Efficiency Analysis of Packaging Lines

F.L. Härte

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CHAPTER 1   INTRODUCTION

This chapter briefly describes the packaging department of the Heineken Brewery in Zoeterwoude. The problem definition and research definition are discussed. Also the idea of efficiency analysis is explained and the outline of this report is given.

1.1   Heineken Zoeterwoude

The Heineken Brewery in Zoeterwoude has a yearly capacity of around 8 million hectolitres of beer. At the packaging department this beer is put into beer containers on 7 packaging lines, which package beer in bottles, cans (or kegs), put the bottles or cans in crates, trays or cartons, and then on pallets. A packaging line is a sequence of high-speed machines. Each machine performs a task of the packaging process. The machines are connected by conveyors which also serve as buffers.

   The efficiency of a packaging line is the percentage of the actual number of filled beer containers versus the possible number of filled beer containers, for a given period of time. The efficiency of most packaging lines is (too) low because of the occurrence of various machine failures. The average line efficiency is between 60% and 90%. The total production costs of beer consist mainly of packaging costs.

   The research project of this report concentrated on packaging line 2, which was installed in the spring of 1996 and is divided in two so-called streets, that can both produce 40.000 bottles per hour. On line 2 four different types of bottles are filled with several types of beer for the export markets. Production continues almost seven days per week and 24 hours per day. Each day consists of three shifts of 8 hours and every shift the line is run by a team of operators. It is a high-tech line with modern machinery, using information technology.

1.2   Problem definition

In order to design and improve packaging lines, it is necessary to have some means of predicting and explaining their performance and identifying the influence of the key line parameters (e.g. machine capacities, failure behaviour, conveyor speed, buffer capacities, etc.).

   Traditionally packaging line practice relied on extrapolation of past experience or on the use of simple rules of thumb. The recent developments in information technology within the packaging process enable the use of analysis methods to assess the efficiency of packaging lines. For the design of packaging lines these methods can help to avoid that the line fails to perform as originally expected, after it has been installed. For already installed packaging these methods can help to identify the sources of loss of productivity.

   The design of new packaging lines is likely to be based on (successful) existing packaging lines, therefore the efficiency analysis of installed lines does not only serve to improve the efficiency of existing lines but also the design of new lines.

   Improving the efficiency of packaging lines leads to lower packaging costs per unit by either increased output or lower personnel costs and/or lower equipment and material costs. It also improves the delivery reliability. Knowing the effect of the line parameters on the efficiency can help in making cost/benefit analysis of packaging lines. Finally, an awareness of the effect of the line parameters on the efficiency might influence the production practice.

1.3 Research definition

The research underlying this report concerns the efficiency analysis of packaging lines. The goals of this research were to increase the knowledge of and insight into packaging lines, to explain the efficiency of packaging lines, and to help improve the efficiency of packaging lines. This is achieved by creating a framework for efficiency analysis of packaging lines using mathematics and information technology. The analysis methods can be applied on both process data of existing lines as well as in simulation studies. Note that efficiency analysis can only detect the 'symptoms', the analysis results have to be interpreted to arrive at a 'diagnosis' and a possible 'cure' or corrective measures to improve the efficiency (figure 1).
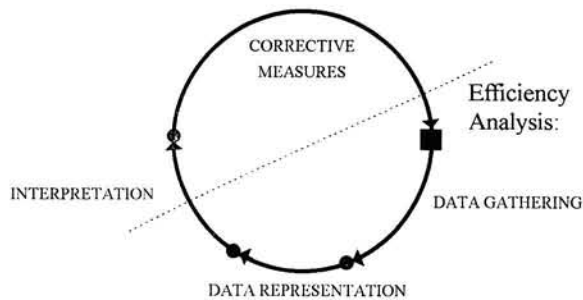
Figure 1: Efficiency analysis and improvement cycle

1.4 Efficiency analysis

Efficiency analysis of a packaging line (new or installed) is the activity of gathering the appropriate data, representing these data in a comprehensible manner, calculating the relevant performance indicators and interpreting these figures. The main goal is to understand or explain the (loss of) production. Often this will lead to corrective measures on the packaging line and feedback about the effectiveness of these measures.

The efficiency analysis of a packaging line should be a multi-disciplinary activity of the data analyst, the technical manager/mechanics or the designer, the quality manager, the production manager and operators, and the administrator of the packaging line.

The data analyst is responsible for the data gathering. The raw data is collected (in a database) manually and/or automatically from the line monitor system. The data analyst corrects these data for errors and noise, and filters out irrelevant data. For existing packaging lines the operators supply data either by writing events on a list or by pushing buttons on the line monitor system, the production manager provides the production schedules (including stops and change-over), and the administrator gives information about all costs. For new packaging lines data from comparable existing lines can be used or data can be generated by simulation; a sensitivity analysis of the efficiency analysis for these data can be performed.

The data analyst transforms the edited data into information by combining these data and then constructing comprehensible graphs and calculating performance indicators. It is his/her job to translate questions on the packaging line into the correct corresponding queries. This will normally lead to a number of standard reports created each time period (shift, week, etc.). These reports should ideally focus on different aspects and together give a complete view. The database should be flexible, meaning that ad hoc queries can easily be made.

The technical manager or designer, quality manager and production manager or operators interpret these (standard) reports (possibly helped by an interpretation of the data analyst) and, if necessary, ask for more information or take corrective measures. The administrator gives the interpretations a financial dimension, allowing cost-benefit analyses. On existing packaging lines the operators should also be informed on their working areas.

The interpretation is based on norm values (determined by the objective and history of the packaging line), historical comparison and comparison among packaging lines. The data should be analysed over different production shift teams, different time periods, different product types, and different packaging lines.

By creating standard and generally applicable methods, the efficiency analysis of packaging lines is made easier, more familiar and comparable. This report mainly focuses on the tasks of the data analyst. Other aspects like technical, quality, and human aspects are not taken into consideration here, but obviously play a important role in interpreting and improving the performance of packaging lines. The aim of this report is to create a framework for efficiency analysis of packaging lines using mathematical methods.

Throughout this report a general view is taken, i.e. all methods can be applied on an arbitrary packaging line. Most examples however apply to packaging line 2 of Heineken Zoeterwoude, although no real data is revealed in this report.

1.5 Report outline

This report presents a framework for the efficiency analysis of packaging lines. In chapter 2 the packaging process and the design principle of packaging lines are described. Then chapter 3 defines the efficiency of a packaging line, and lists the line parameters that influence the line efficiency. These line parameters are formed by the machine and buffer parameters. In chapter 4 the data acquisition process is discussed. Chapter 5 introduces various mathematical methods for efficiency analysis, consisting of graphs and performance indicators. For each method a description is given, the objective and use of the method are presented, the required data are defined, the calculations of the method are explained, and an example is given. Chapter 6 compares analytical and simulation models, and discusses the possibilities of using simulation to analyse the efficiency of packaging lines. Results are listed in chapter 7. Finally, in chapter 8 some conclusions and recommendations are presented. The appendices describe the line logic, basis registration and an example of a simple simulation model.

CHAPTER 2   PACKAGING LINES

In this chapter the packaging process and the equipment of a packaging line are described and the design principle of packaging lines is discussed.

A packaging line is defined as 'the aggregate of distinct machines working together in a sequence to fill beverage containers (bottles, cans, or kegs*), including the preceding and succeeding machines and equipment; usually from the input of packaged and mostly palletised empty goods until the output of packaged and palletised full goods' [10].

In other words: a packaging line is a series system of the stages of the packaging process. For each stage one or more (parallel) machines are used. These machines frequently have to deal with failures. The machines are put in a sequence and connected by conveyors, which can also serve as buffers.

There are many different types of packaging lines, all having their own design characteristics. Some lines are designed for short and flexible production runs (i.e. they can handle different product sizes and product packages), other lines are designed for mass production (i.e. they are dedicated to just one product). Some lines have many parallel machines and/or large buffers, other lines are strictly series and/or have small buffers. Also, designs have to meet space and capital constraints. However, most bottle and can filling lines have similar machinery for the different stages and follow a similar design rule for bringing the machinery together.

For a specific packaging line decisions are made regarding the individual machines, conveyors and other line equipment. The selected equipment is configured in the line layout and the controls are chosen. Each of these factors affects the overall design of the line, and thus the performance of the line. It is important to keep the objective and history of a packaging line in mind when the its performance is being analysed, because the inherent limitations of the line determine the maximum line efficiency.

2.1   Machinery

The packaging process starts with the input of empty bottles or cans†. Then these bottles or cans are washed or rinsed, filled with beer, closed, pasteurised, and labelled (bottles only). Finally the bottles or cans are put into their final packaging (boxes, six-packs, etc.) and gathered on pallets. At several points on the packaging line inspection machines are used. The function of the most important machines of bottle and can filling lines are described below.

2.1.1   Bottle filling line

Basically, there are two types of bottle filling lines: bottle filling lines for one-way bottles and bottle filling lines for returnable bottles. Some filling lines can handle both types of bottles and are called multi-purpose lines.

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* Keg filling line are not considered in this report, but can be approached in a similar way.
† The main flow of a packaging line is formed by the beer: unpackaged beer is the input and packaged beer is the output. In this view, the flow of empty bottles before the filler can be considered as coming from the 'glass street' (similar to the carton street at the packing machine).

One-way bottle filling line

For non-returnable or so-called one-way bottles, there are several packaging options: carton boxes with six-packs, or with an interior partition, trays, etc. One-way bottle filling lines produce mainly for export. Packaging line 2 is an example of a non-returnable-bottle filling line. Figure 2 shows the layout of line 2 and describes its most important machines.

First, pallets with new bottles are placed on the line. The protective foil is removed from the pallet by the defoil machine and the bottles are removed from the pallets by the depalletiser. The bottles are transported to the rinse machine by a bottle conveyor. There the bottles are rinsed with water, and go on to the filling machine. At the filling machine the bottles are filled with beer, closed with a crown and then moved to the pasteuriser. The pasteuriser pasteurises the full bottles to make the beer keep longer. Then the bottles are transported to the labelling machine, which applies the labels onto the bottles. Next the bottles are transported to the packing machine where they are put into the final packaging. The packing machine is supplied with the packaging material by the carton street. This is a series of machines that unfold and glue carton boxes, trays, interiors, six-packs and combine these into the final packaging. The full cartons/trays are transported by a case/tray conveyor to the palletiser, which gathers the case/trays on pallets. A protective foil is applied around the full pallets and finally the pallets are taken from the line and dispatched to the warehouse.

Returnable-bottle filling line

Usually returnable bottles are filled and packed in crates. Returnable bottle filling lines produce mainly for the domestic market.

First, pallets with crates of empty returned bottles are placed on the line. The crates are taken from the pallets by the depalletiser and the bottles are taken out of the crates by the decrate machine; the bottles are transported to the bottle washing machine by a bottle conveyor, and the crates are transported to crate washing machine by a crate conveyor. There the crates and bottles are washed. The bottles go on to the filling machine and the crates go to the crate store. At the filling machine the bottles are filled with beer, closed with a crown and then moved to the pasteuriser. The pasteuriser pasteurises the full bottles to make the beer keep longer. Then the bottles are transported to label machine, which applies the labels onto the bottles. Next the bottles are transported to the recrater, where they are put back into the crates from the crate store. The full crates are transported by a crate conveyor to the palletiser, which gathers the crates on pallets. Finally the pallets are taken from the line and dispatched to the warehouse.

2.1.2 Can filling line

For cans, there are also several packaging options: carton boxes, six-packs, trays, etc.

First, pallets with empty cans are placed on the line. The cans are removed from the pallets by the depalletiser and transported to the rinse machine by a can conveyor. There the cans are rinsed with water, the cans go on to the filling machine. At the filling machine the cans are filled with beer, closed with a lid and then moved to the pasteuriser. The pasteuriser pasteurises the full cans to make the beer keep longer. Next the cans are coded by the laser code machine, inspected and transported to the packing machine, where they are put into the final packaging. The cans are often collated using some shrink-wrap material. The full cartons/trays are transported by a case/tray conveyor to the palletiser, which gathers the cases/trays on pallets. A protective foil is applied around the full pallets and finally the pallets are taken from the line and dispatched to the warehouse.

Bulk glass defoil machine
Pallets with empty new bottles are supplied from the warehouse. The defoil machine removes the foil that protects these pallets. The pallets are transported to the depalletiser.

Bulk glass depalletiser
The depalletiser removes the empty bottles from the pallets layer by layer onto a conveyor to the rinse machine.

Rinse machine
The rinse machine (or rinser) rinses the bottles with water or air before filling.

Filling machine
The filling machine (or filler) puts the beer into the empty bottles and closes the bottle with a crown. The bottles are transported to the tunnel pasteuriser. Before filling the bottles are inspected for being empty; after the fill process the bottles are inspected for being filled correctly. Bottles that do not pass these inspections are removed from the line.

Pasteuriser
In the tunnel pasteuriser the bottles are pasteurised for 45-60 minutes to make the beer keep longer (product stability). The bottles are transported to the labelling machine.

Labelling machine
The labelling machine (or labeller) applies labels on filled bottles: front label, back label, neck label and/or wraparound. Again the bottles are inspected and, if necessary, removed from the line. The bottles are transported to the packing machine.

Packing machine
The packing machine puts the filled bottles in the final packaging. The packaging is supplied by a so-called *carton street*, a series of machine that erect boxes, unfold six-packs and interiors etc. The full cartons/trays are closed, weighted for inspection, coded and then transported to the palletiser.

Palletiser
The palletiser puts the carton/trays with full bottles on the pallets. The pallets are transported to the shrink-foil installation.

Shrink-foil installation
The shrink-foil installation shrinks a protective foil around the full pallets. The pallets are then dispatched to the warehouse.

Bottle conveyors
Bottle conveyors transport the bottles from one machine to the other and consists of segments of chains. Most conveyor also serve as buffers, because of some extra chains.

Case conveyors
Case conveyors transport cartons or trays from one machine to the other. The buffer function of these conveyors is created by the distance between the cases.

Figure 2A: Machine description of packaging line 2
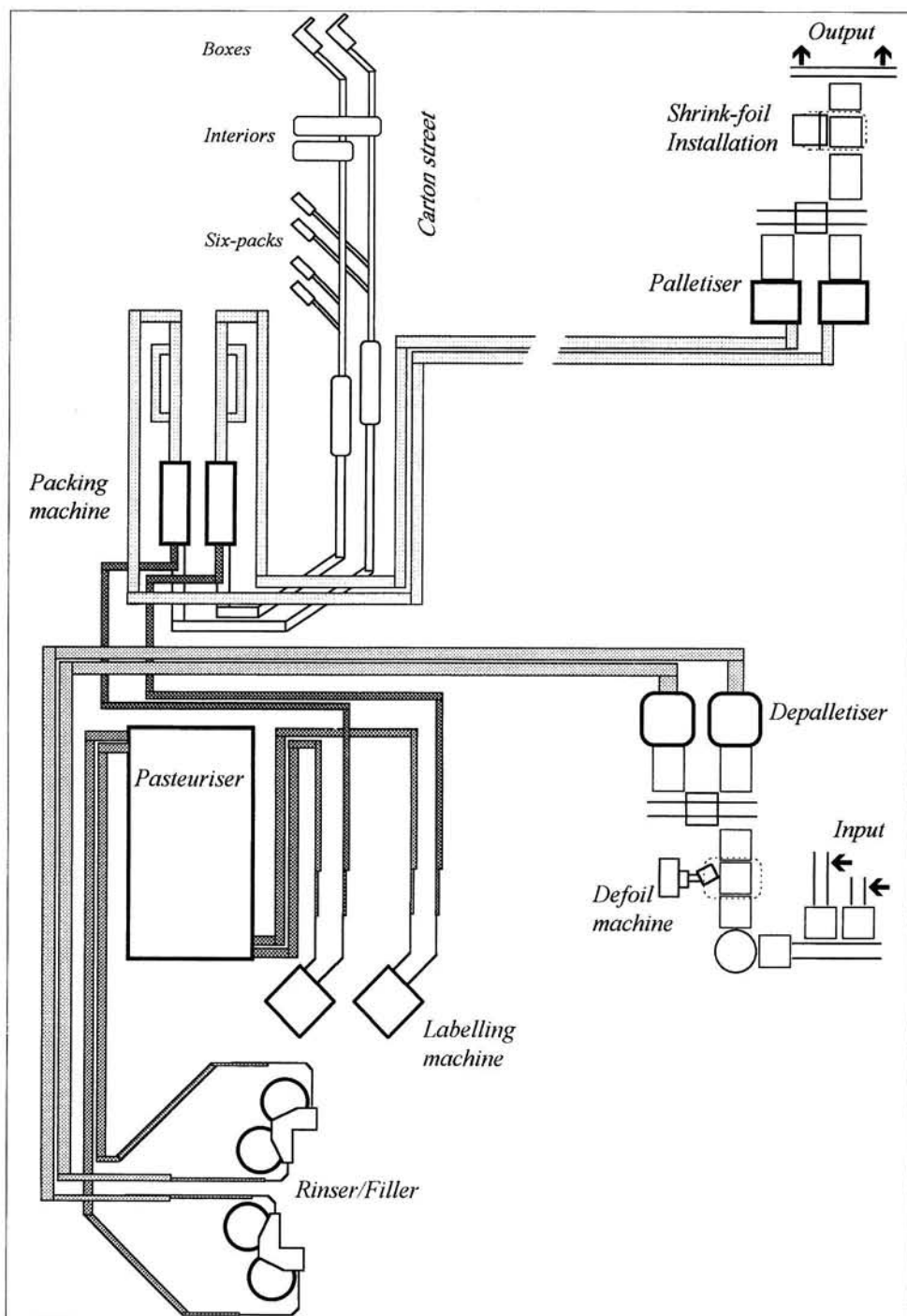
Figure 2B: Layout of packaging line 2

2.2   Bringing the machinery together

Historically the filling machine has been the most important machine, because the filling machine is the most quality critical element of the line and because the filling machine performs the primary function of the packaging line, actually putting the product into the container.

Therefore, on most packaging lines the filling machine* is called the *core machine* and the rest of the line is designed around it [15]. Usually the line efficiency is based on the capacity of the filling machine and other equipment is sized to ensure, as far as possible, that the filler does not stop because of failures on the other equipment. This is done for both efficiency and quality reasons.

2.2.1   Design principle and buffer strategy

The design principle for packaging lines amounts to a *buffer strategy*, which makes sure that the buffers before the core machine are almost full and the buffers after the core machine are partly empty. This allows the core machine to continue in the case of a failure somewhere else on the line. In other words the core machine should have products at the infeed and space at the discharge.

Buffer strategy
This buffer strategy consists of two complementary elements. The first element is formed by the buffers which provide accumulation. Static accumulation is achieved by putting a real buffer between machines (e.g. an accumulation table or a crate store). Dynamic accumulation is accomplished by the conveyors between the machines.

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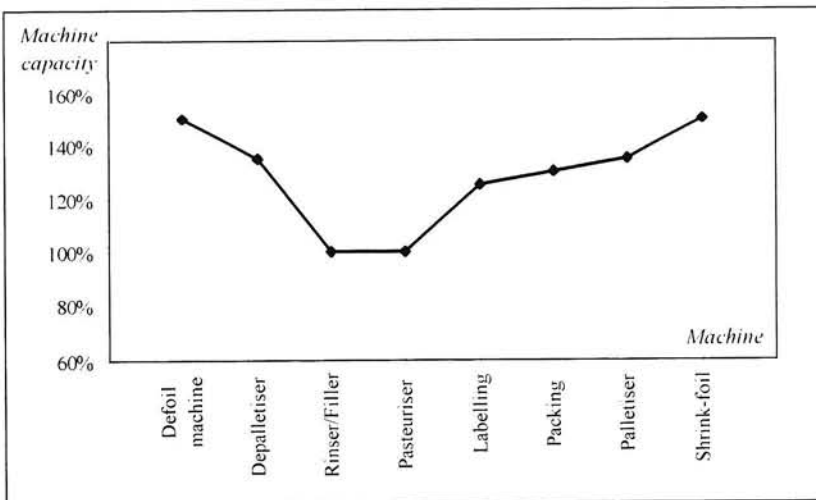
* Sometimes the pasteuriser is taken as the core machine. In the future one of the other machines may become dominant (for instance the packing machine because of the growing diversity of packaging options and promotional packaging). Or the V-shape may even become (more) flat, as the reliability of the machines improves, making buffers obsolete.

The second element is formed by production speeds of the machines. The machines on either side of the core machine have extra capacity or *overcapacity*. This overcapacity ensures that the core machine has products at the infeed and space at the discharge. This enables these machines to catch up after a failure has occurred. After a machine has had a failure and (a part of) the accumulation is used, then the overcapacity of the machine is used to restore the system back to the situation before the failure. The machine before and after the core machine have extra capacity with respect to the core machine. The machines upstream of the core machine each have extra capacity with respect to the next machine, and the machines downstream of the core machine each have extra capacity with respect to the previous machine. This results in the 'V'-shaped capacity graph for the line stages, with the filling machine at the lowest point. Figure 3 shows the machine capacity graph (or V-graph) of a typical non-returnable bottle filling line.

V-graph
The V-graph plays a central role in the buffer strategy of a packaging line. Essentially the V-graph of a packaging line is a graph of the machine (group) capacities in the sequence of the packaging line. In keeping with the packaging line design principle the machines on either side of the core machine have extra capacity. This results in the V-shape of the machine capacity graph with the core stage at the base point (which explains the name V-graph), as shown in see figure 3.

The speed of the machines and the conveyors is adapted on the basis of sensor signals, which indicate whether a conveyor segment (i.e. a buffer) is full or empty. Most machines have several speeds. Often parallel machines are used for a stage, where each machine has extra capacity, so if one of more of the parallel machines fail the other machine(s) can run at a higher speed to compensate for the failed machine(s).

CHAPTER 3   DEFINITIONS

In this chapter the efficiency of a packaging line is defined and the line parameters that influence the line efficiency are described. These line parameters are divided in machine parameters and buffer parameters.

3.1   Efficiency

The efficiency of a packaging line is the percentage of the actual production versus the possible production, for a given period of time. This is the number of filled bottles or cans versus the possible number of filled bottles or cans in a specified time period. It can also be defined as the percentage of the time that is theoretically needed to produce the actual output (=net production time) versus the actual production time. The time definitions for packaging lines are shown in figure 4.

Line Efficiency
The line efficiency η_{line} is a measure of the efficiency of the packaging line during the period specified, and is calculated as follows:

$$\eta_{line} = \frac{\text{net production time}}{\text{actual production time}} \times 100\%$$

$$= \frac{\text{net production time}}{\text{net production time} + \text{internal unplanned downtime}} \times 100\%$$

External unplanned downtime is excluded because this downtime is not caused by the operation of the packaging line itself; taking external unplanned downtime into account would result in an indicator for the efficiency of the organisation instead of just the packaging line[*]. Also external unplanned downtime is hard to measure

As the net production time is equal to the output in production units divided by the nominal line capacity, the Line Efficiency specified in production units is:

$$\eta_{line} = \frac{\text{output in production units}}{\text{actual production time} \times \text{nominal line capacity}} \times 100\%$$

where the actual production time[†] on the core machine (group) is taken as the actual production time and the nominal line capacity is the nominal capacity of the core machine (group).

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[*] In the Brewery Comparison System (BCS) [2] efficiency is defined as the percentage of the net production time versus the available production time. In this report, however the *line* efficiency is considered.
[†] The actual production time is usually the measured time (per production run) between the first bottle into the filler and the last bottle out of the filler minus time lost due to disturbances not under control by direct shift employees, e.g. electricity breakdown, no beer, etc.

TOTAL TIME			
GROSS AVIALABLE TIME			UNUSED TIME
AVAILABLE PRODUCTION TIME		PLANNED DOWNTIME	
NET PRODUCTION TIME	UNPLANNED DOWNTIME		
	internal | external		
ACTUAL PRODUCTION TIME			

Figure 4: Time definitions of a packaging line

Total time
The total time is the duration of the period specified.

Unused time
The unused time is the time that the packaging line has not been utilised for either actual production, planned or unplanned downtime during the period specified. This includes holidays, strikes, time not worked according to work schedule (e.g. Sundays), and no shifts planned according to production plan.

Gross available time
The gross time available (or manned time) is the total time minus the unused time, i.e. the total time that the line is with personnel.

Planned downtime
The planned downtime is the time used by the packaging line without producing, according to the standards used in the production plan. This includes start and finish time periods, cleaning, maintenance/overhaul, changeover time periods, test runs, and idle time (shift available, no work).

Available production time
The available production time is the manned time minus the planned downtime. This is the time which is intended for production.

Unplanned downtime
The unplanned downtime is the time that the packaging line has been occupied with unplanned stops during the period specified. The total unplanned downtime is divided in internal and external unplanned downtime.

Internal unplanned downtime
The internal unplanned downtime is the total unplanned downtime caused by the packaging line functioning in the time period specified. This includes time loss because the average speed is different to nominal speed, additional maintenance (extra to planned), registered and non-registered stops.

External unplanned downtime
The external unplanned downtime is the unplanned downtime not caused by the packaging line functioning in the time period specified. This includes time loss because there are no empties, no beer, no electricity, or no transport available, non-planned changeovers, planning mistakes.

Net production time
The net production time is the time that the packaging line has been occupied with production during the period specified calculated as actual output divided by the line capacity. This is also called the theoretical production time, because it is the time in which the actual output could have been produced given the line capacity.

If the filler is the core machine, then the filler determines the line efficiency except for a time difference between the time of production at the filler and the time of output at the end of the line (which includes the pasteurisation time of 45-60min) and the rejects and breakage after the filler (which is usually less than 1%). Therefore, in the efficiency analysis of packaging lines the focus is on the loss of production time of the filler (or core machine), which is almost equal to the difference between the actual production time and the net production time (i.e. the internal unplanned downtime). Note that loss of production on the core machine cannot be recovered, so the production time of the core machine determines the (maximum) output of the line.

Although the line efficiency is the main performance indicator for packaging lines, the *utilization* (defined as the net production time versus the total time), and the *effectivity* (defined as the available production time versus the manned time), are also important in analysing the performance of a packaging line. In other words whereas efficiency analysis focuses on the reduction of internal unplanned downtime, the reduction of unused time, planned downtime, and external unplanned downtime, can obviously also improve the line performance. In this report quality is not considered, nevertheless this is of course an important performance indicator. Finally, the output of a packaging line is a very important, simple and useful performance indicator.

3.2   Line parameters

A packaging line consists of the different stages of the packaging process, and for each stage one or more (parallel) machine are used. In other words a packaging line is a series system, with the machines or machine groups as components, and these machines are connected by conveyors/buffers. This is depicted in figure 5, in which the buffers upstream of the core machine are full and the buffers downstream are partly empty.

 The line efficiency is then determined by the line parameters, which are formed by the *machine parameters* and the *buffer parameters*[*].

	buffer		buffer		buffer		buffer	
machine		machine		core		machine		machine
				machine				
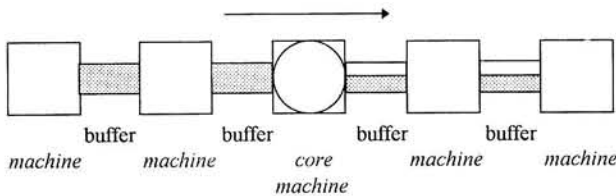
Figure 5: Packaging line as series system

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[*] The influence of other aspects (including some aspects that are hard to quantify, like the weather, the experience of the operator, the quality of the material etc.) is not considered separately but assumed to be incorporated in the failure behaviour of the machines (which therefore varies).

3.3 Machine parameters

The machine parameters are the machine states, the failure behaviour, the machine efficiency and the machine production rates.

3.3.1 Machine states

Each machine can be in one of six states[*]:

Running
A machine is running when it is producing, this can be different speeds and with different reject rates.

Planned down
A machine is planned down in the case the machine is stopped for planned maintenance, changeovers, not in use, etc.

Machine internal failure
A machine has an internal failure when the machine stop is caused by a machine inherent failure. There are often many different failures causes depending on the complexity of the machine.

Machine external failure
A machine has an external failure when the machine stop is caused by external factors, either caused by another part of the organisation (e.g. no supply of empties, no beer, no electricity, etc.)[†], or by the operator(s) of the line (e.g. lack of material such as labels, cartons, glue, etc.) and waiting time.

Starved
A machine is starved (or idle) when the machine stop is due to a lack of cans/bottles or cases. The machine has no input, i.e. the conveyor preceding the machine is empty, because of a reason upstream on the line. Note that some machines can be starved for more than one reasons, e.g. a packer can be starved for bottles and for boxes.

Blocked
A machine is blocked when the machine stop is due to a backup of cans/bottles or cases. The machine has no room for output, i.e. the conveyor succeeding the machine is full, because of a reason downstream on the line. Note that some machines can be blocked for more than one reason, e.g. a depalletiser can be blocked by pallets and by crates.

Hence, a machine is either running, or a machine is not running for one of five reasons. The state 'planned down' and part of the state 'machine external failure' are not included in the calculation. Therefore the loss of production time on the core machine (i.e. the internal unplanned downtime) consists of the total time the core machine has an internal failure or an external failure due to the operation of the packaging line, and the total time the core machine is starved or blocked. This means that efficiency loss can be caused in three ways: either stops (of lower speed) due to the core machine itself, or due to stops upstream of the core machine, or due to stops downstream of the core machine.

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[*] Sometimes it is hard to differentiate between machine internal failures and machine external failure (e.g. poor quality material), or between machine external failures and starvation/backup (e.g. material). The above definitions are based on the assumption that failures are due to the machine (i.e. machine internal failures), related to the machine (machine external failures) or due to other machines of the line (starved and blocked).
[†] This results in external unplanned downtime.

3.3.2 Machine failure behaviour

The internal failure behaviour of a machine is usually described by the means of two (unknown) probability distribution functions[*]: a distribution function for the internal failure or repair times and a distribution function for the running times[†]. The expectation of the failure or repair time distribution is called Mean Time To Repair (MTTR). The expectation of the running time is called Mean Time Between Failures (MTBF)[‡]. These are defined as follows for the period specified:

$$MTTR = \text{Mean Time To Repair} = \frac{\text{total time internal failures}}{\text{number of internal failures}}$$

$$MTBF = \text{Mean Time Between Failures} = \frac{\text{total running time}}{\text{number of internal failures}}$$

The total time of internal failures is simply the sum of the internal failures during the period specified, and the running time is the total time the machine is in the state 'running'.

3.3.3 Machine efficiency

The machine efficiency $\eta_{machine}$ is a measure for the availability of the machine. It is defined as the percentage of time that the machine is ready to operate, for the period specified:

$$\eta_{machine} = \frac{\text{total running time}}{\text{total running time} + \text{total time internal failures}} \times 100\%$$

The machine efficiency is the time the machine produced versus the time the machine could have produced. Obviously, the total planned downtime, external failure time, starved time and blocked time are not taken into account for measuring the machines availability. Also the machine speed is not considered. The machine efficiency is equal to:

$$\eta_{machine} = \frac{MTBF}{MTBF + MTTR} \times 100\%$$

The efficiency of a group of parallel machines is the sum of the machine efficiencies of the machines group, weighted with the proportion of the group capacity formed by the machine capacity.

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[*] Often these distribution functions are assumed to be exponential distribution functions.

[†] Alternatively the failure rate can be specified in terms of numbers per million, e.g. 200 stoppages per one million produced bottles or cans. This means that no matter how fast the machine is running the failure rate will be the same. This might be more in keeping with the quality specifications of the material which is also in units per million (or rather a percentage), and it might also explain why machines often show more failures at higher speeds (i.e. because of the constant failure rate the mean time between failures is shorter at higher speeds). On the other side, however, at higher speeds also the circumstances (e.g. temperature, trembling, etc.) are often different.

[‡] The MTBF is based on running time and not on clock time. Implicitly this assumes that a machine cannot fail while being forced down (e.g. starved of blocked).

3.3.4 Machine production rates

The production rates of a machine (group) are defined as follows:

Machine speed (V_{mach})
The machine speed is the number of products the machine produces per unit of time. Machines can have fixed, pre-selected, or continuously variable speeds. Usually machines have an overspeed, a low speed and one or more speeds around the nominal machine capacity. Machines can have different speeds for different product types.

Machine capacity (C_{mach})
The machine capacity is the maximum machine speed as set in the machine control. Machines can have different machine capacities for different product types[*].

Group capacity (C_{group})
The group capacity is the total maximum production speed of the parallel machines that form the group, as set in the control. This can be lower than the sum of the machine capacities.

Nominal machine capacity (C_{nom})
The nominal machine capacity is the speed of the machine for which the group to which the machine belongs runs at the same speed as the core machine (group); it is determined by the nominal line capacity divided by the number of machines of the group.

Machine overcapacity ($O_{mach}=C_{mach} - C_{nom}$)
The machine overcapacity is the difference between the machine capacity and the nominal machine capacity.

Group overcapacity ($O_{group}=C_{group}-C_{line}$)
The group overcapacity is the group capacity minus the nominal line capacity.

Core machine (group)
One of the machines (or groups) of a line will be the core machine (group) or critical machine (group). The core machine (group) is defined as the machine (group) on which all the line equipment and conveying system parameters are dimensioned. The capacity of the core machine (group) determines the maximum output of the line. Therefore the nominal line capacity is equal to the capacity of the core machine (group).

Nominal line capacity (C_{line})
The nominal line capacity is the smallest machine (group) capacity for the specific product, i.e. the capacity of the core machine (group) for the specific product. From this follows that a packaging line can have different line capacities.

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[*] The technical maximum machine speed can be higher than the (control) machine capacity, the difference is called the *unused capacity*.

3.4 Buffer parameters

The goal of the buffer strategy is to minimise the influence of the different machines on each other and especially on the core machine (most often the filler), by accumulating additional supply before the core machine and creating space after the core machine. In other words the buffers for bottles/cans and crates/cases/trays* between the machines provide accumulation.

There are two types of accumulation: dynamic accumulation and static accumulation. Dynamic accumulation is accomplished by the conveyors between the machines. Static accumulation is achieved by putting a real buffer between machines.

Buffers which are used to avoid starvation of the preceding machine, are called *anti-starve buffers* (these are found upstream of the core machine); buffers which are used to avoid backup of the succeeding machine, are called *anti-block buffers* (these are found downstream of the core machine).

Accumulation
Accumulation is referred to as the time a machine is allowed to stop without disturbing the operation of the machines around it. There are two types of accumulation: dynamic and static accumulation.

3.4.1 Dynamic accumulation

Dynamic accumulation is accomplished by the conveyors between the machines. For bottles and cans these conveyors consist of parallel chains, of which some chains are used for transport, and the other chains are used for accumulation. For cases, crates and trays these conveyors are usually one unit wide and the accumulation is achieved by the spacing of the units. The functioning of dynamic accumulation differs for anti-starve and anti-block buffers.

Anti-starve buffers
The purpose of anti-starve buffers is to prevent that the machine following the buffer becomes starved when the machine before the buffer has stopped. These buffers are therefore found upstream of the core machine. In figure 6 the functioning of this type of buffer is shown. Theoretically the ideal state is when the buffer is full. For bottle/can conveyor this means that both the buffer and transport chains are full; for case/crate/tray conveyors this means that there is no space between the units.

Anti-block buffers
The purpose of anti-block buffers is to prevent that the machine before the buffer becomes blocked when the machine after the buffer has stopped. These buffers are therefore found downstream of the core machine. In figure 7 the functioning of this type of buffer is shown. Theoretically the ideal state is when the buffer is empty. For bottle/can conveyor this means that the buffer chains are empty and the transport chains are full; for case/crate/tray conveyors this means that there is space between the units.

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* Pallet buffers (full or empty) are not considered here, but can be approached in a similar way

Anti-starve buffers

The purpose of anti-starve buffers is to prevent that the machine after the buffer becomes starved when the machine before the buffer has stopped. These buffers are therefore found upstream of the core machine. The ideal state is when the buffer is full, the machine after the buffer is constantly supplied with containers. When before the buffer a failure occurs, the machine after the buffer can continue to run and drains the accumulated containers from the buffer. This lasts for a certain period of time, the so-called accumulation time. At the end of this time period the machine that stopped, has to start running again, otherwise the machine after the buffer stops because it is starved. Because of the overcapacities the ideal state is recovered.

State 1:
The buffer is fully filled and working. The machines M1 and M2 are both running. This situation is called the ideal state.

State 2:
Machine M1 has a failure or is starved by a failure further upstream. The buffer content is decreased by M2 with speed Sb. A gap is created in the bottle or can flow, because M1 is no longer producing.

State 3:
The bottle/can flow reaches the 'critical point' P_{crit}, by the critical time $T_{crit}=L_{buffer}/Sc$. No later than this point M1 has to start running, such that with speed Sc the overtaking container flow can fill up the created space, before it reached the starve point P_{starve} of machine M2 (i.e. the sensor that signals the lack of bottles and stops machine M2).

State 4 and 5:
The overtaking flow approaches the end of the production flow, because of the speed difference. The production flow disappears with the machine production speed and the overtaking flow draws near with the speed of the conveyor.

State 6:
The overtaking flow reaches the production flow, before it has reached the starve point. M2 can continue running, without noticing the failure of machine M1.

State 7:
Because M2 runs at a lower speed than M1 (i.e. M1 has overcapacity with respect to M2), the buffer has filled up again. The ideal state is recovered.
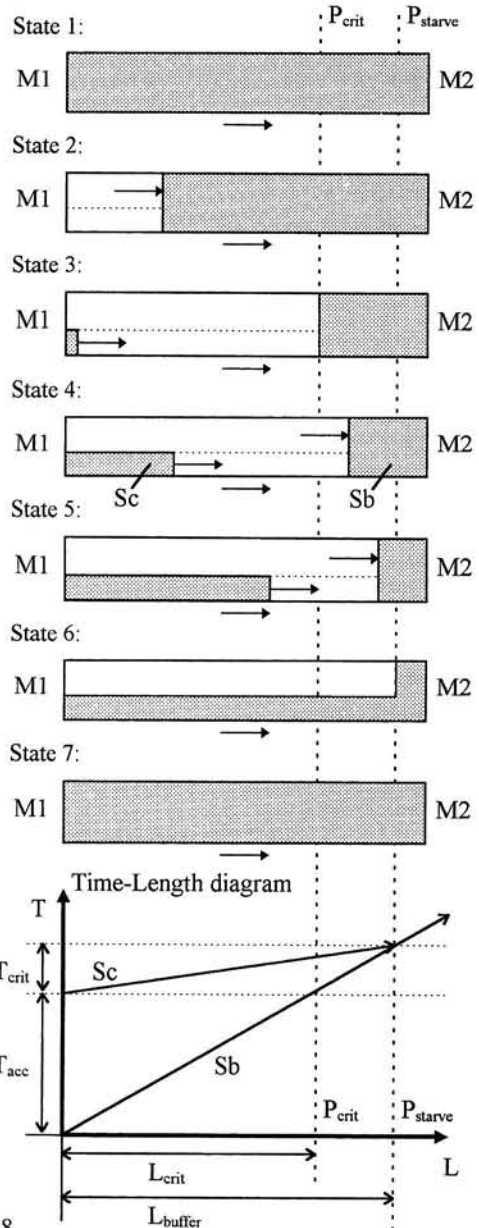
Figure 6: Anti-starve buffers

Figure 6: Anti-starve buffers

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Anti-block buffers

The purpose of anti-block buffers is to prevent that the machine before the buffer becomes blocked when the machine after the buffer has stopped. These buffers are therefore found downstream of the core machine. The ideal state is when the buffer is empty, i.e. only the part of the conveyor used for transport is full. When after the buffer a failure occurs, the machine before the buffer can continue running and fills the buffer with containers. This lasts for a certain period of time, the so-called accumulation time. At the end of this time period the machine that stopped, has to start running again, otherwise the machine before the buffer stops because it is blocked. Because of the overcapacities the ideal state is recovered.

State 1:
The transport part of the conveyor is filled, the buffer part of the conveyor is empty. Machine M2 is running. This situation is called the ideal state.

State 2 and 3:
Machine M2 has a failure or is blocked by a failure further downstream. The backup of containers builds in the direction of machine M1.

State 4:
The backup reaches the 'critical point', M2 has to start running now, otherwise M1 gets blocked (i.e. the sensor that signals the backup of bottles stops machine M1).

State 5 and 6:
Machine M2 has started running again. Because of the overcapacity of M2 with respect to M1 the container flow decreases. The buffer part of the conveyor is drained.

State 7:
The ideal state is recovered.
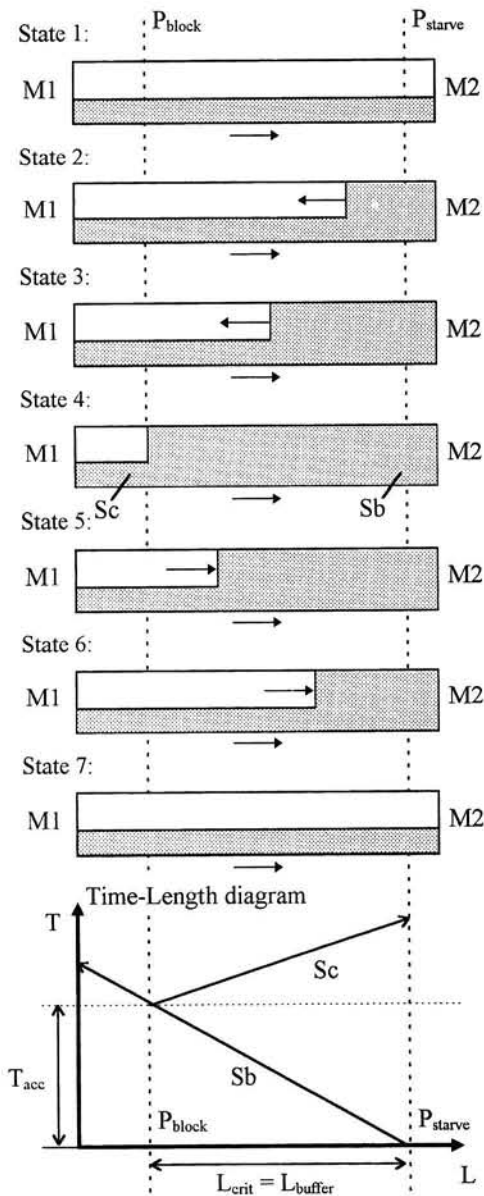
Figure 7: Anti-block buffers

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Bottle and can conveyors
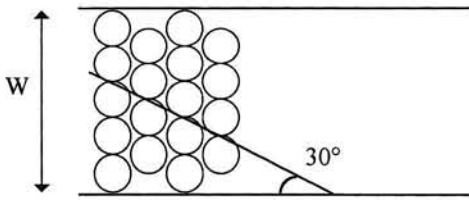
Figure 8: Bottle or can conveyor

For a given bottle or can conveyor[*]:

W	=	width (in mm)
$\varnothing$	=	bottle or can diameter (in mm)
C_{line}	=	line capacity (in bottles/min or cans/min)
Nb	=	number of rows of bottles or cans standing on the width of the conveyor
	=	$\text{ROUND}\left[\dfrac{W-\varnothing}{\varnothing \cdot \cos 30°}+1\right]$
Nm	=	number of bottles or cans per meter of conveyor = $Nb \times \dfrac{1000}{\varnothing}$
Sb	=	speed of bottles in translation (in m/min) when the conveyor is filled with bottles on its whole width
	=	$\dfrac{C_{line}}{Nm}$
Sc	=	chain speed of the conveyor
L_{buffer}	=	length of the buffer, taken as the distance between the block and the starve sensors.
ρ	=	population of bottles or cans on buffer chains of the conveyor over the length of the buffer as a percentage of the maximum number of bottles on the buffer chains of the conveyor over the length of the buffer

Of course the machine failure need not occur when the buffer is full or empty, this means that an optimal accumulation is only possible when the buffer is full or empty. This leads to two buffer times, a nominal accumulation, i.e. the accumulation in the ideal state and the (actual) accumulation, that depends on the present population of the buffer, i.e. the fill level.

φ	=	fill level of conveyor as the percentage of the number of the containers on the buffer versus the possible number of containers on the conveyor.
φ^{nom}	=	nominal fill level, defined as the fill level of the conveyor in the ideal state as set in the control[†] .

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[*] If a conveyor consists of different segments, with either different widths and/or different speeds, the accumulation is calculated for each segment separately and these are then added together.
[†] The maximum number of containers on the buffer can be even higher, but because of machine control and quality reasons (bottle/can damage, label damage, etc.) extra space between the container is achieved in the control. This is called the *unused* buffer capacity.

Nominal accumulation

The nominal accumulation is the accumulation when the buffer is in the ideal or nominal state, i.e. the state when the line is producing without failures. The nominal accumulation is equal to:

$$T_{acc}^{nom} = L_{buffer} \cdot \left(\frac{1}{Sb} - \frac{1}{Sc} \right)$$

For anti-starve buffers this means that the nominal accumulation is equal to the time it takes to empty the full conveyor over the length of the buffer minus the time is takes for bottles to travel the length of the buffer (see also figure 6).

For anti-block buffer this means that the nominal accumulation is equal to the time is takes to fill the conveyor over the length of the buffer minus the time is takes to fill the transportation part of the buffer (see also figure 7).

Actual accumulation

The actual accumulation is the accumulation that the buffer provides when the conveyor is an a given state. The state is described by the population of bottles on the length of the buffer.

$$T_{acc} = L_{buffer} \cdot \left(\frac{\rho}{Sb} - \frac{1}{Sc} \right) \qquad \text{for anti-starve buffers}$$

$$T_{acc} = L_{buffer} \cdot \left(\frac{1-\rho}{Sb} - \frac{1}{Sc} \right) \qquad \text{for anti-block buffers}$$

For anti-starve buffers this means that the actual accumulation is equal to the time it takes to empty the conveyor over the filled length of the buffer minus the time is takes for bottles to travel the length of the buffer (see also figure 5). For anti-block buffer this means that the actual accumulation is equal to the time is takes to fill the conveyor over the free length of the buffer minus the time is takes to fill the transportation part of the buffer (see also figure 6).

From this follows that the *nominal population* of anti-starve buffer is 100% and of anti-block buffers 0%. This does not mean that the whole conveyor is filled or empty, just the conveyor over the length of the buffer. The *nominal fill level* of the conveyor is then around 90% of the maximum number of bottles on the conveyor for anti-starve buffers and around 50% for anti-block buffers.

When the chains and bottles are moving at the same speed (Sb=Sc), there is no accumulation (T_{acc}=0), because there is no possibility to catch up a gap in the flow in accumulation sections upstream of the core machine, or to empty the overfilled accumulation sections downstream of the core machine. When the chain speed goes to infinity (Sc→∞) the accumulation goes to the quantity of bottles the conveyor can accept (=L_{buffer}/Sb), so the higher the chain speed, the higher the accumulation (tending towards the maximum).

Because the line capacity is used in calculating the accumulation, these accumulations can be added to get the total accumulation of each machine with respect to the core machine (filler); in reality, however a machine may be forced down in a shorter time than the accumulation, because of the machine overcapacity, or in a longer time than the accumulation, because of the machine low speed. The accumulation should therefore be regarded as the effective accumulation, with respect to the line capacity, i.e. the core machine.

After the accumulation has been used the buffer has to be restored to its nominal state, this is achieved by the speed difference between the machine before the buffer and the machine after the buffer.

T_{stop} =   accumulation to be regenerated, i.e. the duration of machine stop (in min)
C_M =   capacity of the machine that has had a stop

Nominal recovery time
The nominal recovery time is the time needed to regenerate the nominal accumulation, in other words the time needed to restore the buffer to its nominal state after a machine stop as long as the nominal accumulation.

$$T_{rec}^{nom} = \frac{T_{acc}^{nom} \times C_{line}}{C_M - C_{line}}$$

This means that the number of bottles or cans that were removed from or put on the conveyor during the nominal accumulation (=the numerator) is recovered with the speed difference between the machine that has had a stop (and now running at its maximum speed) and the line capacity (= denominator).

Actual recovery time
The actual recovery time is the time needed to regenerate the accumulation that has been used by the machine stop(s). Stated differently it is the time the machine that has had a stop, has to run at its maximum speed.

$$T_{rec} = \frac{T_{stop} \times C_{line}}{C_M - C_{line}}$$

This means that the number of bottles or cans that were removed from or put on the conveyor during the stop (=the numerator) is recovered with the speed difference between the machine that has had a stop (and now running at its maximum speed) and the line capacity.

Again, because the line capacity is used in calculating the recovery time, these times can be added to get the total recovery time of each machine with respect to the core machine; in reality, the recovery time of a buffer may be shorter because of a bigger speed difference or longer because of a smaller speed difference. The recovery time should therefore be regarded as the effective recovery time, with respect to the line capacity, i.e. the core machine.

The bigger the speed difference (or how steeper the V-shape of the V-graph) the faster machine stops can be recovered.

Case, crate and tray conveyors

For case/crate/tray conveyors the accumulation is generated by the space between the cases. For a given case/crate/tray conveyor:

C_{line} = line capacity (in bottles/min or cans/min)

Lc = length of a case (short side leading) or width of a case (long side leading).

Sb = speed of cases in translation (in m/min), with either a case population ρ or a distance d between two consecutive cases

Sc = chain speed of the conveyor

N = number of bottles or cans in a case = $\dfrac{C_{line} \times Lc}{N \times \rho}$ or $\dfrac{C_{line} \times (Lc + d)}{N}$

L_{buffer} = length of the buffer, taken as the distance between the block and the starve sensors

ρ = population of cases on the conveyor over the length of the buffer as a percentage of the maximum number of cases on the conveyor over the length of the buffer

Otherwise the formulas for bottle and can conveyors apply

3.4.2 Static accumulation

Static accumulation is accomplished by accumulation tables between the machines. Such a table (or stack) is placed next to the conveyor and is often called an ebb and flow table. When the conveyor is full the table start to fill, when the conveyor is no longer full the table starts to empty as shown in figure 9.
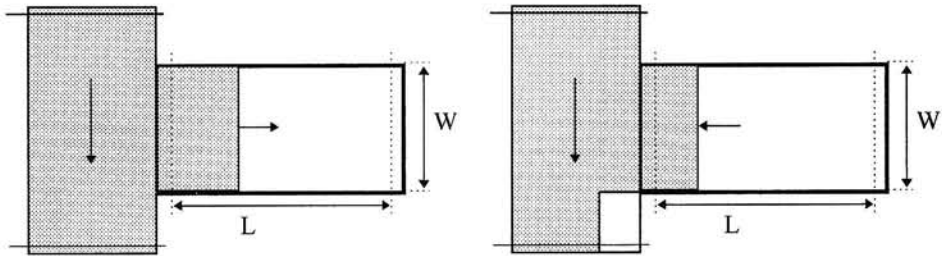
Figure 9: Accumulation table

For a given table:

W = table width (in mm)

L = table length (in mm)

$\varnothing$ = bottle or can diameter (in mm)

C_{line} = line capacity (in bottles/min or cans/min)

N = possible number of bottles or cans on the table = $\text{ROUND}\left[\dfrac{W - \varnothing}{\varnothing \cdot \cos 30°} \times \dfrac{L}{\varnothing} \right]$

= possible number of cases, crates or trays on the table

ρ = population standing on the table as percentage of N

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Nominal accumulation

The nominal accumulation is the accumulation when the buffer is in the ideal or nominal state, i.e. the state when the line is producing without failures. The nominal accumulation is equal to:

$$T_{acc}^{nom} = \frac{N}{C_{line}}$$

Actual Accumulation

The actual accumulation is the accumulation that the buffer provides when the conveyor is an a given state. The state is described by the population of bottles on the length of the buffer.

$$T_{acc} = \frac{\rho \times N}{C_{line}} \quad \text{for anti-starve buffers}$$

$$T_{acc} = \frac{(1-\rho) \times N}{C_{line}} \quad \text{for anti-block buffers}$$

The formulas for recovery are the same as those for dynamic accumulation.

3.5 Setting the line parameters

Some line parameters can be changed (e.g. the machine speeds, the conveyor speeds, the location of the sensors), other parameters vary (e.g. the failure behaviour of the machines). Most line parameters are limited by the line design: the machine capacity, the length of the conveyor. Within these limits there is some room to tune the line parameters to improve the line efficiency.

Ideally, in the line design the slope of the V-graph and the buffer capacities between the machines are determined by the failure behaviour of the machines. The accumulation is adjusted to the MTTR and the recovery time is adjusted to the MTBF. However the exact failure behaviour of the machine is of course not known in advance. So, data of comparable machines must be used and a sensitivity analysis should be done.

Once the line is installed, a true value of the line parameters becomes known. Then efficiency analysis should give an indication which line parameters should be changed to improve the line efficiency.

CHAPTER 4   DATA

In this chapter the data acquisition process is discussed. The line monitor system is described and the methods to determine or estimate the line parameters are explained.

Process registration is not a goal by itself, but should help to improve the performance of the packaging line or department (e.g. by increasing efficiency or decreasing losses) [25]. In keeping with this principle it should be determined what process data is collected and with what level of detail. This normally is a learning process, during which experience on other packaging lines or even other industries can be helpful. Naturally the costs and benefits of registration should be considered, although this is not easy.

The base for good data acquisition is a set of sound definitions of what is to be recorded. For a registration system to succeed the purpose and use of the registration have to be clear. The organisational and technical possibilities and constraints have to be considered.

Data acquisition can be done manually, automatically or both. Manually recorded data is of course less accurate, less detailed, and more subjective than automatic recorded data. However, although the amount of collected data manually is small, it is often more relevant and often has an interpretation, because only incidents or exceptions are reported and an explanation is added. Automatic or electronic data acquisition gives much more data, because every event is recorded, and the data is 'objective', meaning recorded as defined, but often events need to be explained or additional information is needed. Therefore in practice manual and automatic data registration are combined. Both electronically and manually recorded data are entered into a database. Ideally this database is easy to use, i.e. aggregation, graphs etc. can be made quickly with user friendly tools.

Registration can be continuous, e.g. a line monitor system (automatic registration) or a shift event list (manual registration), or registration can be temporarily, e.g. during the installation or upgrading of a packaging line, in which case extra equipment and personnel is used.

4.1   Registration

The data of a packaging line can be divided in *static* and *dynamic* data.

4.1.1   Static data

The static data of a packaging does not change during production and determines the configuration of the packaging line, e.g. the machine capacities, machine control, the configured machine speeds, and the conveyor width, length and speed. Most static data can be easily collected by measurement. An important tool in ascertaining these data is the so-called *line logic*.

Line logic
The line logic is a description of the conditions of the states of the machines and buffers of a line. It can be shown as a set of figures of each machine and its surrounding conveyors and a logical table of the state conditions, or the state conditions are depicted. Basically it is a description of the control of the machines by the signals of the sensors on the preceding and succeeding conveyors (see also appendix A).

4.1.2 Dynamic data

The dynamic data of a packaging line consists of data that is changing. This type of data consists of all line events (or production events), e.g. machine state changes, machine speed changes, number of units produced, buffer fill grade, production planning etc. The line event data can be collected automatically and manually.

Automatic data collection

The layers of the line monitor system for automatic data collection is shown in figure 10. The purpose of a *Line Monitor System* (LMS) on a packaging line is to give insight into the functioning of the packaging line and to improve the performance of the packaging line. An LMS has three tasks: monitoring, visualising, and recording the line performance.

  The process registration can consist of a host of counts, timers, signals etc. The machines and conveyors of a packaging line are each controlled by a so-called Programmable Logic Controller (PLC). This is a computer using a program code for the process tasks. The PLC's give signals or instructions to the machines. These PLC's are connected by a network. The signals of the PLC's are collected by the Supervisory Control And Data Acquisition (SCADA) system. This system visualises the machine and line information on monitors for the operators. The operator also receives signals directly from the machines from differently coloured light bulbs or text displays. From the SCADA system the data is stored in a database. Planning information and other information can be collected through links with other computer systems or databases.
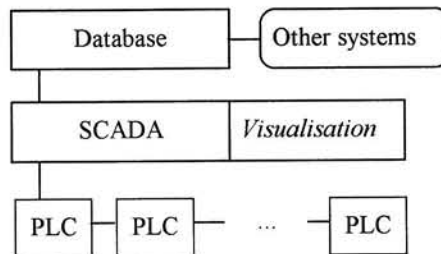
Figure 10: Layers of a line monitor system

Manual data collection

The basic form of manual data collection is the operator writing events on a event list. A modern version of this is typing events directly into a computer system or pushing touch buttons on a computer screen when an event occurs. Or in combination with an automatic data collection system it is just adding remarks to the recorded events afterwards.

In appendix B the basis registration is discussed. This gives an impression of the data that should be collected for the efficiency analysis of packaging lines.

4.2 Database

Both electronically and manually recorded data (static and dynamic) are entered into a relational database. The data model of this relational database is very important, because the features and possibilities of data analysis are partly determined by it. Links with other databases (e.g. product data, planning data, maintenance data) allow more sophisticated analysis (for instance by detecting relationships).

The data manager should filter out irrelevant data and noise or errors to keep the analysis reliable. He creates standard reports of the packaging line and ad hoc queries if asked. Ideally the database is easy to use, i.e. queries, aggregation, graphs etc. can be made quickly with user friendly tools. Of course the features of the database system that are used and needed depend on the detail of the data and the detail of the analysis. An useful feature of an registration system is the use of several counts to calculate the same quantity as a verification of the value.

4.3 Visualisation

The SCADA system usually also offers visualisation. Visualisation give an on-line representation of the packaging line data in text and/or graphics, e.g. the machine state is shown in a machine drawing or the production progress of the current order is shown. The system should lead to shorter machine stops, because of the information it provides to the operator on the cause (and the cure) of the stop, and also lead to less excess order production because of the more accurate information on the production progress. The visualisation system should be flexible and configurable, have a consistent and user friendly graphical user interface (GUI), and be expandable. What is shown on the screens must be based on careful consideration and be recorded in clear definitions. Especially the consistent use of colours is helpful.

An important feature of a visualisation system is the possibility to create so-called *historicals* or *trends*, i.e. graphs of the course of events or machine speeds, buffer contents (see figure 11). Other examples are the development of the MTTR and MTBF over time, the number of failures etc.

4.4 Line parameter estimation

The data collection can be used to determine the value of the line parameters. The methods to estimate the line parameters are discussed below.

4.5 Machine parameters

The machine parameters are the machine states, the failure behaviour, the machine efficiency and the production rates.

4.5.1 Machine state

Recording the machine state amounts to recording the start time and end time or duration of the machine state event as signalled from the PLC. Most machine states are defined in the line logic. However it is not always possible to distinguish the different states, for instance when an operator who opens a machine to clean it, this is automatically recorded as a machine failure, while in fact it could be planned downtime. The detail of recording will also vary. Automatically the machine states are known every single second, manually this is of course not possible.

Usually some extra data is added to the machine states. For a starved machine the material it is starved for (bottles, cases, pallets etc.) is added; for a failure the cause as provided by the machine sensor signals is added.

Sometimes a machine can be in different states, e.g. blocked and failed when an operator opens a blocked machine. Then either everything is recorded and filtered later so that a machine can be in one state at a time[*], or the filtering is done in the PLC, losing data but reducing the data flow. The most common filtering methods are *first-up* (with memory), meaning the machine remains in the first state until this state ends and then the machine assumes the next state; or *priority*, meaning that each state has a priority weight and that of the present state is the one with the highest priority. Something similar is often done for the failure causes. As there are many different types of machine failure and often one failure leads to an other, so again filtering can be applied.

4.5.2 Machine failure behaviour

The estimation of the machine failure behaviour is done through estimation of the MTTR and the MTBF[†]. The following sample estimators are common:

$$\text{MTTR:} \quad \frac{1}{n}\sum_{i=1}^{n} T_i^{fail} = \overline{T}^{fail}$$

$$\text{MTBF:} \quad \frac{1}{m}\sum_{i=1}^{m} T_i^{run} = \overline{T}^{run}$$

with:

n	$=$	number of internal failures
m	$=$	number of run times $= n \pm 1$
T_i^{fail}	$=$	internal fail time i, i=1, ..., n
T_i^{run}	$=$	run time i, i=1, ..., m
$\overline{T}^{fail}$	$=$	average internal fail time
$\overline{T}^{run}$	$=$	average run time

The corresponding confidence interval can be approximated as follows (if n is large):

$$\text{MTTR:} \quad \left[\overline{T}^{fail} - z_{1-\%} \cdot \frac{s^{fail}}{\sqrt{n}}, \overline{T}^{fail} + z_{1-\%} \cdot \frac{s^{fail}}{\sqrt{n}} \right]$$

$$\text{MTBF:} \quad \left[\overline{T}^{run} - z_{1-\%} \cdot \frac{s^{run}}{\sqrt{m}}, \overline{T}^{run} + z_{1-\%} \cdot \frac{s^{run}}{\sqrt{m}} \right]$$

with:

$z_{1-\%}$	$=$	the value of an standard normal distributed random variable X for which $P(X \le z_{1-\%}) = 1 - \tfrac{1}{2}\alpha$
α	$=$	confidence level, usually 5%
s^{fail}	$=$	estimated standard error of the internal failure times T_i^{fail}

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[*] A separate state 'failed and blocked' can also be defined.
[†] Depending on the definition of MTBF the run times or clock times between failures are used

$$= \frac{1}{n-1}\sum_{i=1}^{n}(T_i^{run} - \overline{T}^{rfail})^2$$

s^{run} $=$ estimated standard error of the run times T_i^{run}

$$= \frac{1}{m-1}\sum_{i=1}^{m}(T_i^{run} - \overline{T}^{runl})^2$$

A confidence interval is a measure for the accuracy of the estimate. With a chance of $1-\alpha$ the confidence interval contains the true value of the estimated quantity. The more observations in the sample the smaller the confidence interval (as can be seen in the above expressions the width of the confidence decreases width the square root of the number of observations, i.e. approximately 4n observations result in a confidence interval half as wide)[*].

    Note that the estimates are only a 'snapshot' of the current situation (or period specified), because the failure behaviour of the machines varies. Therefore the changes of the parameter values should be monitored and for estimation a representative sample should be used. Also exceptions should be excluded from the estimation. Often graphical tools can help in estimating a parameter.

4.5.3 Machine efficiency

The machine efficiency $\eta_{machine}$ is measured straightforwardly for the period specified:

$$\eta_{machine} = \frac{\text{total running time}}{\text{total running time} + \text{total time internal failures}} \times 100\%$$

or:

$$\eta_{machine} = \frac{MTBF}{MTBF + MTTR} \times 100\%$$

In practice, these calculation often include waiting time for an operator or mechanic to arrive. Then the machine efficiency is not the pure machine efficiency but the effective machine efficiency. For installation tests the pure machine efficiency should be measured.

4.5.4 Machine production rate

The machine production rates can be measured with the counts of production and rejects of the inspection equipment or the machine display. The conditions for the different production rates are described in the line logic. These conditions can be created or mimed with the sensors. Another method uses a *historical* of the machine speed over a longer time period, and checks the different machine speeds that occur (see figure 11).

    An important tool in controlling the packaging line is to check if the configured speeds in the control correspond with the speeds of the line design. Often machines are shifted down when problems occur or because this create a more even flow. However, from a line efficiency point of view this may not be desired.

    Normally the number of units produced and rejects are recorded for each machine, if possible. This enables the calculation of the line efficiency.

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[*] If we assume the distribution of the failures to be exponential the confidence interval can be calculated exactly using a gamma distribution (see [7] and [8])

4.6 Buffer parameters

The buffer parameters are the accumulation and recovery times of the buffers. Basically there are two estimation methods. The first method calculates the buffer sizes with the equipment specification or measurement of the length and width of the conveyors in real or from the layout. Then the machine speeds are used and the conveyor speeds from the line design are used. And of course the size of the bottles/cans or cases/crates/trays.

The second method measures the accumulation by experiment. So the real machine speeds and conveyor speeds are measured. Then the conveyor contents as set by the control are measured by tests. For instance the buffer between two machines is measured as follows: First stop the machine before the conveyor and let the machine after the conveyor empty the conveyor completely. Then start the first machine again and measure both the time it takes for the second machine to start again and the number of units on the conveyor before the second machine starts again. This is the transport part of the conveyors. Then stop the second machine and measure how many units can be placed on the conveyor by the first machine, resulting in the maximum conveyor fill level. So, the buffer content is simply what is put on the conveyor by the machine before the buffer minus what is taken of by the machine after it, taking into account rejects and machine contents.

The values for both methods can differ because the spacing of the units is set in the control (e.g. to decrease the pressure on the bottles) and the location of the sensors affect the effective buffer. Changes in control often also change then accumulation and recovery. Using a trend[*] of the buffer contents and machine speeds of the machine before and after the machine (see figure 11) the buffer capacity, accumulation and recovery can also be monitored over time.
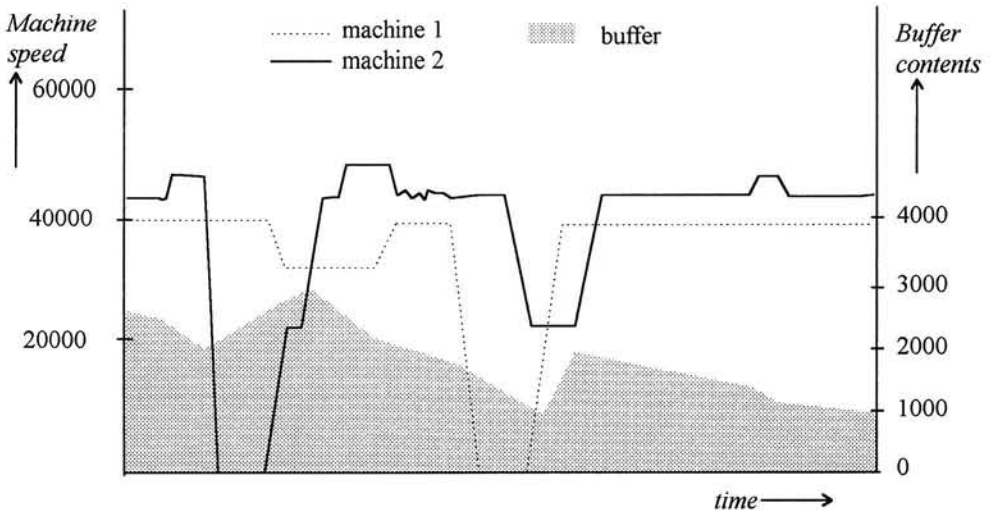

Figure 11: Trend of machine speeds and buffer contents

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[*] The counting of the contents of the buffer has to be reset every once in a while to avoid differences. For instance reset when the buffer is completely empty of full.

The nominal fill level of the conveyor can be ascertained by monitoring the buffer for a certain time in which the machine before and after the buffer function without failures. In that case the machine speeds usually modulate around the nominal machine capacity. These speeds are controlled by the sensors on the conveyors, so also the buffer content modulates between two levels. For example the machine after the buffer runs faster than the machine before the buffer until the buffer content is decreased to a certain level, then the machine after the buffer slows down and the buffer content is increased to a certain level, and then the machine after the buffer shifts up again etc. The nominal fill level is now chosen as the higher level for anti-block buffers and the lower level for anti-starve buffers.

Monitoring the buffer contents can also be useful for determining when to start a new order. In other words if you know how many product there are on the line you know almost exactly when an order is finished.

4.7   Organisational aspects

Technically there are few limitations for a Line Monitor System (LMS). However, some technical and organisational efforts are to be expected. Technical efforts, because the data collection should receive input from the Programmable Logic Controllers (PLC's) of the line equipment, this often requires reprogramming or extra programming. The visualisation also requires some effort. And the LMS needs a stable network, hardware and software environment to ensure the continuity of the data collection. Organisation efforts, because the introduction of a LMS first of all requires a functional specification, i.e. a description of the possibilities and features the system must have. After the system has been installed the users have to be trained and the system should be managed and adapted. Using the LMS should be an integrated task of those involved with the packaging line for the system to be really used successfully.

The use of the system depends on the tools it offers and its user friendliness. Data processing should be fast for standard reports and flexible for ad hoc queries. Often systems are discarded because of the limitations of the system or the unclear and complicated use.

The LMS should built step by step. Creating a overall complete system is simply a technical risk. Also it is not optimal, because the organisation then does not have the opportunity to learn, and expand the system as needed. A cost-benefit decision is impossible and users are hardly involved. This could result in a more than complete (i.e. with a host of unknown and unnecessary features), technical perfect, yet unused LMS.

The first step in building a LMS should be a to determine what kind of system is needed and what is expected from the system (the functional specification). Most LMS systems are adapted versions of standard software packages, but also tailor made system exist, each with their own (dis)advantages. Although cost/benefit analysis is often hard for information technology projects, because some benefits are hard to quantity (e.g. more involvement of operators with the machines, a better overview of the line, etc.) some sort of cost/benefit decision should be made with each expansion of the system.

CHAPTER 5   ANALYSIS

This chapter describes various mathematical methods for efficiency analysis based on the available process data.

The efficiency analysis serves to transform the process data into information on the (loss of) efficiency by representing these data in a comprehensible manner and calculating performance indicators. The interpretation of these figures is based on norm values (determined by the objective and history of the packaging line), historical comparison and comparison among packaging lines. Also incidents and exceptions must be taken into account. The data should be analysed over different production shift teams, different time periods, different product types, and different packaging lines. From this follows that all analysis can be carried out on a time base, because shift teams, production orders etc. all correspond to certain time intervals. Therefore we assume that the time period to be analysed is specified, for instance all the shift of the last week of team A, or the time intervals of all orders of a certain product, etc.

Of each analysis method the following elements are discussed:
- *Description*: description of the method, mostly the idea behind it and the application of the method.
- *Goal*: objective of the method
- *Data*: which data are used and therefore needed for the method
- *Calculation*: the calculations and graphs of the method
- *Example*: example of the method
- *Use*: how the method is used and what is the value of the method
- *Remarks*: limitations, possibilities and cautions of the method

The following analysis methods are discussed:

1. Efficiency limits and buffer strategy performance
2. Machine event summary and Machine efficiency analysis
3. Accumulation rate/Recovery rate and Buffer efficiency analysis
4. V-graph analysis
5. Statistical analysis: Histograms/Frequency
6. Event lists and Event patterns
7. Efficiency Loss Allocation algorithm

5.1   Efficiency limits and buffer strategy performance

Description
The line efficiency is the starting point of the analysis. Theoretically two limits can be derived for the line efficiency. The lower limit is calculated for a hypothetical line with the same machines and machine efficiencies, however without buffers. In other words a stop on one of the machines causes a stop of the line. The upper limit is calculated for a hypothetical line with the same machines and machine efficiencies, however with infinite buffers. In other words the machines function independently from each other. The lower limit is called the *zero-buffer limit*, and the upper limit is called the *infinite-buffer limit*.

By comparing the real line efficiency with these lower and upper limits for the line efficiency, a measure for the performance of the buffer strategy is derived. The closer the real efficiency is to the lower (upper) limit, the worse (better) the buffer strategy is functioning. In other words if the buffer strategy performs well the machines function more independently.

Goal
This method gives a measure for the performance of the buffer strategy and limits for the line efficiency.

Data
The data needed for the line efficiency limits are:
- line component system, i.e. a description of the machines of the line and where they are connected.
- machine efficiencies for all machines (or MTTR's and MTBF's to calculate the machine efficiencies (note that no assumptions are made about the distributions of the failure behaviour)).

The data needed for the buffer strategy performance are:
- line efficiency limits
- actual line efficiency

Calculation
For the lower limit of the line efficiency η_{line}^0 for a series system without buffers we assume that the production rate of the line is the minimum of the machine capacities of the machines and the line availability is the product of the machine efficiencies. Then the line efficiency lower limit or zero-buffer limit is the product of the line production rate and the line availability [3][4].

Line production rate : $R^{low} = \min_{machine} C^{mach}$

Line availability : $A^{low} = \prod_{machine} \eta_{machine}$

Lower limit : $\eta_{line}^0 = R^{low} \times A^{low}$

For a system with parallel machines the production rate and availability of each 'production path' have to be summed to get the lower line efficiency limit.

For the upper limit of the line efficiency η_{line}^∞ for a series system with infinite buffers we assume that the line efficiency is minimum of the Mean Effective Rates of the different machines. This results in the line efficiency upper limit or infinite-buffer limit.

Mean Effective Rate $(MER_{mach}) = \eta_{machine} \times C^{mach}$

Upper limit : $\eta_{line}^\infty = \min_{machine} MER_{mach}$

For parallel machine groups the MER of the group is the sum of the MERs of the machines. And the minimal machine group MER is the upper limit of the line efficiency.

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The buffer strategy performance is defined as the difference between the actual line efficiency η_{line} and the line efficiency lower limit as percentage of the difference between the line efficiency upper limit and the line efficiency lower limit:

$$\text{Buffer strategy performance: } \beta = \frac{\eta_{line} - \eta_{line}^0}{\eta_{line}^x - \eta_{line}^0} \times 100\% \qquad \eta_{line}^0 \leq \eta_{line} \leq \eta_{line}^x$$

Example
Figure 12 shows the six machines of a (series system) packaging line. The combined Rinser/Filler machine is the core machine; the buffer upstream of this machine is full and the buffers downstream are partly empty.
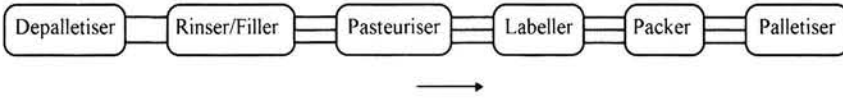
Figure 12: Components of a packaging line

In table 1 the machine capacities as a percentage with respect to the core machine (Rinser/Filler) are shown, and also the machine efficiencies and the Mean Effective Rates for the machines.

Machine	$C_{mach}\%$	η_{mach}	MER_{mach}
Depalletiser	135%	97%	131%
Rinser/Filler	100%	98%	98%
Pasteuriser	100%	99%	99%
Labeller	125%	95%	119%
Packer	130%	93%	121%
Palletiser	135%	96%	130%

Table 1: Machine capacities, machine efficiencies and Mean Effective Rates

The lower and upper limits for the time period specified are shown in table 2; the real efficiency for the period was 87%, the resulting buffer strategy performances is 50%.

Lower limit		Upper limit		Buffer strategy performance
R^{low}	A^{low}	η_{line}^0	η_{line}^x	β
100%	76%	76%	98%	50%

Table 2: Lower and upper efficiency limit and buffer performance

Use
Although the limits are theoretical, they can serve as a indication of the line potential and the influence of each machine on the line efficiency. The buffer performance should be viewed for different time periods. It may be possible to estimate a correlation between the line efficiency the machine efficiencies (for instance always a low line efficiency when the labeller has a low machine efficiency). The method is used on a very global level.

Remarks
- If we assume that a forced down machine cannot fail (so-called operation depended failures) then the availability of a series system is [3][4]:

$$A^{low} = \frac{1}{1 + \sum_{machine}(\frac{1}{\eta_{machine}} - 1)}$$

- For a shift the line efficiency can be 0% because of a long failure or because of a changeover faster than planned the efficiency can be over 100%.
- The machine with the lowest MER is called the *bottleneck* of the line; normally this should be the core machine
- Reaching (and increasing) the upper limit is likely to be the line objective, and often buffers need not really be infinitely large to achieve this, it should be analysed which buffers (or machines) do not perform in keeping with the upper limit.

5.2 Machine event summary and Machine efficiency analysis

Description
The machines of a line are viewed separately using a pie-chart, a summary table of the machine events and the machine efficiency for the analysis period.

The pie chart gives the proportion of the time period specified that the machine was in each of the possible states. The summary table gives an impression of the machine behaviour, e.g. exceptions can be detected (e.g. in the maximum state event duration column) and nervous or non-smooth running can be seen (i.e. many short stops).

Especially the core machine is of importance, because the production time lost on this machine cannot be recovered (i.e. it results in line efficiency loss). The part of the line causing the most core machine stops can be located; this is either the core machine itself (i.e. core machine failures), upstream of the core machine (core machine starvation), or downstream of the core machine (core machine backup). The analysis then focuses to that part of the line.

Goal
The machine event summary, pie chart and machine efficiency give a quick overview of the performance of each machine during the period specified, and especially the core machine.

Data
The data needed for the machine event summary table are:
• total time that a machine was in each of its possible machine states,
• number of occurrences of each machine state,
• minimum, average and maximum event duration for each machine state
• standard error of the event duration
In effect all machine events are needed.

The data needed for the machine pie chart are:
• total time that a machine was in each of its possible machine states,
• time period specified, which ought to be equal to the sum over the total time that the machine was in each of its possible states

The data needed for the machine efficiency are:
- total time that the machine was running
- total time that the machine had an internal failure

Calculation
The machine data are put in a table with one row for each machine state and column totals at the bottom. On each row the total time of the state, the number of state occurrences, the minimum, average, and maximum event duration of the machine state, and the standard error of the event duration. The pie chart is calculated for the total state times, which add up to the total time of the period specified (otherwise a pie slice 'unknown' is added). The machine efficiency is calculated as defined.

Example
Figure 13 and table 3 show an example for a Filler for a shift of 8 hours.

Machine: *Filler*
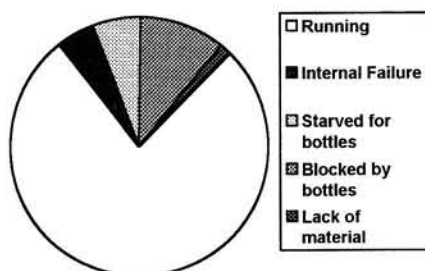
Figure 13: Time pie-chart machine states

Machine state	Sum	Number #	Mean	Min	Max	S.E.
Running	6:09:23	112	0:03:18	0:00:12	0:09:14	0:00:16
Internal Failure	0:22:34	32	0:00:41	0:00:07	0:03:43	0:00:15
Starved for bottles	0:29:02	27	0:01:05	0:00:53	0:04:02	0:00:24
Blocked by bottles	0:51:57	59	0:00:53	0:00:23	0:02:19	0:00:19
Lack of material	0:07:04	12	0:00:35	0:00:19	0:01:17	0:00:34
Total	8:00:00	242	0:01:59	0:00:07	0:09:14	0:00:43

$$\text{Machine efficiency} = \frac{6:09:23}{6:09:23 + 0:22:34} = 0.942$$

Table 3: Machine event summary table

Use
The method focuses on each machine separately using data facts. It gives a overview of the machine registration data. By comparing different shifts changes in the machine behaviour can be detected. Also relations between machine can be analysed by looking at the machine interaction with these machine event summaries (i.e. the number of backups compared to the number of machine stops of the next machine). Operators can get information on their machines and the machine behaviour can be compared over different products. Also a need for further analysis can be found.

Remarks
- extra machine data can be added like the number of units produced, rejects, average speed, MER, etc.
- it can also be useful to divide the state running into sub-states for each specified speed, then the number of speed changes gives an impression of the functioning of the machine and the surrounding machines (e.g. are there many speed changes, are all speeds used, and for how long). Also the sum of each total time per machine speed multiplied by the speed should give the number of units produced. Drilling down even further down the failure behaviour and rejects could be identified for each speed.

5.3   Accumulation rate/Recovery rate and Buffer efficiency analysis

Description
Although the machines are of course the essential parts of the packaging lines, the conveyors/buffers also have an important task: they allow the machines to function independently. The buffers should cover the short stops or *microstops* (a few minutes and shorter) and are not designed to cover the longer stops or *macrostop* (longer than a few minutes). It is assumed that microstops cannot be totally avoided, because of dirt, irregularities in the material, breaking glass, etc. and the high speed of the machines. Macrostops are the result of (lack of) maintenance or improper use, they are often called breakdowns to contrast them with failures.

The buffer strategy consists of two parts: the buffers and the overcapacities. In 5.1 the performance of the buffer strategy as a whole was calculated, but also for each buffer separately the performance can be calculated, using the ratio of the accumulation and the Mean Time To Repair. the ratio of the recovery time and the Mean Time Between Failures, and the buffer efficiency [15].

Goal
The buffer efficiency analysis, and accumulation and recovery rates give a quick overview of the performance of each buffer during the period specified.

Data
The data needed for the accumulation rate are:
- Mean Time To Repair (MTTR) for the machine before the buffer for anti-starve buffers and for the machine after the buffer for anti-block buffers
- Nominal accumulation of the buffer

The data needed for the recovery rate are:
- Mean Time Between Failures (MTBF) for the machine before the buffer for anti-starve buffers and for the machine after the buffer for anti-block buffers
- nominal recovery time of the buffer
- Mean Time To Repair (MTTR) for the machine before the buffer for anti-starve buffers and for the machine after the buffer for anti-block buffers
- actual recovery time of the buffer for a failure of length MTTR

The data needed for the buffer efficiency are:
- total time that a machine was in each of its possible machine states, for both the machine before and the machine after the buffer

Calculation

Both types of buffers: anti-starve and anti-block buffers are treated separately. There is basically no difference between static and dynamic accumulation here.

Anti-starve buffers

Let machine A and machine B be the machines before and after the buffer as shown in figure 14, the flow is from A to B. The core machine is B or one of the following machines. The objective of the buffer between machine A and B is to prevent machine B from becoming starved. Machine A has an higher machine capacity than machine B to catch up when machine A has had a failure (see figure 6).
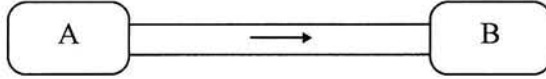

Figure 14: Two machines connected by a buffer

The accumulation rate is equal to the rate of the accumulation of the buffer and the MTTR of machine A:

$$\text{accumulation rate} = \frac{T_{acc}^{nom}}{MTTR_A} = \frac{\text{accumulation capacity in containers}}{C_B^{nom} \times MTTR_A}$$

The accumulation rate is also equal to the maximum buffer content divided by the average decrease of the buffer content by machine B during the average failure time of machine A. For instance, an accumulation rate of 1.5 means that the buffer provides an accumulation of 1.5 times the average failure time of machine A. Obviously the higher the accumulation rate the less influence the failures of machine A have on machine B.

The recovery rate is equal to the increase of the buffer content during the average run time of machine A because of the speed difference between machine A and B, divided by the average decrease of the buffer content by machine B during either the nominal accumulation time or the average failure time of machine A.

$$\text{nominal recovery rate} = \frac{MTBF_A \times (C_A - C_B^{nom})}{C_B^{nom} \times T_{acc}^{nom}}$$

$$\text{mean recovery rate} = \frac{MTBF_A \times (C_A - C_B^{nom})}{C_B^{nom} \times MTTR_A}$$

The higher the recovery rate the more failures of machine A will be covered. The recovery rate is a measure for the ability of a machine to catch up its own failures. For instance a recovery rate of 2 means that the average run time of machine A is 2 times as long as the time needed to recover the average stop of machine A. Note that the mean recovery rate is equal to the nominal recovery rate multiplied by the accumulation rate.

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Because machine A has an higher machine capacity than machine B the following should hold:

$$T^B_{starve} \leq T^A_{stop}$$

or:

total time machine B is starved ≤ total stop time of machine A except blocked by machine B
= total time internal failures machine A
+ total time machine A is starved
+ total time machine A is stopped not caused by machine B
(e.g. lack of material, blocked for another reason, etc.)

In short the total time that machine B is starved should be less than the total time machine A is not running that can cause machine B to become starved. If machine B has an higher capacity than machine A than machine B can become starved by just emptying the buffer because of its higher production speed.

The difference between the starved time of machine B and the stop time of machine A is due to the buffer between machine A and B. The buffer efficiency η^{AB}_{buffer} is defined as:

$$\eta^{AB}_{buffer} = \frac{T^A_{stop} - T^B_{starve}}{T^A_{stop}} \times 100\%$$

This buffer efficiency is the percentage of the maximum starve time of machine B that is eliminated by the presence of the buffer and the extra capacity of machine A. For instance a buffer efficiency of 60% means that on average a stop time of one minute on machine A would result in 24 seconds of starve time on machine B, i.e. 36 seconds are covered by the buffer. If there would be no buffer the starve time of machine B would be equal to the stop time of machine A.

If the buffer efficiency is negative then either every stop of machine A stops machine B, the buffer itself is causing problems, there is a delay before machine B starts after a stop, or machine B has an higher capacity than machine A.

The value of this buffer efficiency can be distorted by macrostops which are longer that the accumulation time of the buffer and therefore cannot be covered by the buffer (for instance a machine failure of an hour will cause a stop of almost an hour on the other machines). Then it is better to use the buffer efficiency for the number of occurrences:

$$\eta\#^{AB}_{buffer} = \frac{\text{number of stops of machine A} - \text{number of times machine B is starved}}{\text{number of stops of machine A}} \times 100\%$$

For instance, a buffer efficiency of 60% means that six out of ten stops on machine A do not result in a stop of machine B, i.e. four out of ten stops of machine A do result in a starvation of machine B. Again only the stops of machine A not caused by machine B should be counted. If there would be no buffer the number of stops of machine A would be equal to the number of times machine B is starved.

Anti-block buffers

Let machine A and machine B be the machines before and after the buffer as shown in figure 14, the flow again is from A to B. Now, however, the core machine is machine A or one of the previous machines. The objective of the buffer between machine A and B is to prevent machine A from becoming blocked. Machine B has an higher machine capacity than machine A, to catch up when machine B has had a failure (see figure 7).

The accumulation rate is equal to the rate of the accumulation of the buffer and the MTTR of machine B:

$$\text{accumulation rate} = \frac{T_{acc}^{nom}}{MTTR_B} = \frac{\text{accumulation capacity in containers}}{C_A^{nom} \times MTTR_B}$$

The accumulation rate is equal to the maximum space on the buffer divided by the average increase of the buffer content by machine A during the average failure time of machine B. For instance, an accumulation rate of 1.5 means that the buffer provides an accumulation of 1.5 times the average failure time of machine B. Obviously the higher the accumulation rate the less influence the failures of machine B has on machine A.

The recovery rate is equal to the decrease of the buffer content during the average run time of machine B because of the speed difference between machine A and B, divided by the average increase of the buffer content by machine A during either the nominal accumulation time or the average failure of machine B.

$$\text{nominal recovery rate} = \frac{MTBF_B \times (C_B - C_A^{nom})}{C_A^{nom} \times T_{acc}^{nom}}$$

$$\text{mean recovery rate} = \frac{MTBF_B \times (C_B - C_A^{nom})}{C_A^{nom} \times MTTR_B}$$

The higher the recovery rate the more failures of machine B will be covered. The recovery rate is a measure for the ability of the machine to catch up its own failures. For instance a recovery rate of 2 means that the average run time of machine B is 2 times as long as the time needed to recover the average stop of machine B. Note that the mean recovery rate is equal to the nominal recovery rate multiplied by the accumulation rate.

Because machine B has an higher machine capacity than machine A the following should hold:

$$T_{block}^A \leq T_{stop}^B$$

or:

total time machine A is blocked $\leq$ total stop time of machine B except starved by machine A
$=$ total time internal failures machine B
$+$ total time machine B is blocked
$+$ total time machine B is stopped not caused by machine A
(e.g. lack of material, starved for another reason, etc.)

In short the total time that machine A is blocked should be less than the total time machine B is not running that can cause machine A to become blocked. If machine A has an higher capacity than machine B than machine A can become blocked by just filling the buffer because of its higher production speed.

The difference between the blocked time of machine A and the stop time of machine B is due to the buffer between machine A and B. The (reverse) buffer efficiency η_{buffer}^{BA} is defined as:

$$\eta_{buffer}^{BA} = \frac{T_{stop}^B - T_{block}^A}{T_{stop}^B} \times 100\%$$

This reverse buffer efficiency is the percentage of the maximum block time of machine A that is eliminated by the presence of the buffer and the extra capacity of machine B. For instance a buffer efficiency of 60% means that on average a stop time of one minute on machine B would result in 24 seconds of block time on machine A, i.e. 36 seconds are covered by the buffer. If there would be no buffer the block time of machine A would be equal to the stop time of machine B.

If the buffer efficiency is negative then either every stop of machine B stops machine A, the buffer itself is causing problems, there is a delay before machine A starts after a stop, or machine A has an higher capacity than machine B.

The value of this buffer efficiency can be distorted by macrostops which are longer that the accumulation time of the buffer and therefore cannot be covered by the buffer (for instance a machine failure of an hour will cause a stop of almost an hour on the other machines). Then it is better to use the buffer efficiency for the number of occurrences:

$$\eta\#_{buffer}^{BA} = \frac{\text{number of stops of machine B} - \text{number of times machine A is blocked}}{\text{number of stops of machine B}} \times 100\%$$

For instance, a buffer efficiency of 60% means that six out of ten stops on machine B do not result in a stop of machine A, i.e. four out of ten stops of machine B do result in a backup of machine A. Again only the stops of machine B not caused by machine A should be counted. If there would be no buffer the number of stops of machine B would be equal to the number of times machine A is blocked.

Use
The performance of the buffer is a tool to determine problems or bottleneck on a packaging line. Buffer with low efficiencies are either very small buffers or are not functioning well. Again the values of the accumulation rates, recovery rates and buffer efficiency should be monitored over time.

Remarks
- more detailed analysis involves correcting these buffer performance indicators by leaving out stops longer that the accumulation time of the buffer. Note that although buffers are not designed to cover these stops, their influence should not be neglected. Likewise changeovers influence the buffer performance.

- instead of using the MTBF sometimes the mean time between stops can be used; and the mean time of stop instead of the MTTR. This may give a more complete picture of the machine interference, because starvation and backup can interrupt recovery.

- as in queuing theory, where the service rate should be greater than the arrival rate to avoid an 'explosion' of the system, it is expected that the recovery rate should be greater than 1 to ensure a stable packaging process, and also an accumulation rate greater than 1 is preferable.

- a part of the starvation and backup is also eliminated by speed reduction of the machine that are becoming starved or blocked.

- for each buffer the buffer efficiency can be calculated in both directions, although the buffer is of course designed to function in one direction. If an anti-starve (anti-block) buffer has a low (high) normal buffer efficiency and a high (low) reverse buffer efficiency, this indicates that the buffer is mostly empty (full), which is of course unwanted.

5.4   V-graph analysis

Description
The machines on either side of the core machine have extra capacity to restore the accumulation after a failure has occurred. And this overcapacity increases for each machine going upstream or downstream from the core machine. The graph of the machine capacities has a 'V'-shape with the core machine at the base.

The V-graph of a packaging line is basically a graph of the machine capacities in the sequence of the line. The V-graph can be expanded with the Mean Effective Rate of the machine, which gives the effective V-graph (using machine efficiencies). The actual line efficiency can also be shown. A more detailed V-graph shows a bar for each machine and the machine state totals are shown as bar segments of each machine bar. This V-graph gives a overview of the machine event summary for the machines of the line. The V-graphs can help identify the bottleneck machine, as this is the machine which has many internal failures, and the preceding machine has a lot of block time and the succeeding machine has a lot of starve time. The buffer efficiencies of 5.3 can also be shown in the V-graph.

Goal
The V-graph creates a line view instead of viewing the machines and buffers separately; this means that machine interaction can be seen on a global level. It also helps to identify the bottleneck machine of the packaging line.

Data
The data needed to create the V-graph are:
• line component system, i.e. a description of the machines of the line and where they are connected.
• machine capacities for each machine

The date needed to add the effective V-graph are:
• Mean Effective Rate (MER) of each machine,
  or machine efficiency of each machine to calculate the MERs

The data needed to add the actual line efficiency is:
• Line efficiency for the period specified

The date needed to add the machine bars and machine state bar segments are:
- total time that a machine was in each of its possible machine states,
- time period specified, which ought to be equal to the sum over the possible states of the total time that the machine was in that state

In effect the same data as needed for the machine event summary pie chart.

The data needed to add the buffer efficiencies are:
- buffer efficiencies for each buffer, although these can be calculated using the machine bar segments

Calculation

Usually both the V-graph of machine capacities and the effective V-graph are shown together as in Figure 15.

$$\text{Mean Effective Rate (MER}_{\text{mach}}) = \eta_{\text{machine}} \times C^{\text{mach}}$$

The machine with the lowest M.E.R. is called the *bottleneck machine*, i.e. the machine with the lowest effective production capacity [11]. In keeping with the design this should be the core machine. The mean effective rate of the bottleneck machine gives the upper limit of the efficiency (see also paragraph 5.1). A line for the line efficiency can be added.

The bar V-graph (figure 16) has a bar for each machine and for each machine the machine state total times are projected on the machine bar (provided these add up to the total time of period specified, otherwise a bar segment 'unknown' is added). So, each machine state has a bar segment within the machine bar, proportional to the total time of the state with respect to the total time of the period specified.

$$\text{machine state bar segment} = \frac{\text{total time of machine state}}{\text{total time of the period specified}} \times \text{machine capacity}$$

The bottleneck machine is then identified as the machine which transforms backup into starvation, i.e. the previous machine is blocked and the next machine is idle, whereas the machine itself has few starvation and backup, but a lot of failures (or loss of speed). Again a line can be added for the line efficiency, the machine state running can then be divided in a part running at nominal line speed and a part loss of speed.

Finally the buffer efficiencies can be shown by connected the bar segments of the machine before the buffer with the relevant bar segments of the machine after the buffer, as in figure 17. For anti-starve buffers all stops of the machine before the buffer that could cause starvation are connected with the starvation of the machine after the buffer; for anti-block buffers all stops off the machine after the buffer that could cause backup at the machine before the buffer are connected with the block time of the machine before the buffer. Note that the order arrangement of the different machine states bar segments is important. Also the value of the buffer efficiency can be shown in the graph or in a corresponding table.

Example

Three examples of V-graph are shown in figure 15-17. Figure 15 is a basic V-graph with machine capacities and MER, figure 16 is a bar V-graph with the machine states projected on the bar of the machine capacity and MER, and figure 17 is a bar V-graph with buffer efficiencies.
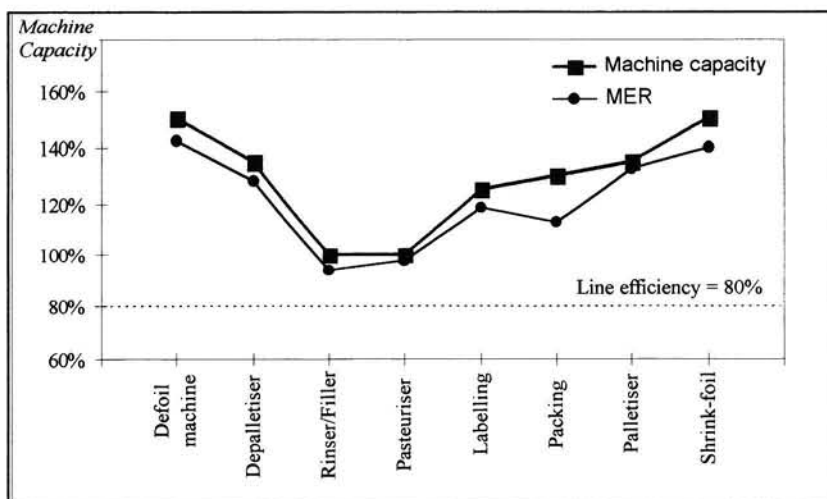
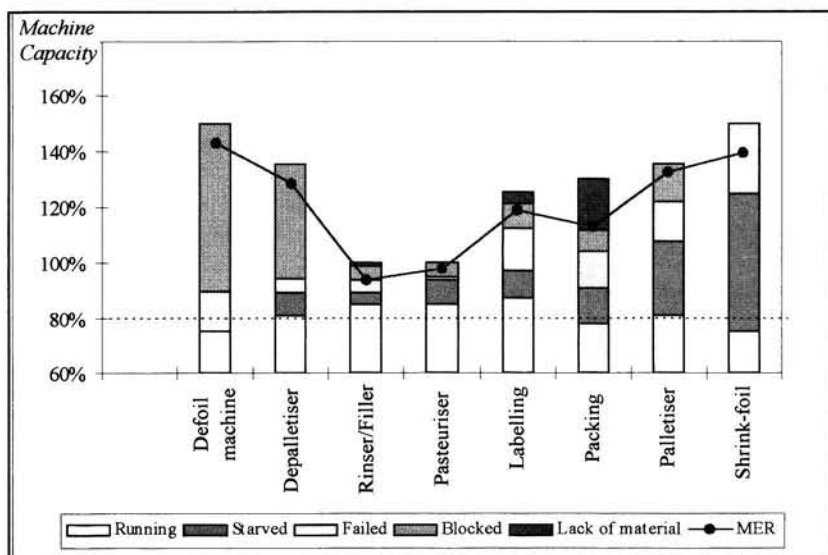*Figure 15: V-graph: machine capacities, MER and Line efficiency*

Figure 16: V-graph: partition of machine capacities over machine states and MER
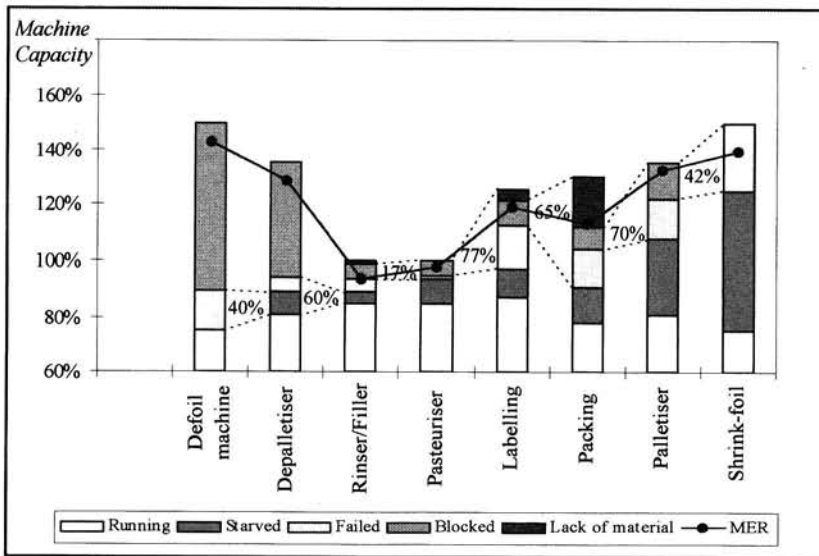
Figure 17: V-graph: machine capacities and buffer efficiencies

Use

The main use of the V-graph is the overview it gives of the machines and buffers of the line. It is a tool to detect exceptions and bottlenecks. The V-graph is useful in comparing different packaging lines.

Remarks

- note that overcapacities are only useful in combination with buffers.
- there should be a choice which machines are shown in the V-graph, for instance leave out unimportant machine or machines with so much overcapacity that the whole graph gets out of proportion; or create a separate graph for the carton street and the packing machine
- for groups of parallel machines, the machines can simply be added together
- the V-graph can be even more detailed either by adding a division in failure types (e.g. between microstops and macrostops) or by adding a division in different machine speeds (e.g. a bar segment for each machine speed instead of just one segment 'running' or a bar segment for the net production time (=number of units produced/machine capacity) and a residual bar segment 'loss of speed'.
- another V-graph shows the different machine speeds of the machines of the line. This can be seen as a part of the line logic. For each machine the speeds as set in the control are marked in the graph. One would expect, for instance, that all machines have a speed almost equal to the nominal line capacity, to allow the line can run in equilibrium.
- another way of creating a line overview is showing the machine efficiencies and buffer efficiencies in lay-out of the line next to each machine and buffer respectively.

5.5   Statistical analysis: Histograms

Description
The machine events can be analysed statistically is various different ways. This analysis should of course have an aim, and is often triggered by some signal or indication of a characteristic or relation of the observed quantities (a so-called *conjecture* or hypothesis). Statistical analysis is less detailed than an event list, but more detailed than the machine event summary. It can give more insight than either the event list and the machine event summary. All the classical statistical methods can be of use. Here only histograms for the machine state events are discussed.

Goal
In general statistical analysis is used to confirm of reject conjectures on certain observed quantities. Histogram analysis is used to identify the distribution of the machine behaviour i.e. machine event duration.

Data
The data needed to create an histogram diagram are:
*   duration of each machine state event, for the machines and machine states being analysed

Calculation
An histogram is a (bar) graph of the frequency distribution of a certain group of events over certain chosen intervals (usually with the same width). First the interval width is chosen (e.g. 20 sec.) then all events are assigned to the interval that contains the duration of the event. Often not only the number of events per interval (=frequency) are reported but also the total duration of these events for each interval (pareto diagram).

Example
An example of an histogram of the failures of a machine is shown in figure 18. The number of occurrences is shown as a line, the total time of the events in each interval is shown as a bar. Also the accumulation of the buffer after the machine is shown.
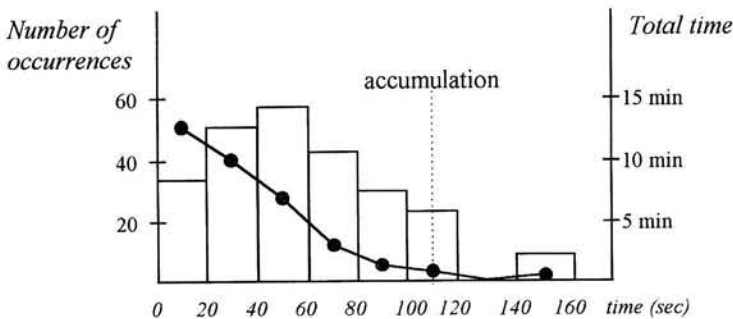

Figure 18: Histogram of machine failures

Statistical analysis is used to combine the detailed data into some sort of summary, to get an impression of the data. In particular histograms are used to analyse the machine state events. The development and changes in the machine behaviour (and thus the histograms) should be monitored over time. In this way relationships between certain quantities can be established.

Remarks
- the shape of the failure and run distribution is shown using a *histogram*, though often for convenience exponential distributions are chosen. Also separate estimates of the MTTR and MTBF (or even the distribution function) can be made for each type of failure.
- some examples of the variety of possibilities for statistical analysis are: relationships between product types and machine behaviour or line efficiency, energy use during the different machine states of the pasteuriser, comparison of rejects between glass or carton suppliers, efficiency trends over teams or shifts, influence of changeovers, relationship between rejects and start/stop behaviour of machines or failures, recovery and accumulation, etc.
- a histogram can also be used to look at the buffer performance. For instance, if the starve events of the machine before the buffer are put in a histogram and the stop events of the machine after the buffer in another histogram. Again the accumulation can be shown.

5.6   Event list and Event patterns

Description
From the machine events a more detailed overview can be given in an event list, sorted by duration or by start time. Also event lists for each machine state separately can be given, or even a detailed failure list with a failure type or cause for each failure. Also time restrictions on the event length can be set. These are all simply database queries resulting in a table of data. Also queries over more than one machine can be given, e.g. comparing two parallel machines, or matching two consecutive machines for backup and starvation.

Graphically this can be represented by colour patterns on a time line, one line for each machine. The different machine states all have their own colour. In this way nervous machine behaviour can be detected quickly and if the time-scale is small enough cause and effect relations can be identified between failures and starvation or backup. Also graphs per machine or machine state or combinations of machines and machines states can be generated, or again graphs using time limits. Basically event lists are a tool to quickly scan the machine event data, and event patterns could be called graphical queries.

Goal
The event lists and event patters give a detailed overview of the machine events of the period specified for monitoring (e.g. identifying exceptions, detecting cause and effect relations, etc.).

Data
The data needed for the event lists and event patterns are:
• start time and end time of every machine state event, for all the machines of the line

Calculation

Basically the event list is the result of a database query. With a selection for which machines state events should be regarded, per machine which machine states, minimum and maximum event duration, sorted by machine, duration, and/or start time or end time.

The event patterns are a graphical representation of these queries. For each selected machine a time line is drawn for the period specified, and each event is shown on this line from start time till end time with the corresponding colour.

Example

Figure 19 shows two event lists for a certain machine, sorted by start time and sorted by duration, over a given period. Figure 20 shows an event pattern for three machines.

Event list   Machine A   0:00:00 – 8:00:00 all events > 0 min, sorted by start time

State	Duration	Start time	End time
Running	0:03:26	0:00:00	0:03:26
Blocked	0:04:13	0:03:26	0:07:39
Failed	0:00:04	0:07:39	0:07:43
Blocked	0:02:14	0:07:43	0:09:57
...			

Event list   Machine A   0:00:00 – 8:00:00 all failures > 5 min, sorted by duration

State	Duration	Start time	End time
Failed	0:14:34	6:46:00	7:00:34
Failed	0:09:22	4:07:48	4:17:10
Failed	0:06:11	4:21:27	4:27:38
...			

Figure 19: Event lists, sorted by start time or duration

Machine

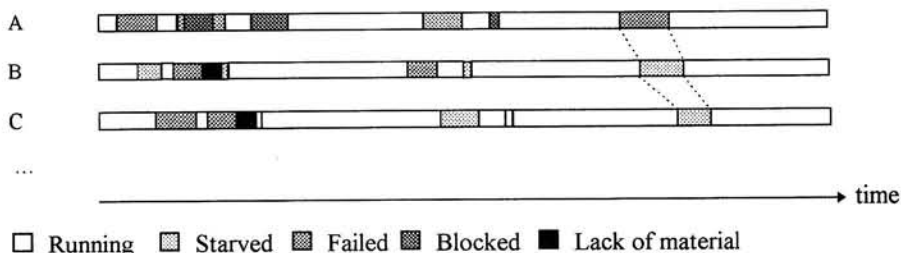□ Running ▦ Starved ▓ Failed ▨ Blocked ■ Lack of material

Figure 20: Event pattern of three machines

Use

Event lists and event patterns can be used to get a picture of the functioning of the packaging line over the period specified, a view of the machine interference and an impression of the machine failure behaviours or event sequences.

Remarks
- the usefulness of the event lists and event patterns can be enhanced when data on changeovers, planned downtime, lunch breaks etc. are added.
- more detailed lists and patterns distinguish between different types of failures and different machine speeds.
- the functioning of a buffer for anti-starve buffers can be shown in detail with an event pattern of the starve events of the machine after the buffer and the stops of the machine before the buffer that can cause starvation at the machine after the buffer; the functioning of a buffer for anti-block buffers can be shown in detail with an event pattern of the block events of the machine before the buffer and the stops of the machine after the buffer that can cause backup at the machine before the buffer.
- a better way of following the buffer functioning is to combine these event pattern with a graph of the machine speeds of the machine before and after the buffer, and the buffer content for the same period of time (see figure 11).

5.7   Efficiency Loss Allocation algorithm

Description
The analysis methods described above all give an impression of the functioning of the packaging line. However one would like to have hard figures instead of patterns and indications. The efficiency loss allocation (ELA) algorithm was developed to achieve this for packaging line 2.

The ELA algorithm concentrates on the total loss of production time of the core machine of packaging line 2: the filling machine. As mentioned above, this loss is almost equal to the loss of efficiency. The loss of production time is allocated to the machines of the packaging line.

The algorithm works as follows. For each buffer the fill level is monitored, and if the fill level differs from than the nominal fill level the cause(s) of this difference are recorded. This is done in discrete time steps: for all events of the machine before and the machine after the buffer. When loss of production has occurred this is allocated to the causes that have been recorded at that moment.

The fill level of a buffer is a function in time. The buffer fill level at a certain moment can be viewed as a bar with a height equal to the number of units in the buffer. If this bar differs from the nominal height (corresponding with the nominal fill level) the causes are shown in bar segments (figure 21).
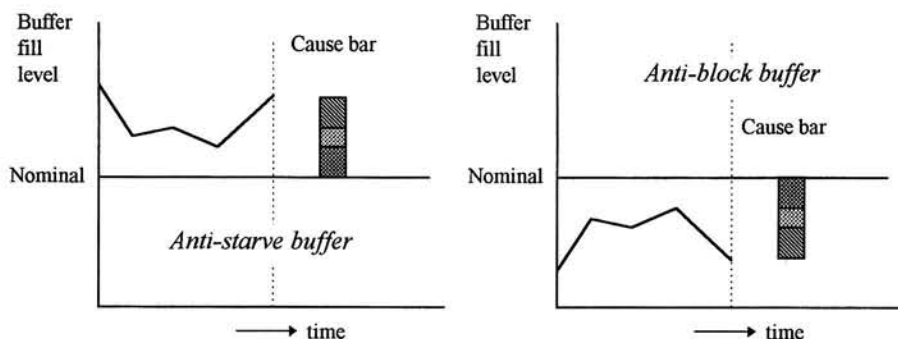

Figure 21: Buffer contents and cause bars for anti-starve and anti-block buffer

For an anti-starve buffer all causes of the buffer fill level below the nominal fill level are recorded (as more than nominal is OK); for an anti-block buffer the causes of the buffer fill level above the nominal fill level are recorded (as less than nominal is OK). The so-called 'cause bar' consists of the bar segments of the causes for the fill level above or below nominal.

At the end of each machine event that is relevant for the buffer (i.e. the union of start and end times of the events of the machine before and the machine after the buffer) this cause bar is updated: adding or increasing a cause, rescaling, or emptying the cause bar. The buffer fill level changes because of the differences in speed of the machine before and the machine after the buffer: the total change is the integral over time of this speed difference.

A loss of production time is allocated to the present causes in the cause bar at the end time of a loss event (i.e. machine stop or machine speed lower than nominal). This allocation is propagated until the core machine (the filling machine). For instance the backup of the labelling machine is allocated to the packer and palletiser, then the backup at the pasteuriser caused by the backup of the labelling machine is also allocated to the packer and palletiser, and again for a backup of the filling machine caused by this backup of the pasteuriser. This is called *cause propagation*. The total allocation of production loss at the filling machine is listed.

The cause bar consists of the fill level of the buffer above or below the nominal fill level with a bar segment for each cause. When the fill level remains between the nominal fill level and the fill level at loss of production (machine stop or loss of speed), the cause bar corresponds to the extra or lower fill level. When the machine before or after the buffer gets blocked or starved and the directly responsible cause continues, somehow the cause bar of that cause has to be increased (otherwise the cause would not be weighted fairly*). This is done with a *virtual fill level*. The bar segment of the cause is then increased (or decreased) with a segment of the extra units that are virtually put on or removed from the buffer during event, equal to the backup of starvation time within the event multiplied by the nominal machine capacity of the stopped machine. The virtual fill level is then higher than the real fill level. When the fill level decreases (in the case of backup) or increases (in the case of starvation) the virtual fill level is rescaled to the real fill level. The cause bar segments decrease proportionally. Once the fill level is equal to the nominal fill level, the cause bar is cleared.

Failures remain a cause, until the fill level of the buffer is recovered to the nominal fill level. The list of causes is only as long as the number of machines, yet other causes can be added (e.g. start-up, changeover, lunch break, external downtime etc.)

The main idea of the algorithm is that the ratio of the causes is constant under rescaling. This allows the loss allocation at the end of the events, and is useful in allocating starvation through gaps in the product flow.

Note that there is a difference between the fill level of a buffer and the arrangement of the product on the buffer (e.g. gaps in the product flow). The arrangement of the buffers is, signalled by the sensors on the buffers, as far as possible. Implicitly it is assumed that at the nominal fill level no backup or starvation can occur (as at the nominal fill level no causes are listed).

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* For instance, the bar segment of an event that causes the machine to become blocked and continues would otherwise stay constant, with the virtual fill level the segment is proportionally increased with the event duration. In other words otherwise the last event that causes the machine backup would receive a smaller cause weight.

Goal

The ELA is used to allocate the total loss of production time of the core machine (i.e. the filling machine for packaging line 2) over the period specified, to the machines of the packaging line by monitoring the buffer fill levels. This results in a table of the loss of production time caused by each machine or a pie chart of the total loss of production time with a pie part for each machine (this is called a *Filler Loss Analysis* [19]). By knowing how much production loss each machine causes, the bottleneck of the line can be identified and effort and further analysis can be directed to that machine(s) to improve the line efficiency.

Data

The data needed to run the ELA-algorithm are:

Static data
- for each buffer: the maximum fill level, and the nominal fill level,
- if available: the fill levels at backup, starvation, change of speed of machine before and after the buffer
- for each machine: the machine speeds as set in the control, and the nominal capacity

Dynamic data
- current machine speeds
- buffer fill level of the buffer before and the buffer after the machine at each machine event

Calculation

The steps of the ELA-algorithm are described below:

STEP 0:   INITIALISATION

Start with:
- all buffer empty, then for the buffers before the filler the cause of the lack is 'start-up' and for the buffers after the filler no cause is needed, or
- all buffer at their nominal fill level, or
- all buffers at the current fill level, then the cause for lack or extra fill level is 'initialisation'.

STEP 1:   MONITORING THE FILL LEVEL

The fill level of the buffers is monitored all moments relevant for the buffer and causes are recorded in a list for each buffer.

Time

Let B be a buffer en M1 the machine before B and M2 the machine after B. The machine state events of M1 and M2 are relevant for B. Let $T1_i$ be the end time of event i on machine M1 with i=1,2,3,... (this is also the start time of event i+1); let $T2_j$ be the end time of event j on machine M2 with j=1,2,3,... (this is also the start time of event j+1). Then let S_k be the time of moment k relevant for B, with k=1,2,3,... with S_k= min { (min_i ($T1_i | T1_i > S_{k-1}$), (min_j ($T2_j | T2_j > S_{k-1}$) }where $S_0=T1_0=T2_0=0$, i.e. the start time of the period specified.

Production rates:
v1(t) = speed machine m1 op at time t
v2(t) = speed machine m2 op at time t

$v1^{nom}$ = nominal speed machine m1 at time t
$v2^{nom}$ = nominal speed machine m2 at time t

Fill level:
$FL_B(t)$ = fill level of buffer B at time t [in units], this can be measured, otherwise:

$$FL_B(s_k) = FL_B(s_{k-1}) + \int_{s_{k-1}}^{s_k} \{v1(t) - v2(t)\} \, dt \approx VG_B(s_{k-1}) + \{v1(s_{k-1}) - v2(s_{k-1})\} \times \{s_k - s_{k-1}\}$$

FL^{nom}_B = nominal fill level of buffer B, lower bound (upper bound) of nominal fill level
interval for anti-starve (anti-block) buffer of a chosen value
FL^{min}_B = minimal fill level of buffer B, i.e. at this fill level production loss starts
FL^{max}_B = maximal fill level of buffer B, i.e. at this fill level production loss starts

$VFL_B(t)$ = virtual fill level of buffer B at time t [help variable]
= the true fill level plus the extra fill level for continuing causes

Causes:
For the machines a list is kept of the causes:

$O_m(s_k)$ = cause contribution of machine m for the fill level of the buffer other than
nominal $O_m > 0$ for an anti-block buffer and $O_m < 0$ for an anti-starve buffer.

For all s_k :

1. list is empty, if $FL_B(s_k) > FL_B(s_{k-1})$ for an anti-block buffer $FL_B(s_k) < FL_B(s_{k-1})$ for an
   anti-starve buffer, then put $O_m(s_k) = FL_B(s_k) - FL^{nom}_B$ in the list with m the machine of
   the causing event or in the case of backup of starvation the propagated list of causes.

2. list is not empty and there is a new cause (i.e. $FL_B(s_k) > FL_B(s_{k-1})$ for an anti-block
   buffer and $FL_B(s_k) < FL_B(s_{k-1})$ for an anti-starve buffer), then put $O_m(s_k) = FL_B(s_k) -$
   $FL_B(s_{k-1})$ in the list.

3. a) list is not empty and $FL_B(s_k) < FL_B(s_{k-1})$ for an anti-block buffer,
   for every machine m on the list: $O_m(s_k) = \alpha \cdot O_m(s_{k-1})$ with $\alpha = \{FL_B(s_k) - FL^{nom}_B\} /$
   $\{FL_B(s_{k-1}) - FL^{nom}_B\}|_{\alpha \geq 0}$
   b) list is not empty and $FL_B(s_k) > FL_B(s_{k-1})$ for an anti-starve buffer,
   for every machine m on the list: $O_m(s_k) = \alpha \cdot O_m(s_{k-1})$ with $\alpha = \{FL_B(s_k) - FL^{nom}_B\} /$
   $\{FL_B(s_{k-1}) - FL^{nom}_B\}|_{\alpha \geq 0}$

4. a) $FL_B(s_{k-1}) = FL^{max}_B$ and the event that led to the backup continues, then increase this
   cause with $O_m(s_k) += (s_k - s_{k-1}) \times v1^{nom}$, and calculate the virtual fill level: $VFL_B(s_k) =$
   $FL^{max}_B + O_m(s_k)$
   b) $FL_B(s_{k-1}) = FL^{min}_B$ and then event that led to the starvation continues, then decrease
   this cause with $O_m(s_k) -= (s_k - s_{k-1}) \times v2^{nom}$, and calculate the virtual fill level: $VFL_B(s_k) =$
   $FL^{max}_B - O_m(s_k)$

5. a) if $FL_B(s_k) < FL^{max}_B$ and $VFL_B(s_k) > FL_B(s_k)$ then scale the causes by a factor
$\quad\quad \alpha=\{FL_B(s_k)-FL^{nom}_B\} / \{VFL_B(s_k) - FL^{nom}_B\}|_{\alpha \geq 0}$
b) if $FL_B(s_k) > FL^{min}_B$ and $VFL_B(s_k) < FL_B(s_k)$ then scale the causes by a factor
$\quad\quad \alpha=\{FL_B(s_k)-FL^{nom}_B\} / \{VFL_B(s_k) - FL^{nom}_B\}|_{\alpha \geq 0}$

So, at each time s_k the list of causes is known (or empty)

If $FL_B(s_k)= FL^{max}_B$ or $FL_B(s_k)= FL^{min}_B$ and recovery starts then allocate the loss to the causes: STEP 2, else STEP 1.

STEP 2:   LOSS ALLOCATION

Production loss is allocated to the causes at the end of the production loss event.

Allocation:
A list is kept of the total loss a machine has causes:
$S_m(t)$ = total loss allocated to machine m at time t, $S_m(0) =0$

Allocation:
For all causes in the relevant list at time s_k increase the allocation for back-up and decrease the allocation for starvation:

$S_m(s_k)= S_m(s_k) +$ production loss $\times O_m(s_k)/\Sigma_m O_m(s_k)$

with: production loss $= V^{nom} \times (t_i - t_{i-1})$ machine stop
$\quad\quad\quad\quad\quad\quad\quad + (V^{nom} - V(t_{i-1}))\times (t_i - t_{i-1})$ loss of speed before stop
$\quad\quad\quad\quad\quad\quad\quad + (V^{nom} - V(t_{i+1}))\times (t_{i+1} - t_i)$ loss of speed after stop

So, the production loss is allocated to the causes in the list at the end of the loss event.

Example
The ELA-algorithm results in a clear and useful table (table 4) or pie chart (figure 22) of the production loss.

Machine	Production loss (min)	%
Depalletiser	9	18%
Rinser/Filler	18	36%
Pasteuriser	1	2%
Labelling	10	20%
Packing	4	8%
Carton street	6	12%
Palletiser	2	4%
Total	50	100%

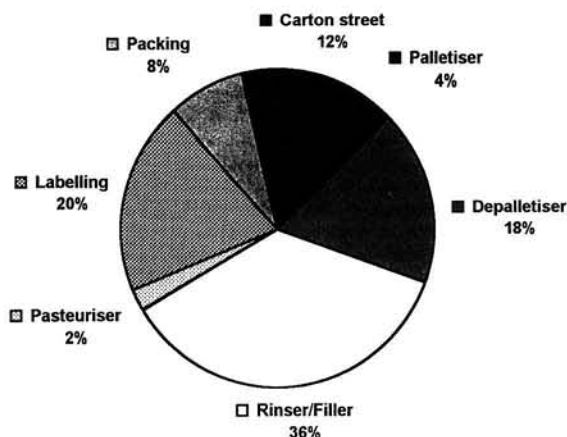*Table 4: Output table ELA algorithm*

Figure 22: Output pie-chart ELA-algorithm

Use
The ELA algorithm is both useful from a more theoretical point of view, for instance in simulation studies when all parameters can be controlled, and useful from a practical point of view, i.e. if the resulting table and/or pie chart are available every shift. The loss allocation gives on overview of the influence of each machine on the line efficiency. The influence of changes in machine behaviour can be expressed in hard figures. It improves the experience based estimates that are being made about the causes of efficiency loss.

Remarks
- The algorithm is very logical: using the buffer contents to track the causes of efficiency loss seems obvious, and all the dynamic data that is needed can be collected. However, the nominal fill level plays an important role is not easy to determine, and also the cause weight created using the virtual fill level is not totally apparent. Also for packaging lines with parallel components the algorithm has to be adapted
- in the algorithm the nominal speed is used, because the loss of production is with respect to the filler and the real speed at which the machine would have run at is very hard to determine.
- the resulting table is called an Filler Loss Analysis [19] table, using buffer efficiencies an approximation of this table can be calculated*. Allocating the loss of production time of all machines of the line would result in a so-called Lost Time Matrix [23]
- when the cause bar segments are recorded as percentages of the total cause, the virtual fill level is not necessary but the segments are rescaled accordingly.
- the algorithm depends on the nominal fill levels of the buffers. Therefore a sensitivity analysis for these values can be made, by simply choosing and comparing different values for the nominal fill level while using the same data.
- visualisation of the calculations of the algorithm can give insight (for instance the buffer contents, the cause bars, the loss allocation, etc.)

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* For instance first multiply the total stop time of the labeller with the buffer efficiency of the buffer between the pasteuriser and the labeller and then multiply this with the buffer efficiency of the buffer between the filler and the pasteuriser to get the approximation of the efficiency loss cause by the labeller.

CHAPTER 6   SIMULATION

This chapter compares analytical and simulation models and discusses the possibilities of using simulation to analyse the efficiency of packaging lines.

6.1   Mathematical models

A model is a representation of the operation of the system. To the user of a model, it either is a mathematical formula or a computer program which, when supplied with the numerical values of various parameters, will make a numerical prediction of the system performance measures. By changing the values of a parameter the user can gain insight into its influence on the system performance. The model may even enable the optimal values of the parameters to be found (where optimal means that they optimise the performance of the system as described by the model).

Models are intended to support decisions about the system, so there rarely is one model that will support all decisions. The basic approach to modelling [5] involves the following steps:

1. *Identify the issues to be addressed:* ascertain the needs of the user: what is the problem? how will the model be used? when is it needed?
2. *Learn about the system:* identify the performance measures of interest to the user, characterise the relevant aspects of the components and key parameters of the system.
3. *Choose a modelling approach:* use simulation or analytical models, do models already exist?
4. *Develop and test the model:* obtain data on the parameters of the model, make 'reasonable' assumptions.
5. *Verify and validate the model:* check the model for internal consistency (verification), and assess the accuracy of the results (validation).
6. *Develop a model interface for the user:* ensure that the user can actually use the model and convince the user of the value of the model.
7. *Experiment with the model:* develop an understanding of the factors influencing the performance of the system.
8. *Present the results:* give recommendations based on the model results, explain the possibilities and limitations of the model, promote the model.

There are two types of mathematical models: *simulation* models and *analytical* models. Simulation models represent the events that could occur as the system operates by a sequence of steps in a computer program. The logical relationships that exist between events must be known. The probabilistic nature of many events, such as machine failures, are represented by sampling from a distribution representing the pattern of occurrence of the event. Simulation studies are time consuming but can handle even very complex system models.

Analytical models describe the system using mathematical relationships. These are used to derive a formula or procedure by which the performance measures of the system can be calculated. This type of model often relies on the presence of an elegant mathematical structure. Analytical models are easy to use and provide insights into what determines the system behaviour. However, often further assumptions have to be made with respect to the relationships of the model. This resulting model is then approximate rather than exact.

In developing a model there are a number of considerations:
- *complexity versus simplicity:* decide how much data to represent; more detail is likely to better resemble the reality, yet requires more time and is harder to verify and validate. On the other hand a simple model may not represent the system adequately. Simulation models can be used for whatever level of complexity is desired. Analytical models are quite limited in the complexity of the system they can describe, and although approximate models can handle larger systems, these models are difficult to verify.
- *flexibility:* both the system and the decision making about the system evolve over time, this means that the model should permit changes in the system modelled (ranging from changes of the parameter values to changes of the system structure). For both simulation models and analytical models it is easy to change the parameter values. Simulation models can often be easily adapted to analyse related system structures, whereas changes in the system structure often require a totally new analytic model.
- *data requirements:* in general the data mainly determine the value of the model, often the data available is not in the form required by the model, the data collection, applicability of the data, sensitivity assessment of the model to errors in the data are important aspects. Most analytical models require far less data than simulation models.
- *transparency:* in order for the model to be accepted by the users, the model assumptions and procedures must be reasonably transparent to others beside the model developer(s), this often requires understandable documentation. Simulation models are often written in specially developed simulation code, which is only transparent to a programmer. However, the logic of the simulation model can be described to the user. Analytical models are usually transparent to those who have the appropriate mathematical skills.
- *efficiency:* models can consume significant resources, both in their development and in their use. The effort required to develop a simulation model is more predictable than the effort needed to arrive at an analytical model. Analytical models generally do not require much time to use to get results. Simulation models require substantial time, especially when changes in parameter values are to be explored.
- *user interface:* a user interface is essential to enable correct use of the model, both with respect to the required input and the interpretation of the results. Simulation models often have a visual and interactive interface, which shows an animation* of the operation of the system. This can be very valuable both in developing and using the model. The interface of analytical model is mostly restricted to input and output screens.

Effective modelling of systems often require both analytical and simulation models. Analytical approximations are often tested with simulation models, and simulation models are validated by looking at extreme cases, where the system performance can be easily predicted with analytical models (for instance when it is assumed that machines never fail). As mentioned in paragraph 5.1, analytical models exist for the extreme cases of packaging lines without buffers and packaging line with infinite buffers.

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* Simulation and animation can also be used in training operators

6.2 Packaging line models

To analyse the efficiency of packaging lines both simulation and analytical model can be used.

6.2.1 Analytical models

Due to the complexity of packaging lines analytical models are rare. The complexity is caused by the relatively large number of machines of a packaging line and the presence of buffers. The functioning of these buffers generates the probabilistic interference of the machines, each having their own capacities, speeds and failure behaviour. Also the characteristics of a packaging lines like the V-graph machine capacities, and the transport function of conveyors/buffers are usually hard to incorporate into these models.

In the literature of manufacturing systems like flow lines and automatic transfer lines only exact models for two machines are to be found. For models of three or more machines only some scarcely applicable approximations are known, because many extra assumptions have to be made. However, the general idea behind some of these analytical models or procedures can be helpful. For instance from the point of view of a buffer the line consists of just two machines. Also integrating several machines into one is an effective simplification [9].

If exponential distributions for the failure behaviour of the machines are assumed, markov chain models can be formulated for these manufacturing systems, yet the number of states is too large* to solve the model [4].

6.2.2 Simulation models

Simulation of packaging lines can be performed on several detail levels, ranging from global and simplified simulation models to simulation models that consider the forces exercised on each bottle.

Simulation is often used when the problem or model definition is too complex to be solved by an analytic method. Appendix C presents a simple simulation model that was used to estimate the expected line efficiency of packaging line 2. This model only takes into account the machine capacities, the buffer capacities and the MTTR and MTBF of the machines.

Simulation represents the movement of bottles, cans, cases, pallets or people through a set of relationships. These pieces are referred to as the entities of the system. There are basically two types of simulation: discrete event and continuous simulation. These terms relate to how the entities move through the system. *Discrete event* simulation occurs when the dependent system variables change discretely at specified points in simulated time, referred to as 'event times'. For instance, modelling the arrival of beer bottles at a filler is a discrete event simulation because there is a specific event when each bottle reaches the filler and the model is updated at the time of each of these events. In a *continuous* simulation model, the state of the system is represented by dependent variables that change continuously over time. For instance, the transfer of beer from one tank to another is a continuous process and is modelled as a continuous function over time. Simulation of packaging lines to analyse the line efficiency involves discrete event simulation of the production units of the packaging line.

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* The number of states of a markov chain model is determined by the number of states of each machines (running, failed, etc.) and the number of states of each buffer (the number of units in the buffer, ranging from zero to a few thousand). For a simplified version of one street of packaging line 2 consisting of 6 machines and 5 buffers the number of states is already of the order 10^{20}.

The advantages of simulation are:

- *understanding and learning:* the construction and use of a simulation model will provide understanding of the operation of the entire packaging line system; also the influence of the line parameters is learned
- *timing:* new policies and procedures can be tested on the model before use on the real system, or a new machine can be evaluated for its applicability and its effect on the rest of the packaging line before it is even ordered
- *troubleshooting:* process bottlenecks, often not readily obvious, of the packaging line can be identified
- *experimentation:* new situations and solutions can be tried without risk, i.e. without the costs of actually implementing the proposed change, and without disturbing the real packaging line

The disadvantages of simulation are:

- *specialised skills:* there is need for specialised skills to analyse the problem and build the models; these skills involve knowledge of probability theory, statistics and programming or the simulation software[*]
- *interpretation:* simulations deal with random data and thus the output must be interpreted with care; for instance confidence intervals should be constructed and sufficient simulation runs should be generated
- *costs:* simulation is time consuming; the benefits form the simulation should cover the costs to construct and exercise the model; note that the costs of simulation decreases as more simulation models are built, i.e. as experience increases

To ensure the success of a simulation study there are three necessary conditions:

- there must be a stakeholder who knows what the target problem is, and can determine what will constitute a solution to the problem. This person or group must be in a position to assign resources for the analysis of the problem and the development of the simulation model. Also they must have the capability of implementing the results of the simulation. This condition is often called *management commitment.*
- there must be the resources for analysis of the input data to the system model. This is a time consuming and time sensitive task, because the data must be fresh and relevant for the model to have any validity
- there must be the expertise to construct and exercise the model, and provide analysis of the output of the model in the form of recommendations for the stakeholder

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[*] Specialised simulation software developed for packaging lines is available, e.g. Pritsker Packaging Lines ® [12]

6.2.3 Simulation modelling process

The simulation modelling process involves the following steps:

1. *Problem formulation:* Defining the problem solving objective
2. *Model building:* Abstracting the system into mathematical/logical relationships in accordance with the problem formulation and preparing a computer model
3. *Data acquisition:* Identifying, specifying and collecting data
4. *Verification:* Establishing that the computer model executes as intended
5. *Validation:* Establishing that a desired accuracy or correspondence exists between the simulation model and the real system
6. *Experimentation:* Executing the simulation model to obtain output values
7. *Analysis of results:* Analysing the simulation outputs to draw inferences and make recommendations for problem resolution
8. *Documentation:* Detailed description of the model and its use

Step 1 and 2 lead to a clear problem and model definition, which ensures that only the relevant aspects of the system are modelled. Step 3 is often difficult and time consuming, although with the introduction of Line Monitor Systems (see also chapter 4) more and better data becomes available. Using sensitivity analysis (or what-if analysis) the influence of errors in the data and the assumptions that were made, can be determined. Step 4 and 5 check the applicability of the model. Step 6 and 7 involves the design of experiments and the interpretations of the results. Step 8, finally, secures the knowledge that was obtained and enables reusability of the model and methods.

Simulation models can be developed in a number of ways. One is to try and include all the required detail of the system from the beginning. This tends to result in long development and debugging time and usually makes the resulting code unreadable to all but the developer. Another approach is to develop models of system components and, after each component model has been debugged, tested and validated, link the components two at a time, test and validate, then three at a time, test and validate, and so on. Ideally this results in a library of simulation models of various components and subsystems, and of various detail level. This approach is called the *micro-macro approach* and is useful in developing models of large systems and especially valuable in terms of reusability.

In order to evaluate the simulation results of a complex system like a packaging line tools to analyse the results/data are needed, i.e. methods to determine the influence of parameters. Suitable tools are the efficiency analysis methods as described in chapter 5. Of course, in simulation studies the parameter values can be controlled and varied and thus more insight can be obtained. However data analysis of the process data of existing packaging lines is a essential step before simulation models are constructed. The ultimate model validation is to use the individual machine events of a packaging line (as recorded by the Line Monitor System), and the actual control of the line (as programmed in the PLCs of the line equipment) as input for the simulation model and compare the system results with the real results. Simulation is particularly useful when the packaging line is just being designed, when changes and improvements can be made easily and quickly. After the packaging line has been installed, it is of course much more difficult to alter the system features.

6.2.4 Packaging line simulation use

Simulation is a valuable tool for efficiency analysis of packaging lines and can be used to answer the following questions about packaging lines:

♦ Should a certain machine with a machine efficiency of 87% be replaced by another machine with a machine efficiency of 98%?
♦ What would happen if the maximum speed of a certain machine would be increased by 10%? Or decreased?
♦ Which buffer capacities should be increased to improve the line efficiency?
♦ Should the conveyor speed of a buffer be changed?
♦ What is the expected optimal order sequence to produce a certain set of orders?
♦ Do the benefits of stopping a certain machine every two hours for cleaning and inspection cover the loss of production time during the stops?
♦ How do two or more design alternatives compare?
♦ Should we use two or three parallel machines for a certain stage in the packaging process?
♦ What would happen if the control of a certain conveyor or machine was changed?
♦ How much should a certain machine be improved (e.g. increase MTBF, or decrease MTTR) to improve the line efficiency?
♦ What is the influence of the value of certain line parameters on the line efficiency?[*]
♦ What is the maximum or expected productivity of a certain packaging line?
♦ What is the effect of lunch breaks on efficiency?
♦ etc.

Simulation is a powerful tool to analyse complex models, when analytical models cannot supply the solution. Although process data analysis of packaging lines is indispensable for process control and often leads to improvements of the line efficiency, many questions can only be answered using simulation.

Short term simulation involves creating quick and less detailed models that can be used to get a quick impression, e.g. to upgrade a packaging line. Long term simulation involves creating a simulation model during the design of the packaging line, and using this model throughout the life of the line.

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[*] Perturbation analysis may be a useful method to enhance the value of simulation studies

CHAPTER 7   RESULTS

This chapter briefly describes the results of implementing the efficiency analysis on packaging line 2.

On packaging line 2 a pilot system was implemented for the process registration and efficiency analysis of line 2. This pilot project was called RVC2 ('RendementsVerklaring Colonne 2'). It involved PLC-programming, visualisation, spreadsheet calculations and database applications.

First the line logic of packaging line 2 was constructed [16]. This formed the base for the basis registration [24]. The static data were mostly measured and collected manually. And the dynamic data events were collected and visualised on the Line Monitor System and stored in a database. These data were analysed using spreadsheets and also a database application was built. This application featured most of the analysis methods described in chapter 5. Overall this first phase required more effort than expected, because some technical problems had to be mastered. Especially the PLC reprogramming required a lot of time. But also creating a stable data collection process proved to be difficult.

It was a deliberate choice to keep the first phase simple. Thus only the machine states were recorded and for instance no causes were recorded for the machine failures. Although future expansion were considered in the implementation, the goal was to create a bounded but functioning system.

The efficiency analysis with this pilot system led to some small improvements. It was noted that the infeed of some machines was not optimal, because there were many very short lack of input events on these machines. Also it was found that one machine had many short failures. On the whole the opinion was formed that short failures (less than one minute) may have a big influence on the line efficiency, whereas previously the focus was on long failures only. Also suppliers of machines were informed about the performance of their machines.

Next the data collection was expanded to enable the implementation of the ELA algorithm. This algorithm was only partly implemented, just far enough to prove that the ELA algorithm works. The Visual Basic application is called Revecon2 [24].

Also the visualisation was expanded with figures of machine speeds and buffer contents (figure 11). These showed a very volatile behaviour of some of the machines. Studying the line logic around these machines, some inconsistencies in the control were found. After these flaws were corrected, a more smooth production resulted.

Finally the data collections was also used for a study of the energy use of the pasteuriser, a simple simulation study of line 2 (see appendix C) and a more detailed simulation study. Also many questions were directed to the project team, for instance about data collection for machine acceptance tests, data on the difference in machine behaviour between boxes with six-packs, and boxes with an interior partition, losses of packaging material, machine speeds, etc.

The technical aspect of the RVC2 project are described in [16] and [24].

The results of the project are of course the definitions and the mathematical methods of the framework for efficiency analysis. This gives insight of what data is to be collected, and what can and should be done with data. This knowledge can be useful in installing or improving Line Monitor Systems on other packaging lines, and also help improve the efficiency of these packaging lines.

Some improvements were made on packaging line 2 with the help of the pilot system. Especially signals/symptoms/patterns that are not usually noticed were helpful, because longer periods (hours, days) can be viewed/scanned and analysed in minutes. Short stops of only a few seconds are normally not recorded but form a large part of the total number of stops. Also the line logic and the trends of the machine speeds and buffer contents have proved to be useful.

Unfortunately the efficiency analysis is not yet performed on a regular basis. Also the combination of automatic and manual data has not been achieved. However, it was found that there certainly is a need for data, are rather a need for tools to transform this data into information. The framework for efficiency analysis as described in this report and implemented on packaging line 2 is a step in the right direction.

CHAPTER 8   CONCLUSIONS

This report presents a framework for the efficiency analysis of packaging lines. To improve the efficiency of packaging lines information is needed. The framework describes how this information can be gathered from the process data.

Data gathering is not a goal by itself, but should support and improve the process control and decision making on packaging lines. Technically there are few limitations for data registration of the packaging process. However, the data registration system should be built with a vision or an expectation of the use of the data and a functional specification of the possibilities and features of the information system. In this respect much can be learned from the history and use of existing information systems, for instance the benefits, problems, errors of the system, etc.

In general, the information system must be based on a well thought-out data model and a set of sound definitions. The line logic provides the definitions of the machine and buffer states and thus forms a base for the data collection. It is probably best to built an information system stepwise, i.e. start with a basis registration and expand it step by step. For each step this results in a functioning system, and also some sort of cost/benefit decision can be made for each expansion. Visualisation is also an important part of the system, because it makes the data readily accessible.

Data analysis of the process data should not be time consuming but supported by easy to use tools. This means that the information system should have data analysis tools. Data acquisition has no value without knowing what can and must be done with the data (i.e. data analysis). On the other hand, data analysis has no value if it is not based on good process data.

The framework presented in this report is the missing link to transform the process data into useful information for efficiency analysis. This is achieved by constructing comprehensible graphs and calculating easy to use performance indicators for the machines and buffers separately, and for the line as a whole.

Simulation can also be a valuable tool for efficiency analysis, because simulation can help answer a range of questions that cannot be answered using data analysis. However, simulation should always be preceded by data analysis, not only because the collected data forms the input of the model, but also because data analysis can lead to valuable insights that are easier to achieve and more directly applicable. In simulation studies the level of detail should gradually be increased, depending of course on how much detail is required.

The success of efficiency analysis depends on the ease with which it can be performed, this means that tools should be available and standard reports should be generated quickly. Next to the technical implementation, also the organisational implementation is a crucial factor for the success of efficiency analysis. This entails training, maintenance of the information system and of the system environment, and making efficiency analysis an integrated task of those involved with the packaging line.

Especially the machine operators should be directly involved in the efficiency analysis. They probably have the most time to perform efficiency analysis, but lack the skills. Therefore the data analyst should support them in developing these skills and in creating the tools that facilitate the analysis.

Although, there is definitely much interest for the analysis of process data, it is not obvious which actions can and should be taken as a result. Yet, it is expected that by collecting and comparing information on the different packaging lines, efficiency analysis can be a powerful tool in helping Heineken to achieve its objective of cost leadership.

Because of this interest and potential for efficiency analysis, further research on and implementation of efficiency analysis systems is needed, in which both the technical and organisational aspects must be considered. The emphasis should be on using information systems and actually performing efficiency analysis, in other words: *learning by using*.

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Summary

This report presents a framework for the efficiency analysis of packaging lines. The framework consists of a set of clear definitions and the description of various mathematical methods to create comprehensible graphs and easy to use performance indicators.

The developments in information technology enable the installation of so-called line monitor systems on packaging lines. Technically these systems can collect almost every piece of data of these lines. In this report this data acquisition process is briefly discussed. It is emphasised that data collection is not a goal by itself, but should support and improve the process control of the packaging lines. The control of packaging line equipment can be described using the line logic.

At Heineken a lot of data is collected on some of the packaging lines, but unfortunately at present this data is not being used. This is simply because the appropriate tools to analyse the data are not available.

The framework presented in this report provides the missing link to transform the process data into useful information. This is done by constructing comprehensible graphs and calculating easy to use performance indicators for the machines and buffers separately, and for the packaging line as a whole. The ultimate efficiency analysis tool is the so-called Efficiency Loss Allocation algorithm, which allocates the efficiency loss to the machines of a packaging line. Using this algorithm the bottleneck machine of the line can be identified directly.

The efficiency analysis tools described in this report have been implemented in a pilot system on packaging line 2 of the Heineken Brewery in Zoeterwoude. This system has helped in improving the efficiency of this line.

The value of line monitor systems is determined by the tools and features the system offers. Therefore the efficiency analysis tools of this report should be incorporated in new and existing line monitor systems. Efficiency analysis of packaging lines can thus be made easier, more familiar and comparable, and become an integrated task of the users of those involved with the packaging line.

Another valuable tool for efficiency analysis is simulation. The possibilities of simulation are discussed and a simple example of a simulation study of packaging line 2 is given. Simulation uses the process data collected by the line monitor system. For the analysis of simulation results the same efficiency analysis tools should be applied as for the actual process data of packaging lines.

APPENDIX A: LINE LOGIC

The line logic is a description of the conditions of the states of the machine of a packaging line. It can be presented as a figure of each machine and its surrounding conveyors and a logical table of the state conditions or the state conditions are depicted. Basically it is a description of the control of the machines by the signals of the sensors on the preceding and succeeding conveyors.

It is an important tool that gives insight into how the machines of a packaging line react on the population of product on the buffer. Collecting the data for the line logic can lead to changing the control of the machine, because the control is not optimal. For the operator it is also useful to know the line logic of the machines of his working area. The definition of the states of the machines in the line logic is the definition of registration of the machine states by the line monitor system. (see also [16])

Example
Figure 23 shows an example of the line logic of a certain machine. The sensors S1, S2,..., S6 are used to control the speed of the machine. The sensor signals are: 'free' and 'not free'. The speed conditions are given in three ways: textual description, summary table, and using figures (figure 24).
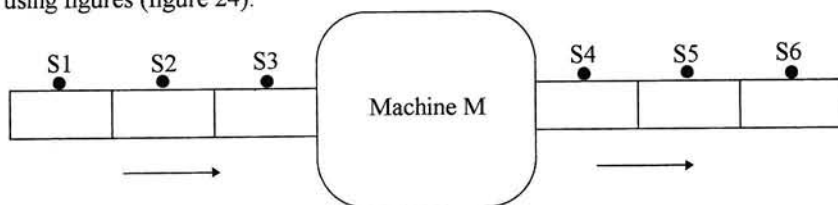

Figure 23: Line logic machine M

Text
Machine M can be in one of the following 5 states:
- High speed, if S1 and S2 are not free for 15 sec. and not starved or blocked
- Normal speed, if not blocked, starved, high speed or low speed.
- Low speed, if S2 is 20 sec. free and not starved or blocked.
- Blocked, if S4 is not free
- Starved, if S3 is free

Table

Sensor Time	S2 free 20sec	S1 not free 15sec	S2 not free 15sec	S3 free	S4 not free
High speed		True	True	False	False
Normal speed*	False			False	False
Low speed	True			False	False
Blocked					True
Starved				True	

---
* Normal speed is the machine state if no other machine state conditions are satisfied
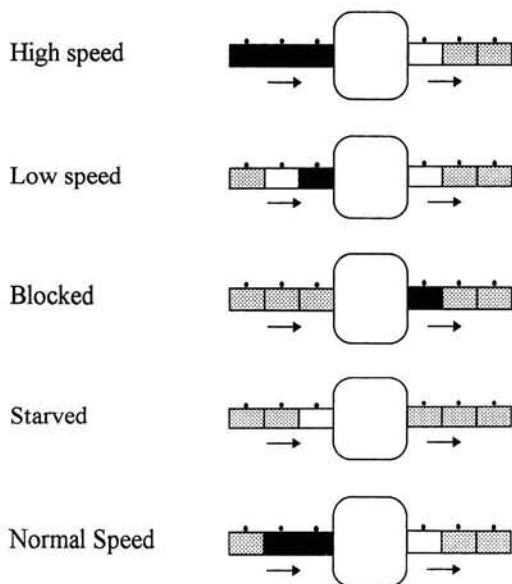
71

Figure 24: Graphical state representation

The advantage of the graphical method is that possible state transitions can easily be seen; the disadvantage is of course that the time restrictions of the state conditions are less clear.

APPENDIX B: BASIS REGISTRATION

Technically almost everything can be recorded. But the question is what is done with this data, or why the data should be collected. The data acquisition or information system should be flexible and configurable, have a consistent and user friendly graphical user interface (GUI), be stepwise expandable and based on clear definitions.

The basis registration is the specification of the first step of the data acquisition as implemented on packaging line 2. It gives an impression of the data that should be collected as a first step for the efficiency analysis of packaging lines (see also [24]).

Static data
The following static data must be collected after each change and checked every month:
- machine capacities (for each product type)
- machine state definitions as determined in the line logic

Dynamic data
The following dynamic data must be collected when the packaging line is used for production:
- start and end time of every machine state event: running, failure, starved, blocked, not in use; for blocked and starved the corresponding material should be recorded (e.g. starved for bottles, blocked for pallets, etc.)*

Essentially only the machine state is recorded. This should also be visualised on the line monitor system, so the registration can be easily verified.

Expansions

Once the basis registration is implemented, the data acquisition and visualisation can be expanded, for several analysis and operation purposes:
- failure reason for each machine failure
- division between internal and external machine failures
- partition of the state running in separate states for each speed (e.g. running at high speed, etc.)
- measurement of the machine speeds, both the specified speed and the actual speed
- counting the number of produced units for each machine
- counting the number of products on each buffer
- counting the rejects, and recording the reasons for rejects
- production planning and reality
- etc.

These expansions allow further analysis by detecting relations between quantities and also can help to achieve a better process control.

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* A machine can be in only one state (see also chapter 4)

Recommendations

Some recommendations in implementing a Line Monitor System (LMS) to perform efficiency analysis are:

- construct a functional specification before implementing a LMS
- create a stable technical environment
- consider the organisational implementation
- build the system step by step
- try to make information technology decisions based on cost/benefit analysis
- emphasise aspects like easy to use analysis tools, user friendliness, intuitive graphical user interface, and flexibility
- combine automatic and manual data, especially record planned downtime, incidents and exceptions
- implement the LMS before the packaging line is taken in use, so the process data is available in the line acceptance test
- etc.

APPENDIX C: SIMULATION USING UNICORN

This appendix describes a simple simulation model for series models of packaging lines, that was developed by professor Roger Cooke of the Delft University of Technology. Only indicative conclusions may be drawn from this simulation model.

First the software package Unicorn is described, then the mathematical model is formulated. Finally an example is given of an application of the simulation model on packaging line 2.

C.1   Unicorn

Unicorn[*] is computer program for performing uncertainty analysis on moderately sized problems [6]. The program is mainly designed to facilitate experimentation with small to medium sized problems so as to gain insight into the probabilistic behaviour of real mathematical models.

C.2   Mathematical model

A packaging line is modelled as a continuous production line with buffers, constant production rates, discrete time and stochastic availability. The model is explained below with six machines and five buffers:

Figure 25: Representation of a six-machine packaging line

Let v_i be the production rate of machine i, i=1,...,6; i.e. v_i units can be processed in one time step. Now b_j is the actual amount in buffer i, i=1,...,5 at time δ; the dependence on δ will be suppressed in the notation. And k_i is the maximal amount in buffer i. At the first time step, b_i=0. For every time: $0 \le b_i \le k_i$, i=1,...,5.

The time δ is chosen such that the maximal amount moved in one time step, v_i, i=1,...,6; is at most one half of the buffer size k_j, j=1,...,5.

A variable x_i is introduced as a state indicator for machine i, such that at each time step:

$$x_i = \begin{cases} 1 \text{ if machine i is available} \\ 0 \text{ if machine i is not available} \end{cases} \quad i=1,...,6$$

At the first time step we assume every machine is working. Further, we introduce for each time step the throughput for machine j:

th_j = number of units moved from j-1 to j

We use the notation PREV(z) to indicate the value of z in the previous time step, where z may be any of the above variables.

Mass balance equations
The mass balance equations may then be written as:

$$\Delta OUT = \min\{v_6 * x_6, PREV(b_5)\}$$

$$b_5 = \min\{k_5, PREV(b_5) - \Delta OUT + \min\{v_5 * x_5, PREV(b_4)\}\}$$

$$b_4 = \min\{k_4, PREV(b_4) - th_5 + \min\{v_4 * x_4, PREV(b_3)\}\}$$

...

$$b_1 = \min\{k_1, PREV(b_1) - th_2 + v_1 * x_1\}$$

The throughput quantities can be expressed as:

$$th_5 = b_5 - (PREV(b_5) - \Delta OUT)$$

$$th_4 = b_4 - (PREV(b_4) - th_5)$$

...

$$th_1 = b_1 - (PREV(b_1) - th_2)$$

It will be observed that b_i can be computed on the basis of x_i, b_{i+1},..., b_5 and the previous values of the buffers.

Availability
We assume that the up- and down-events for machine i can be modelled as independent failure and repair distributions. We use a discrete version of the exponential distribution, so that events which happen during a time step are modelled as if they occurred at the end of the time step. Thus, if machine i is down at the beginning of the previous time step, the probability of it being up at the beginning of the current time step is: $1 - e^{\mu_i}$, where μ_i is the repair rate for machine i. If machine i is up at the beginning of the previous time step, the probability of it being up at the beginning of the current time step is: $e^{-\lambda_i}$, where λ_i is the failure rate for machine i. The time step must be chosen such that the probability of a failure-and-repair in one time step in negligible.

Let U_i be uniformly distributed on [0,1]; then setting:

$$x_i = \begin{cases} 1 \text{ if } PREV(x_i) = 1 \text{ and } U_i \le e^{-\lambda_i} \\ 1 \text{ if } PREV(x_i) = 1 \text{ and } U_i \le 1 - e^{-\mu_i} \\ 0 \text{ otherwise} \end{cases}$$

we have that x_i has the required distribution; the periods in which $x_i=1$ contiguously approximately follow an exponential distribution with 'failure rate' λ_i, and the periods when $x_i=0$ contiguously approximately follow an exponential distribution with 'repair rate' μ_i^*.

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* In the implementation the U_i are chosen as independent, but there is no mathematical necessity for this.

The availability of x_i is the probability that $x_i=1$. In general this is a function of time and depends on the initial state of x_i when time begins. However, for large time values the initial state is 'forgotten' and the 'equilibrium availability' of x_i is found by setting $P(x_i=1)=P(PREV(x_i)=1)$ in:

$$P(x_i=1)=P(x_i=1|PREV(x_i)=1))P(PREV(x_i)=1)+ P(x_i=1|PREV(x_i)=0))P(PREV(x_i)=0)$$

The result[*] is:

$$P(x_i=1)=(1-e^{-\mu i})/(1-e^{-\lambda i}+1-e^{-\mu i})$$

Output variables
The following variables are evaluated at each time step:

TIME is the cumulative elapsed time up to the time step
ΔOUT is the increment in output for that time step
OUT is the cumulative output up to that time step
RATE is OUT/TIME

What the model does not describe
The model does not describe variations in production rate within each time step. Nor does it model the processing time for each machine. The pasteuriser for example requires about 45min to process the bottles. Once the pasteuriser is full, of course, bottles enter and leave at the same rate and the processing time is effectively zero. However, following each product change and buffer drainage, 45 min will be consumed in simply filling the pasteuriser.

The model can accommodate dependencies between machine unavailabilities, One might anticipate that unavailabilities of adjacent machines would be negatively correlated, since machines will not fail while they are starved or blocked due to the unavailability of a neighbour. Further one would expect such negative dependence to be strongest immediately following a buffer evacuation and to decrease in strength as buffer contents increase. The model, however cannot handle temporal behaviour of correlation, it can only replicate average correlation over time.

Further, the model assumes that for each machine the failure and repair processes are independent and exponential. This assumption could be relaxed.

Zero- and Infinite-buffer limits
The performance of the line can be theoretically bounded by the zero-buffer and the infinite-buffer limits.
    With zero buffers, the line behaves as a series system: the failure of one machine brings the entire line down, and the availability of the line is the product of the individual availabilities. This assumes that the machines can fail independently; in particular it assumes that one machine can fail while another is down. The rate of the line when all machines are up is the rate of the slowest machine.

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[*] The commonly used formula $\mu_i/(\mu_i+\lambda_i)$ is approximated for $\mu_i \leq 0.1$ and $\lambda_i \leq 0.1$

With infinite buffers in equilibrium, the effectively slowest machine will never be starved or blocked. Machines upstream and downstream from this machine (we assume that there is a unique effectively slowest machine) produce at an average rate equal to that of the slowest effective rate. They will be starved and blocked from time to time. So, the throughput of the slowest machine is independent of failures of other machines. With infinite buffers, as the line approaches equilibrium, the production rate approaches the slowest effective rate.

When the line is first started with empty buffers, it behaves somewhat like a series system. As soon as one machine is down, the entire line goes down and there is no output. If all machines are up the production rate is equal to the lowest production rate. However, the availability of the system is the product of the availabilities of the individual machines. If these availabilities were at equilibrium, then the expected output per time step is the zero buffer limit. On the other hand, the machines are assumed to start in the up state, whereas the zero buffer limit assumes the initial state has been 'forgotten'.

As a general rule, if the buffers are large enough to make the line behave like the infinite buffer line at equilibrium, then we could improve the machine with the slowest effective rate by increasing its speed, increasing its MTBF, or decreasing its MTTR, and these improvements translate directly to the line. However, improvements beyond the next slowest effective rate would not pay off in higher production. This general rule does not hold if the line does not reach equilibrium, or if the equilibrium is not the infinite buffer equilibrium.

C.3   Example

The simulation model can be used to determine the maximum productivity of a series packaging line, like packaging line 2. This paragraph describes how this is done, however no real data are shown here.

First the notion of maximum productivity must be defined. Next, the model parameters are listed, i.e. the line parameters that determine the productivity. Then the parameter values must be estimated, and using these values the model can be validated. Next the zero- and infinite buffer limits for the productivity can be are calculated and the maximum productivity can be estimated with the simulation model. The influence of the values of the model parameters can be shown in so-called high-low diagrams.

Maximum productivity

As a measure for the productivity we use the line efficiency η_{line}, i.e. the percentage of the actual output versus the possible output (see also chapter 3).

We consider the line efficiency that is achieved during normal production. So, changeovers, maintenance, start-up etc. are not considered. This line efficiency is the long term average line efficiency (or equilibrium efficiency), or equivalently the expected line efficiency during normal production. The value of this expected efficiency should be equal to the norm efficiency as specified in the production plan, because disturbances of this efficiency, because of changeover, maintenance, start-up etc., should be incorporated with norm times or lower norm efficiencies. During normal production the real efficiency varies around the expected efficiency.

Line parameters

The expected line efficiency is a stochastic variable, i.e. the value of this variable cannot be predicted with certainty. The line efficiency is a function of the line parameters. We consider the packaging line to be a series system of machines and buffers as shown in figure 26. The line parameters are formed by the machine and buffer parameters.
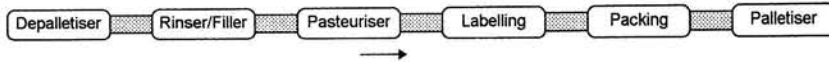
Figuur 26: Series system of machines and buffers

The following machines are considered:
1. *Depalletiser*, where starvation of the depalletiser is also taken into account in the availability, i.e. input problems and failures of the defoil machine are incorporated
2. *Rinser/Filler*
3. *Pasteuriser*, we assume it is full and thus functions just like the other machines
4. *Labelling machine*
5. *Packing machine*, where the packer and closing machine are seen as one machine (because there is no buffer in between) en the starvation of the packer for boxes (i.e. problems of the cartons street) are taken into account in the availability
6. *Palletiser*, where backup of the palletiser is taken into account in the availability, i.e. output problems and failures on the shrink-wrap installation are incorporated.

The values of the line parameters determine the line efficiency. These values have been collected and/or estimated. Static data can be measured or retrieved from the line specification. Dynamic data should be collected in a representative sample.

Machine parameters

The machine parameters we consider are: the machine capacity and the failure behaviour, expressed in MTTR and MTBF. The machine capacity is the maximum machine production rate. These can be shown in a V-graph (see 5.4).

The exact failure behaviour of a machine cannot be determined, because the data is never 100% correct, and because the failure behaviour changes over time. With the available data an average failure behaviour can be estimated for the period specified. We use:

Estimate for the MTTR of a machine: $\dfrac{\text{total time internal failures}}{\text{number of internal failures}}$

Estimate for the MTBF of a machine: $\dfrac{\text{total time} - \text{total time internal failures}}{\text{number of internal failures}}$

Using the individual failures confidence intervals can be constructed in the normal way.

Buffer parameters

We only consider the buffer capacity, i.e. no transport characteristics of the buffers are modelled. The buffer capacity is the maximum number of units in the buffer

Model validation
The above model is validated by using the data of a number of shifts and compare for each shift the true output or efficiency with the output or efficiency that is predicted by the model. A given machine behaviour can lead to different results, i.e. there is a certain spread in the results. Therefore several runs should be made with the model, each with a different random seed. If the true output is in the range of generated outputs the model is good.

The results for the model varied. In general the model predictions are reasonable for such a simple model. Some shifts are the predictions are good, and some shifts they are very bad (especially for shifts with many machine failures). Because of the limitations and assumptions of the model, the results should be interpreted carefully.

Zero- and Infinite buffer limits
For the expected line efficiency two limits can be determines, by considering two extreme cases: the line without buffers will give a lower limit, the line with infinite buffers will give an upper limit. On the line without buffers every machine failure stops the entire line. On the line with infinite buffers the machines function independently. In reality the situation of the line is somewhere between these two extremes.

The limits are defined as follows. The lower limit is the product of the machine availabilities × the minimum of the machine capacities; the upper limit is the minimum of the effective rates (see 5.1).

Simulation
The simulation model described above is used to estimate the expected line efficiency (i.e. the long term rate). The simulations show that it takes some time to reach this expected line efficiency when the line is started with empty buffers. This is probably because the line with empty buffers resembles a line without buffers, and a line in equilibrium is more like a line with infinite buffers.

Influence analysis
To determine the influence of the line parameters on the expected line efficiency so-called high-low graphs are created using simulation. To construct such a graph the line parameters are varied one at a time, taking a high value and a low value. The difference between the expected efficiencies for the high and the low value show how much influence the line parameter has on the expected efficiency. An example is shown in figure 27.
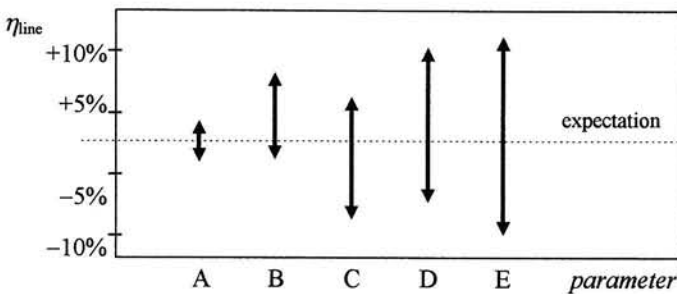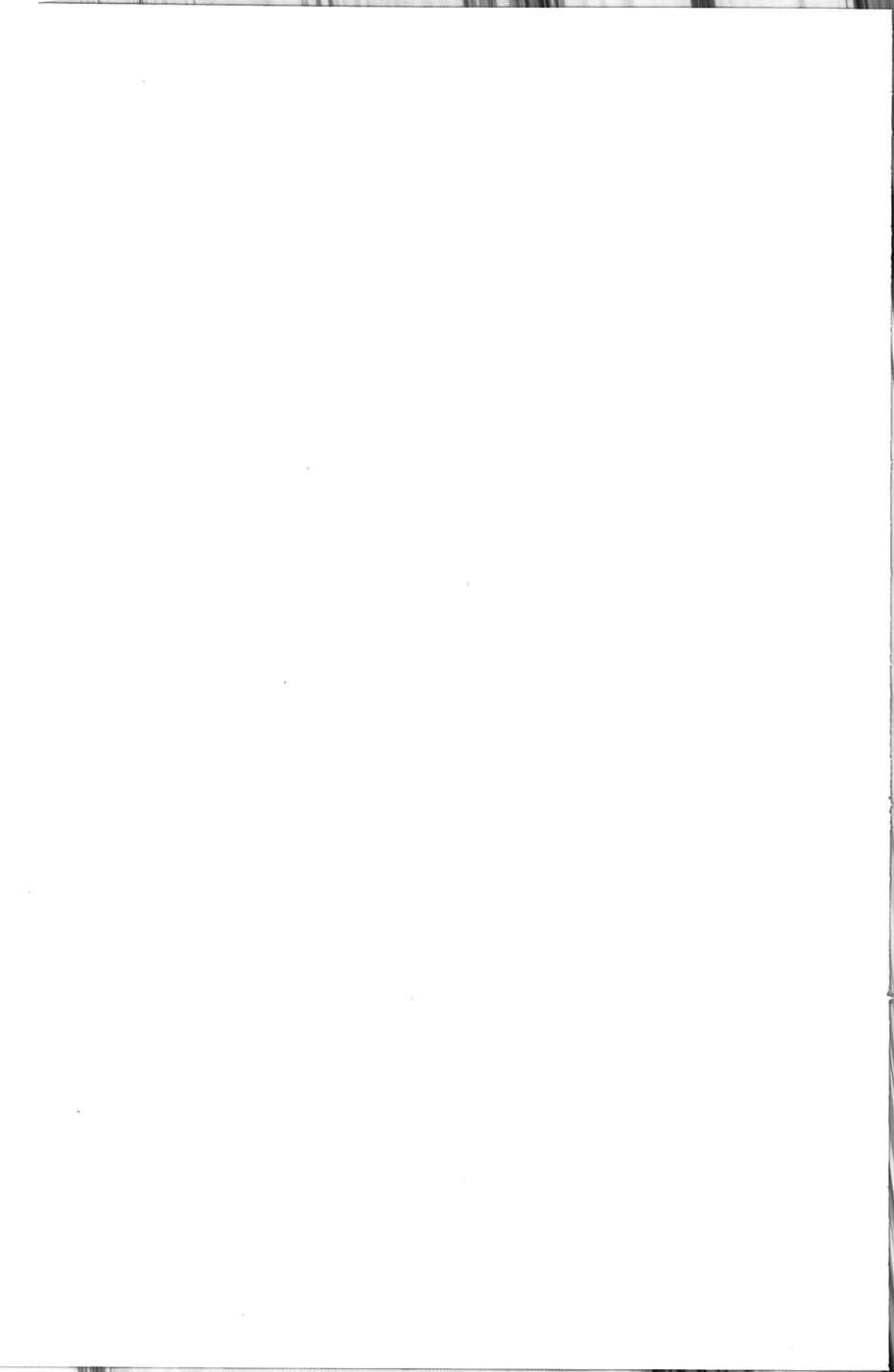

Figure 27: High-low diagram for the line efficiency, with 5 parameters

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