary to analyse the differences found in the controller algorithms of the model in relation to the Tetra Alblend. It is, however, certain that by increasing both K and T_i of the level PI-controller, LC7, the level control becomes faster and more stable. The generation of the buffer tank setpoint can also be modified to suit the level process better by setting the filter time constant in the output flow estimator, T_f, equal to T_i in the PI-controller.

9.4 Omola as a tool in beverage technology

Omola is a superior tool for simulating systems including both discrete-time as well as continuous-time processes. Its object oriented nature provides, furthermore, easy modelling and great flexibility. The fact that derivatives do not have to be expressed explicitly in the dynamic models also helps to make the modelling easier. To proceed creating models of other Tetra Pak modules and components, forming a Tetra Pak database of simulation models, is a very reasonable way to approach the future.

The OmSim simulation environment is very well designed to provide easy presentation of the experiments. The initial solver and the simulation routines, however, have a somewhat "black box" nature. Error messages are often sparse and the possibilities to trouble shoot a simulation error could be greater.

Omola is developed at the Department of Automatic Control at Lund Institute of Technology and is therefore not a commercial software. Hence the documentation and tutorial material is not very extensive. For a user without previous experience in modelling it takes quite some time to learn all the possibilities in Omola. The introduction to the Omola and OmSim software would be made easier with a more extensive tutorial's manual.

10. References

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