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RAM and buffer analysis of beer filling lines - a case study

Análise RAM e de transportes de linhas de envase de cerveja - um estudo de caso

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Supervisor: Prof Patrícia Fazzio Martins Martinez, PhD

Este exemplar corresponde à versão final da dissertação de mestrado defendida pela aluna Bruna Mancuzo de Almeida e orientada pela Profª. Drª. Patrícia Fazzio Martins Martinez.

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Engenharia - a natureza é engenharia, a cultura também, a ciência está logo atrás, só o caos não é engenheiro.

Elena Ferrante - A filha perdida, p. 45.

Abstract

The bottling process is one of the key steps in a brewery plant. As it is intensive on energy and labor, any process improvement can represent relevant savings. The gaps that can be explored to raise line efficiency are the retrofit of existing filling lines and maintenance improvement. Although the bottling is an established process, the relevant literature in this field tends to focus on macrodowntimes (stops longer than 5 minutes), although microdowntimes are as relevant as them. This gap in the literature occurs mainly due to the scarcity of data. In this context, technologies as Industry 4.0 allow us to study and evaluate microdowntimes for all filling line equipment instead of a single machine. Therefore, in this study, we evaluated microdowntimes of a whole returnable line through the application of a Reliability, Availability, and Maintainability (RAM) analysis, that is commonly applied to macrodowntimes. Moreover, we analyzed unpublished data from three returnable bottle filling lines to suggest easy to use rules of thumb based on buffer analysis, that helps to identify if some line conveyor is negatively contributing to line efficiency. From RAM analysis, we verified that four machines of the evaluated returnable line require reliability improvement actions. It would not have been possible with the analysis of a single piece of equipment, as is often presented in the literature. In addition, we concluded that the suggested rules of thumb can be applied without any additional concerns for similar filling lines. For filling lines with a considerable different layout (as a can line), the rules can still be applied with some restrictions. For further research, we suggest evaluating these rules of thumb on different manufacturing lines, such as can and bottle manufacturing. Moreover, we suggest the investigation of the most frequent failure types and the specific actions to mitigate them.

Key words: filling line, Industry 4.0, reliability, buffer analysis, microdowntime.

Resumo

O processo de envase é uma das etapas-chave em uma fábrica de cerveja. Como é um processo intensivo no uso de energia e mão-de-obra, qualquer melhoria no processo pode representar ganhos significativos. As lacunas que podem ser exploradas para aumentar a eficiência da linha são o retrofit de linhas existentes e melhorias de manutenção. Embora o envase seja um processo estabelecido, a literatura relevante no assunto tende a focar em macroparadas (paradas que duram mais que 5 minutos) apesar de as microparadas serem tão relevantes quanto. Essa lacuna na literatura acontece principalmente devido à escassez de dados. Neste contexto, tecnologias como as da Indústria 4.0 nos permitem estudar e avaliar microparadas para todos os equipamentos de uma linha de envase, em vez de máquinas individuais. Portanto, neste estudo, nós avaliamos as microparadas de uma linha de envase retornável completa através da aplicação da técnica da análise de Confiabilidade, Disponibilidade e Mantenabilidade (do inglês, análise RAM), a qual é comumente aplicada às macroparadas. Além disso, analisamos dados inéditos de três linhas de envase de garrafas retornáveis com o intuito de sugerir regras simples baseadas na análise dos transportes, que auxiliam na identificação de alguma esteira que esteja contribuindo negativamente para a eficiência da linha. A partir da análise RAM, nós verificamos que quatro máquinas da linha de retornáveis analisada necessitavam de ações de melhoria de confiabilidade. Isto não seria possível analisando-se um único equipamento, como é frequentemente apresentado na literatura. Além disso, nós concluímos que as regras práticas sugeridas podem ser aplicadas sem qualquer restrição adicional para linhas similares. Para linhas de envase com disposição consideravelmente diferente (tais como linhas de latas), as regras permanecem aplicáveis, mas com algumas restrições. Para futuros trabalhos, nós sugerimos que as regras práticas sejam aplicadas e avaliadas em linhas de produção diferentes, como as de fabricação de latas e garrafas. Adicionalmente, nós sugerimos a investigação dos tipos de falhas mais comuns e as ações específicas para mitigá-las.

Palavras-chave: linha de envase, Indústria 4.0, confiabilidade, análise de transportes, microparadas.

List of Abbreviations and Symbols

Symbol	**Meaning**
BW	Bottle Washer
CDF	Cumulative density function
CoV	Coefficient of Variation
CvM	Cramér-von Mises
CW	Crate Washer
DCR	Decrater
DIN	*Deutsches Institut für Normung* - German institute for standardization
DPL	Depalletiser
FL	Filler
IID	Independent and Identically distributed
IU	Inspector Unit
LB	Labeller
MER	Mean efficiency rate
MTBF	Mean Time Between Failures
MTTR	Mean Time To Recover
N	Number of events
NIST	National Institute of Standards and Technology
OEE	Overall equipment efficiency
OPC	Open Platform Communication
PCK	Packer
PL	Palletizer
PLC	Programmable Logical Controller
P-P	Probability–probability
PU	Pasteurization Unit
Q-Q	Quantile-quantile

Symbol	**Meaning**
R	Programming language and software for statistical computing
RAM	Reliability, availability and maintainability
RCR	Recrater
SD	Standard Deviation
TBF	Time Between Failures
TTF	Time to Failure
TTR	Time To Recover
TTT	Technique of Total time on Test

β	Buffer strategy performance
C_{machine}	Machine speed
η_{line}	Line efficiency
η_{machine}	Availability
η_{buffer}	Buffer efficiency
$F(t)$	Cumulative failure distribution function evaluated at time t
$g(t)$	Function that describes the time to recover data evaluated at time t
$M(t)$	Maintainability function evaluated at time t
$\mu(t)$	Recover rate evaluated at time t
n	Capacity in containers of the conveyor
$R(t)$	Reliability function evaluated at time t
T^i_{stop}	Total stop time of machine i
T^i_{starve}	Total starvation time of machine i
T^i_{block}	Total block time of machine i

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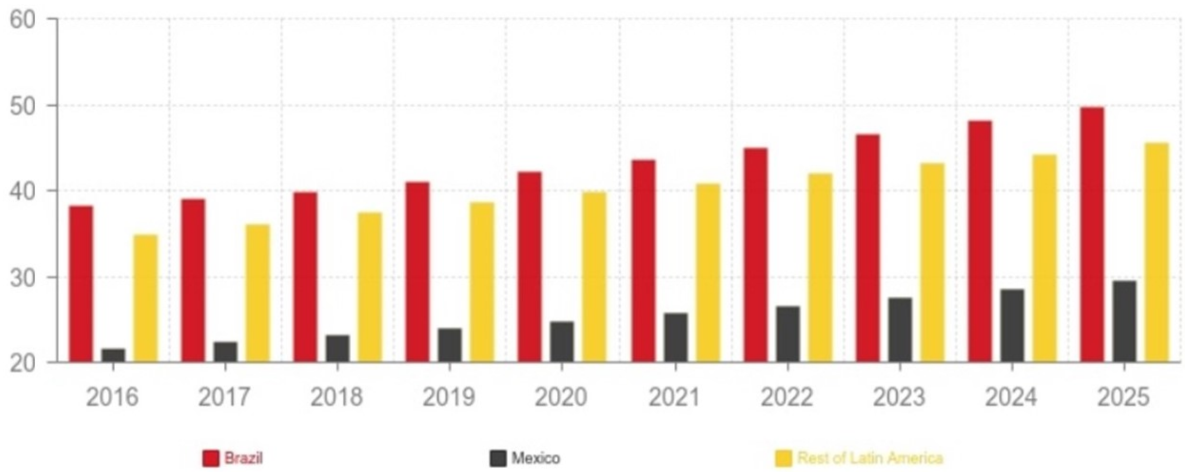
Chapter 1: Introduction

Brew market is expected to grow 1.8 % a year globally until 2025 (ALLIED MARKET RESEARCH, 2019). In 2017, this market valued $593,024 million. For Latin America, this projection is considerably higher, approximately 3.0% of annual growth (INKWOOD RESEARCH, 2019). Figure 1.1 shows the beer market projection for Brazil, Mexico and other Latin America countries.

Figure 1.1: Latin America Beer Market, by Geography (in $ Billion)

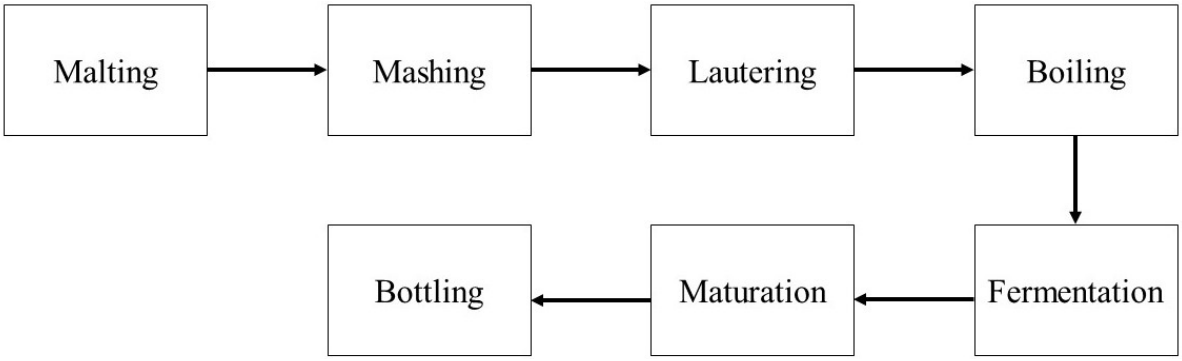


Source: INKWOOD RESEARCH, 2019.

The most expressive growth is expected to be in Mexico, however Brazil would still be the most important market in Latin America. In order to explore these growing markets, while decreasing costs and increasing process efficiency, it is needed to promote innovative process improvement technologies, such as Industry 4.0. This kind of techniques facilitates data analysis and, consequently, process management.

In a beer manufacturing industry, several units can be individually studied and optimized (malting, mashing, lautering, boiling, fermentation, maturation and bottling). Figure 1.2 shows a simplified block diagram of the brewing process.

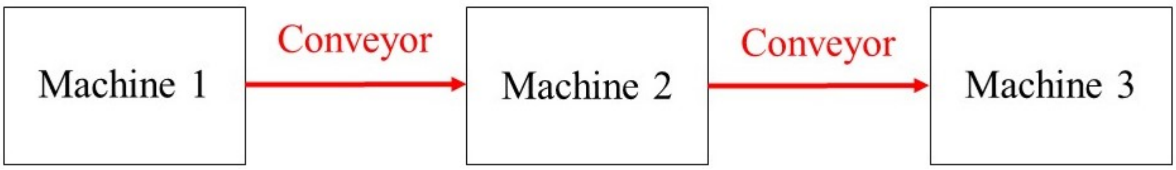
Figure 1.2: Block diagram of a simplified brewing process.



Source: Adapted from Wunderlich and Back (2008).

Considering all steps of brewing process, the bottling stage presents a substantial potential for optimization. This step is performed by a set of machines and conveyors, called filling line. The main functions of conveyors are to transport the containers from one machine to another and provide a buffer of containers between them. Figure 1.3 shows a generic representation of a filling line.

Figure 1.3: Generic filling line.



Filling lines studies usually are focused on efficiency improvement. The three most common methods to increase it are: to improve machine reliability through preventive maintenance policy, upgrade some specific machine (this technique is also known as line retrofit) and increase buffer size.

Even though the beer market is relevant and its growth is expressive, several papers that study food and beverage production lines do not address the beer industry. The existing studies about line reliability usually focus on machine maintenance parameters and do not tackle the effect of increasing buffers size to improve overall line efficiency.

Reliability, availability and maintainability (RAM) analysis is often used to evaluate maintenance policy. This methodology focus on machine's reliability and points out which machine should have their maintenance revised and/or improved (KUMAR *et al.*, 1989; LIBEROPOULOS and TSAROUHAS, 2005).

In order to contribute to machine and buffer analysis techniques, this thesis aimed to verify the following hypothesis:

1. In a filling line, other machines apart from the filler directly impact on overall line efficiency;
2. It is possible to identify if a buffer is contributing negatively to line efficiency through simple to calculate line and buffers indicators.

These hypothesis were verified by applying the available methodology of RAM analysis on a whole returnable beer filling line, focusing on stops shorter than 5 minutes (microdowntimes), which is unique in literature. In addition, it focused on developing easy to use rules of thumb based on buffer analysis, that helps to identify if some line conveyor is negatively contributing to line efficiency.

1.1 How this thesis is structured

Chapter 2 summarizes the state-of-the-art of RAM and buffer analysis. In addition, it describes the problem statement. Chapter 3 details the objectives of this thesis. Chapter 4 describes the definitions necessary to understand the methodology and results discussed on this thesis. Chapter 5 describes the methodology used by this study. Chapter 6 details the results and discussion and, lastly, Chapter 7 describes the conclusions and suggestions for future work.

Chapter 2: Literature Review

The following literature review covers the most relevant works published related to reliability, availability, maintainability (RAM) and buffer analysis. However, it does not intend to be exhaustive.

This chapter has tree sections: RAM analysis, buffer analysis and literature summary and problem statement. The first two sections show the studies results of each topic and, in the last section, we evaluate the results critically and expose were is the gap we aim to fill.

2.1 RAM Analysis

Reliability, availability and maintainability (RAM) analysis are crucial to manufacture industry, specially food and beverage sectors that now are characterized as automated flow line manufacturing systems (TSAROUHAS, 2018 and ZENNARO *et al.*, 2018). Kumar *et al.* (1989) published one of the first studies that investigated the reliability of non-repairable systems. They studied a mine operating system. The main results achieved were: TBF are well fitted with Weibull distribution and, TTT (Technique of Total time on Test) plots results showed that the independence hypotheses was not valid for all compounds of the studied system.

Similarly to Kumar *et al.* (1989) work, many other authors focused on reliability and maintainability analysis on a large number of industrial sectors (BARABADY and KUMAR, 2005; BABBS and GASKINS, 2008 and REGATTIERI *et al.*, 2010). In particular, regarding beverage filling lines, Härte (1997) published one of the first works. Due to its importance to the present study, we discuss his results later.

One of the latest papers using reliability analysis to investigate the impact on OEE of a bottling line was developed by Zennaro *et al.* (2018). This work concluded that 57 % of line inefficiency was caused by micro downtime. In addition, it suggested that working on only three machines of the whole filling line was possible to have a deeper understanding of 80 % of its micro downtime causes. Besides developing this interesting conclusions, this papers has also evaluated a considerable amount of papers about these topics:

1. Downtime data and analysis;
2. OEE evaluation in industries;
3. Reliability and maintainability of production equipment;
4. Importance of probability distribution of data collected and tools;
5. Simulation of production systems as a tool of improvement;
6. Methods for downtime analysis.

The first work regarding reliability and maintainability analysis for TBF and TTR parameters that Zennaro *et al.* (2018) cited was Barabady and Kumar (2005). This work presented a case study describing reliability analysis of crushing plants in a bauxite mine. They concluded that the Weibull distribution was the best fit for TBF parameter for the majority of cases. Moreover, they verified that to achieve 75 % of reliability on the studied systems, the recommended maintenance interval would be 10 hours.

Liberopoulos and Tsarouhas (2005) performed the first work that evaluated a whole production line on food and beverage industry. They analyzed a manually acquired data of 4 years period of an automated pizza production line. Their results were: the best fit for TBF and TTR parameters [1] was the Weibull distribution and TBF and TTR are independent events.

Tsarouhas *et al.* (2009, 2014) developed two different studies that evaluated a juice and an yogurt filling line. The juice filling line results (TSAROUHAS *et al.*, 2009) suggested a revision on maintenance strategy for two machines, in order to increase production. In addition, the most frequent failures were fitted a theoretical probability function. Similarly to the juice filling line results, the yogurt production line analysis (TSAROUHAS and ARVANITOYANNIS, 2014) suggested that the current maintenance policy is not adequate and it points out two machines (pasteurization boiler and filling machine) that should have their reliability improved in the first place.

As far as we know, the work developed by Tsarouhas and Arvanitoyannis (2010) is the only one that applied RAM analysis to a beer filing line, although it was limited to only one piece of equipment.

[1] In this work, they prefer to use the term TTF - time to failure, instead of TBF (time between failures).

In this thesis, we aimed to analyze the machines and the conveyors. Thus, a buffer analysis will also be conducted. Therefore, the next section lays out the most representative works about it.

2.2 Buffer analysis

Haines (1995) was the first to compile design principles for filling lines. His study concerns of machine and buffer parameters. He emphasizes that the accumulation functions of the conveyors have two objectives: enables the machine to run at different speeds (enabling the V-graph) and work independently. In other words, if a piece of equipment stops for a short period, the others are able to keep producing for a certain time.

Aiming to achieve these two objectives, he developed two different buffer parameters: accumulation and nominal recovery ratios [2].

Following the same line, Härte (1997) extended Haines (1995) parameters for buffers and machines. He investigated many machine and buffer parameters of a beer packaging line owned by Heineken. His main contribution was to define a framework to acquire the necessary data (automatic or manual acquisition). In addition, he defined and suggested many analysis parameters that should be monitored in order to improve line efficiency.

Cooke *et al* (2005) used some of the parameters developed by Härte (1997) to evaluate the data from a filling line. They built a line model and simulated some line parameters, such as buffer size. Their objective was to identify improvement opportunities on the line. Their model was validated with line data. The main conclusion of the work was, for the studied line, the buffer sizes are adequate and, the main opportunity for line efficiency improvement is increasing machines' availability.

Van Leer (2014) also developed a simulation model in order to improve line efficiency. But, he focused on determine the best set up for the sensors of a critical conveyor. In addition, he identified a bad configuration on the pasteurization unit blockage status which was impairing line efficiency. As final recommendations, Van Leer (2014) suggests that more attention should be given to conveyors and buffers, as they also play an important role regarding to line efficiency.

[2] The names for these parameters are different on the article. Accumulation ratio is accumulation size and nominal recovery ratio is recovery rate.

Basán *et al* (2014) developed a work similar to Cooke *et al* (2005). They also created a line model and evaluated different scenarios based on line data. Their results suggested that line efficiency would increase if one of the conveyors speed was increased. Moreover, they indicated that increasing the efficiency ratio of a particular machine would not necessarily increase line efficiency.

Scholten (2016) used a line model to identify its bottleneck and suggest some improvements. His results indicated that the line bottleneck was the buffer size. He identified that instead of increasing buffer size, an alternative was to relocate some sensors allowing a better regulation of machine speeds. This modification enabled the buffers to absorb more failures, without further investment.

Ujam and Godwin (2018) used most of Härte (1997) machines and buffers parameters to identify the line bottleneck. Moreover, they created a line simulation to evaluate line performance subject to different configurations. The best results were elected to perform a plant trial on the studied filling line. Based on their results, they recommend increasing attention on regulation of machine speeds based on sensors activation/deactivation. In addition, they observed that some operational inefficiencies have impairing effects on line efficiency.

2.3 Literature summary and problem statement

Although there is an expressive number of papers in literature regarded to failure data, most of them deal with a single piece of equipment or are related to baking industry.

Even though the methodology described on the previous RAM analysis studies is relevant to the topic, most of the them focus on unplanned downtime events higher than 5 min (macrodowntimes). These results are interesting to evaluate machine maintenance, but microdowntime events (with duration lower than 5 min) are neglected. The main reason is how the data is collected, for most of the studies analyzed they were manually collected by operators or maintenance technicians.

Industry 4.0 advances enabled a broad availability of data. For filling lines, equipment status and speeds can be highlighted. These kind of information allow us to use the available RAM analysis methodology to focus on machine microdowntimes. Evaluating this kind of stop allow us to identify which machine (or machines) are impairing line efficiency besides the filler.

Regarding to buffer analysis, all papers that included some aspect of it evaluated the impacts on line efficiency through simulation. They all achieved interesting results, but running a simulation on a plant daily routine is almost impossible. Thus, it is relevant to develop a procedure that is rapid to analyze and does not require much engineering and computational effort.

This study aims to combine machine reliability analysis with buffer assessment to develop some rules of thumb that enable line managers and engineers to perform a fast assessment of line bottleneck.

Chapter 3: Objectives

This study has two main objectives:

1. Verify through RAM analysis if more machines besides the filler directly impact on overall line efficiency;
2. Develop and to test rules of thumb for filling lines, that are capable to identify if a buffer is contributing negatively to line efficiency.

The RAM analysis aims to identify which line machines, from a whole returnable filling line, are impairing line efficiency and, consequently, require further maintenance.

The rules of thumb intends to identify the actual bottleneck of any filling line with simple line parameters. They were built based on the results of three returnable bottle lines and validated against a can line.

The specific objectives of this thesis are:

3.1 RAM Analysis

1. Treat historical data of a returnable bottle filling lines;
2. Evaluate TBF (time between failures) and TTR (time to recover) statistical distributions;
3. Analyze TBF and TTR trends to evaluate if these parameters change over time;
4. Identify which theoretical probability function fits better TBF and TTR data;
5. Estimate reliability and maintainability for the whole filling line;
6. Identify the machines that require further improvement through effective maintenance policies.

3.2 Procedure to develop and to test rules of thumb for filling lines

1. Calculate the availability of each machine;
2. Calculate buffer performance parameters;
3. Identify the actual line bottleneck;
4. Apply the same methodology for other two returnable bottle filling lines;
5. Propose some rules of thumb based on the results achieved for all returnable bottle filling lines evaluated;
6. Test the proposed rules of thumb on a can filling line;
7. Compare and discuss the findings for each line.

Chapter 4: Definitions

This chapter describes what a filling line is, its design principles and its main components (machine and buffer) parameters and definitions. Therefore, it is divided into four sections: filling lines, design principles, machine and buffer parameters.

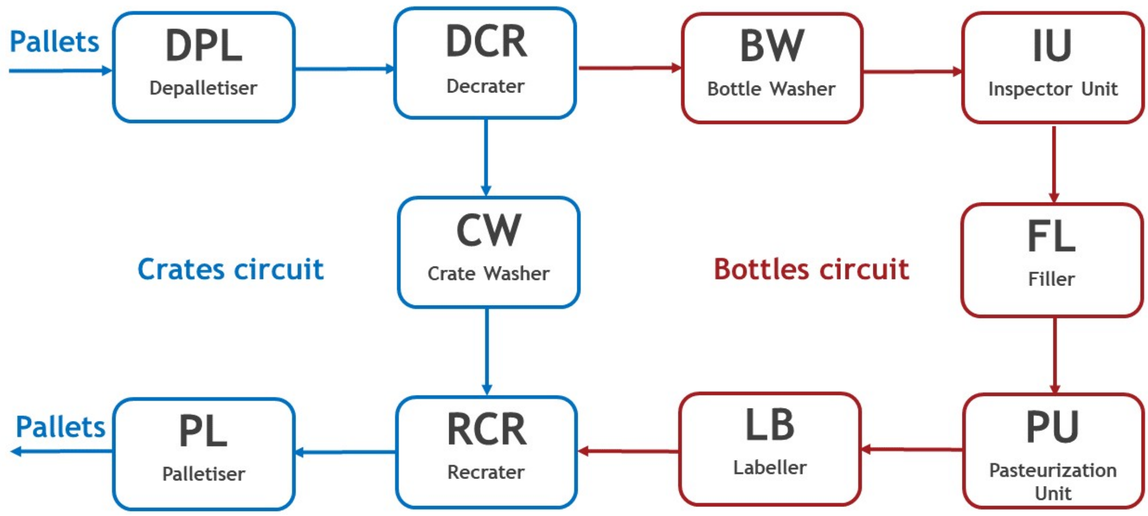
We summarized the main definitions of our domain of study. For this, we primarily used the Haines (1995) and Härte (1997) studies that should be consulted for a more detailed description of all these concepts.

4.1 Filling lines

A filling line can be described as a set of different machines (more than one can be used for each step) connected by conveyors. Its main objective is to fill and prepare for expedition beverage containers, such as bottles (plastic or glass), cans or kegs (DIN 8782, 1984).

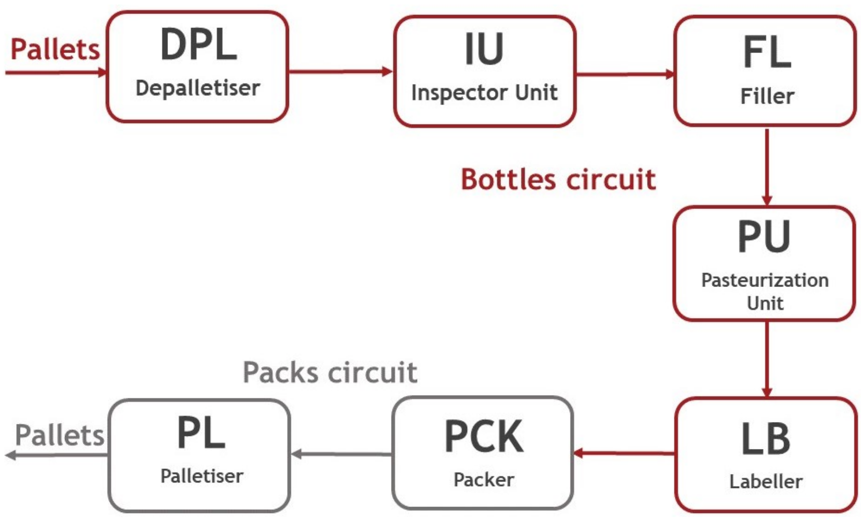
There are many types of filling lines. Although, it is possible to highlight three of them: one-way bottles, returnable bottles and cans. Figures 4.1, 4.2 and 4.3 show a block diagrams for a conventional returnable bottle, one-way bottle and can filling line, respectively.

Figure 4.1: Block diagram for a conventional returnable bottle filling line.



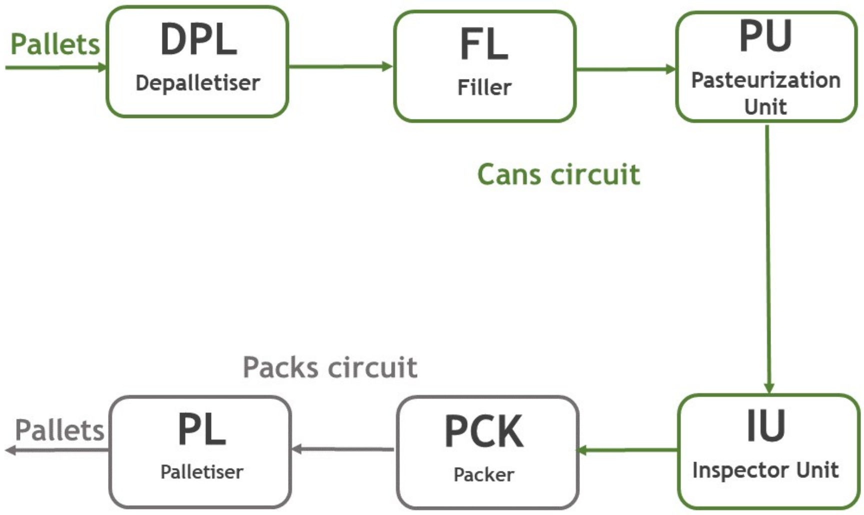
Source: Adapted from Haines (1995)

Figure 4.2: Block diagram for a conventional one way bottle filling line.



Source: Adapted from Härte (1997)

Figure 4.3: Block diagram for a conventional can filling line.



Source: Adapted from Haines (1995)

Returnable bottle lines are one of the most complex process involving packaging lines. It includes a minimum of ten machines. The process begins with a depalletizer, which dismantles pallets formed with crates full of empty and dirty bottles. These crates are carried by conveyors to a decrater machine. It then separates bottles from crates and, from this point, bottles and crates are sent to different machines: bottle washer and crate washer, respectively.

The next step for bottles is inspection. The filler machine receives the good bottles, fills with beer and caps them. Afterwards, bottles are pasteurized to guarantee beer shelf life. The next step is labell the bottles and, then send them to a recrater. There the bottles are put on empty and clean creates (they are sent from crate washer). After filling these crates with labelled bottles, they are palletized and sent to distribution centers.

One particularity of returnable bottle lines is the crate circuit. It works independently from the bottle circuit, but they can influence each other. The two machines that connect them (decrater and recrater) are responsible for most part of the negative influences. For example, if the crate washer fails and/or there is an accumulation of crates on decrater exit conveyor, this machine would be blocked and, depending of how long this situation persists, the bottle washer would indicate a starve status. In other words, for this case, the decrater would indicate a blocked status and the bottle washer a starved one at the same time because of the crate circuit.

There are three main differences between returnable and one-way filling lines: one-way lines do not need to wash their containers, the packers are responsible for creating the packs and their packs are not returnable.

For all three examples of filling lines mentioned there is a pallet circuit. It will not be analyzed in this thesis, because it would require evaluate how the logistics is organized. Then, it is not the focus of this study.

Table 4.1 exposes the functions of the different pieces of machine exposed in the previous Figures.

Table 4.1: Main function of each equipment of a returnable bottle line

Machine	Main function
Depalletiser	Transfers crates with empty bottles from pallets on the line.
Decrater	Takes out bottles from crates and send them to Bottle Washer. Crates are send to Crate Washer.
Crate Washer	Washes crates coming from Decrater.
Bottle Washer	Washes bottles coming from Decrater.
Inspector Unit	Inspects washed bottles to guarantee that they are completely clean, without residues and physical defects.
Filler	Fills bottles with beer and seals them with a metal cap (capping machine).
Pasteurization Unit	Makes a temperature ramp that guarantees beer determined shelf life.
Labeller	Labels each bottle.
Packer	Packs a group of cans or bottles.
Recrater	Organizes bottles inside clean crates.
Palletizer	Palletizes crates with full and labeled bottles.

This section presented the basic concepts related to the types of filling lines and their main equipment. The next topic aims to introduce the design principles of filling lines.

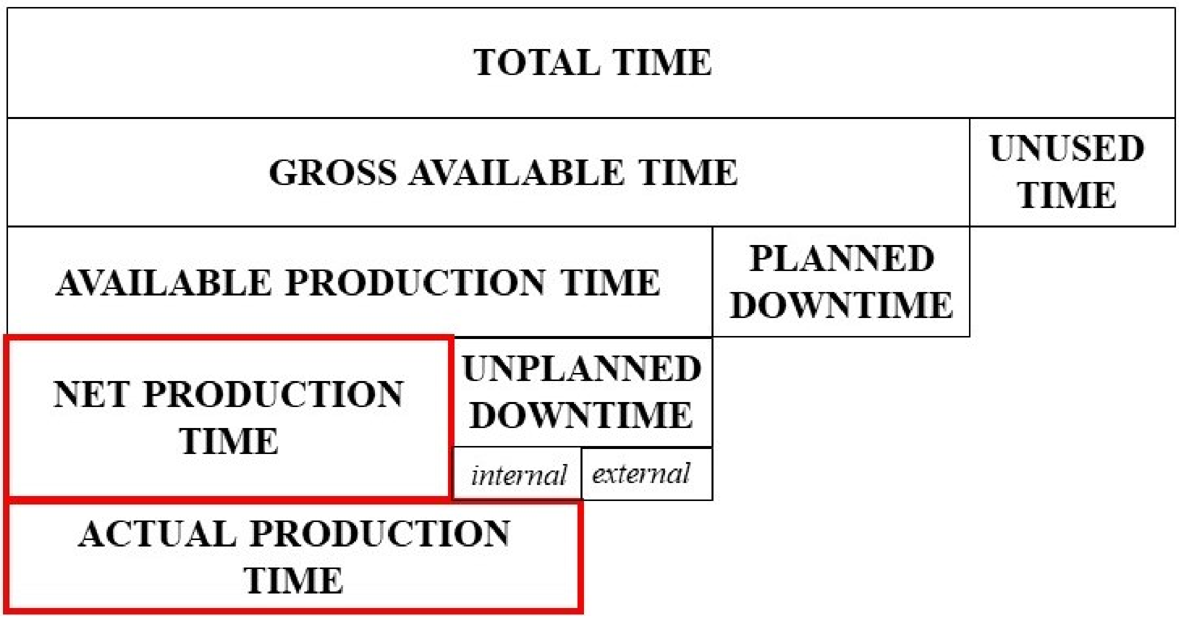
4.2 Design principles

In order to design a filling line for a given capacity, three factors must be considered: running time, machine speeds and buffer capacity.

4.2.1 Time definitions

The definition of time for filling lines is the first step to calculate their parameters. In this context, exists, at least, nine different *"types"* of time. Figure 4.4 illustrates how they are related.

Figure 4.4: Time definitions of a packaging line



Source: Adapted from HÄRTE (1997)

Figure 4.4 shows nine different definitions of time for a packaging line. The definition of each of them is described bellow:

1. **Total time**: is the total duration of the analyzed period;
2. **Gross available time**: occurs when there is a team available to operate the line;
3. **Unused time**: is the time when a filling line has not been utilized during a specific period and it was not a planned neither a unplanned downtime. Examples: holidays, strikes and time not worked accordingly to work schedule;

4. **Available production time**: is the time that is intended to produce.
5. **Planned downtime**: is the time when a filling line is planned to not be producing. Examples: cleaning, maintenance, startup/shutdown;
6. **Net production time**: (also called theoretical production time) is the effective time that a filling line is available to produce;
7. **Unplanned downtime time - internal**: is related to unplanned stops during a specified period, whose main factor is a machine average speed lower than its nominal;
8. **Unplanned downtime time - external**: is related to unplanned stops during a specified period, whose main factors were extrinsic from the filling line, such as lack of beer, electricity and container;
9. **Actual production time**: is the sum of net production time and internal unplanned downtime.

The time definitions are important to calculate line parameters, that are described further on.

4.2.2 V-graph theory

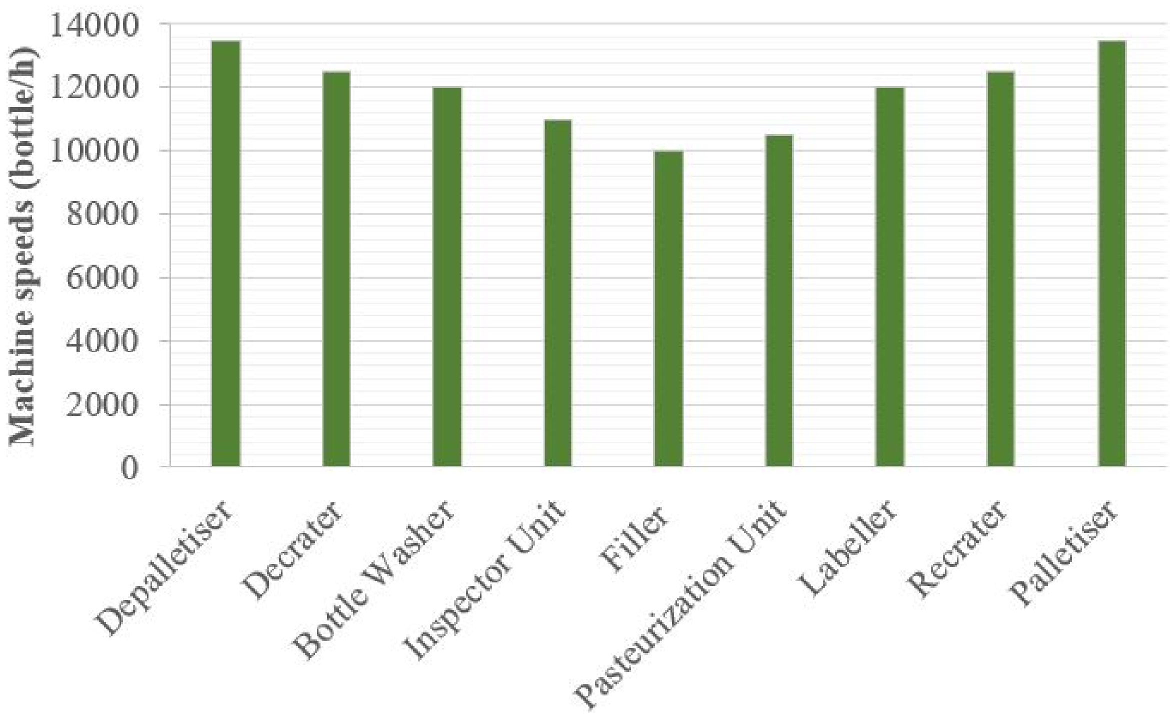
A filling line is composed of a considerable number of machines, but the filler is the most critical. This criticality is due to its role: it performs the primary function of a filling line. In other words, the filler is the machine that actually put beer in the containers. In addition, the filling process is very critical in terms of quality. Thus, that is why a filler can be called the line *core machine*. Depending on design choices, the pasteurization unit is considered a core machine instead of the filler.

The core machine is the design speed base for the whole filling line, independently of which machine is selected to play this role. The concept of core machine can also be applied for a group of machines, such as fillers if the line evaluated has more than one.

Machines before and after core machine have to be designed with an overcapacity when compared to core machine. It is necessary to allow adjacent machines to minimally recover from its own downtime in order to not compromise core machine production. This overcapacity has to be increased as further the machine is to the core machine.

The described design strategy is the V-graph theory. The name comes from the shape of the plot of all machines capacities side by side. Figure 4.5 shows an example of machine speeds design of a returnable bottle filling line.

Figure 4.5: Example of a V-graph applied to a returnable bottle filling line



The V-graph theory is a requisite to understand how a machine failure could be propagated through the whole filling line. Moreover, it is the base to understand buffer parameters.

4.2.3 Buffer sections

The design of a filling line usually considers that buffers before core machine have to be constantly full and buffers after core machine have to be constantly empty. This principle is called *buffer strategy*. It allows the core machine to achieve its maximum production. The main reason is that buffer strategy considers that the core machine will always have containers to fill and space at discharge in case of a failure of another machine.

The V-graph theory and buffer strategy allow machines of a filling line to fail and not cause avoidable downtime to other machines.

4.3 Line Parameters

Line efficiency is the most common parameter calculated for filling lines. It is the ratio between the net production time and the total duration of production considering downtime periods. In practical terms, this definition corresponds to the ratio between the actual production and what could have been produced, had unplanned downtime not taken place (Equation 4.1).

$$\eta_{line} = \frac{\text{net production time}}{\text{net production time + internal unplanned downtime}} \cdot 100\% \tag{4.1}$$

Although unplanned downtime do not have a direct influence on line efficiency, it is important to other areas, such as logistics.

Equation 4.1 can also be written in terms of produced units, as it is shown in Equation 4.2.

$$\eta_{line} = \frac{\text{produced units}}{\text{actual production time} * \text{nominal line capacity}} \cdot 100\% \tag{4.2}$$

All the parameters listed in Equation 4.2 considers the core machine as a reference.

In order to have a closer look on each filling line parts, we list, on the following sections, definitions and parameters of machine and conveyors.

4.4 Machine Parameters

The machine parameters discussed on this chapter are: machine states, failure distribution, efficiency, production rates and OEE (overall equipment efficiency).

4.4.1 Machine States

Each machine has five different states:

1. **Running:** machine is effectively producing.
2. **Starved:** machine stops due to a lack of material income (cans/bottles).
3. **Blocked:** machine stops due to a lack of backup of output material (cans/bottles).

4. **Failed:** machine is not producing, and it is not blocked or starved.

5. **Planned down:** machine is programmed for not to be working.

For this work, mechanical failures root causes were not discriminated (internal or external failure).

4.4.2 Failure behavior

Each machine has its own failure distribution. In this work, this parameter includes internal and external failures. Two main functions describe a machine failure behavior: MTBF[1] (Mean Time Between Failures) and MTTR (Mean Time To Recover). See equations 4.3 and 4.4, respectively.

$$MTBF = \frac{\text{total running time}}{\text{number of failures}} \tag{4.3}$$

$$MTTR = \frac{\text{total failed time}}{\text{number of failures}} \tag{4.4}$$

On Equations 4.3 and 4.4, the total failed time is the sum of all failures during the specified period and the running time is the total time that the machine effectively producing.

As $MTBF$ and $MTTR$ are mean values, another possibility to calculate them is identifying each TBF and TTR separately and then calculate their mean. To use this approach, a formal definition of these parameters is necessary.

The main definition for TTR is the time that a machine stays on failure, even though after this event it stops again for starvation or blockage. Using a similar analogy, a TBF occurs between two failure events, independently if the machine could not produce due to an unplanned downtime. Figure 4.6 illustrates the previous descriptions.

[1]This parameter is based on running time and not on clock time, which assumes that a machine cannot fail while being forced down (starved or blocked)

Figure 4.6: TBF and TTR examples of an hypothetical machine

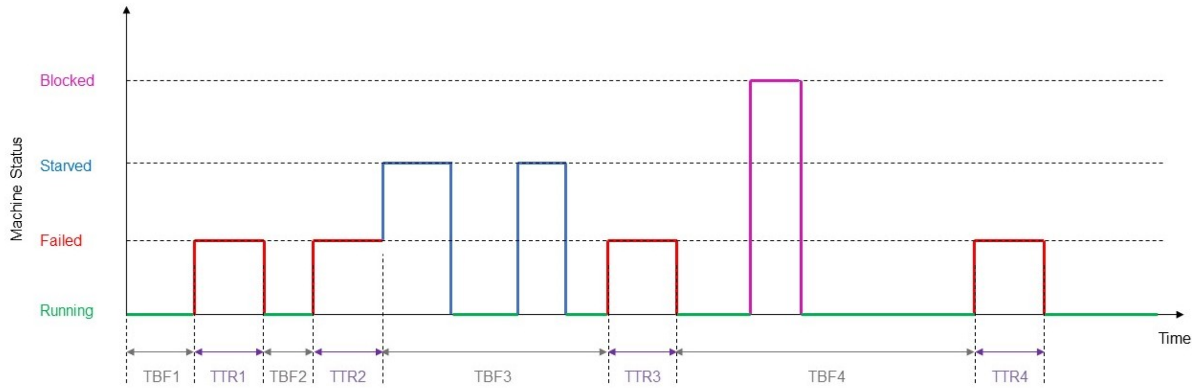


Figure 4.6 shows that TTR calculation do not depend on the machine state before or after the failure, but just the failure itself. TTR2 illustrates this remark by considering the end of the failure when the machine presented a starved state.

Another interesting remark in Figure 4.6 is the TBF calculation. While TBFs 1 and 2 included only status *running*, TBF3 included two starvation and TBF4 a blockage event. This implies that a TBF event occurs every time that a machine is not on failure.

This work calculates TBFs and TTRs for every machine analyzed. This approach allows the statistic evaluation of each machine failure behavior.

4.4.3 Availability

Availability, also known as machine efficiency, is defined as the percentage of time that the machine is ready to operate, for a specified period. This parameter is expressed in Equation 4.5.

$$\eta_{machine} = \frac{\text{total running time}}{\text{total running time + total failed time}} \cdot 100\% \tag{4.5}$$

Equation 4.5 can also be expressed in terms of MTBF and MTTR, as shown in Equation 4.6.

$$\eta_{machine} = \frac{\text{MTBF}}{\text{MTBF + MTTR}} \cdot 100\% \tag{4.6}$$

If a step of the filling line has more than one machine (parallel equipment) the efficiency of this step is calculated summing the individual availability weighted by each capacity.

4.4.4 Machine production rates

There are several production rates associated to a machine (or a group), their definitions are listed below:

1. **Machine speed**: it is defined as the number of products (cans, bottles or kegs) per a unit of time (hours, minutes) that the machine is able to produce.
2. **Nominal machine capacity**: it is defined as the speed in which the machine has to produce to maintain the speeds defined on its "V-graph". When the machine is the core, its nominal speed is simplified to its maximum physical for a specific container.[2]
3. **Group nominal capacity**: if a stage on the filling line has more than one machine, the nominal speed for this group is the sum of its machines nominal speed.
4. **Nominal line capacity**: it is the core machine (or group) nominal capacity.

4.4.5 OEE (Overall Equipment Effectiveness)

The OEE (Overall Equipment Efficiency) is another possible indicator to define when one needs to consider a specific machine or a line as a whole. It is a quantitative metric that has been used for monitoring and controlling the productivity of a production line and/or a specific piece equipment (TSAROUHAS, 2013). OEE includes three major parameters: availability, performance efficiency and quality rate. Equation 4.7 shows how OEE is defined:

$$\text{OEE} = \text{Availability} * \text{Performance efficiency} * \text{Quality rate} \tag{4.7}$$

Each of these three performance indices have their own definitions and main wastes associated. Table 4.2 shows both of them.

[2]Depending on the volume of the container the same filler, for example, can have different nominal speeds.

Table 4.2: Indices, definitions and main wastes

Indicator	Definition	Main Wastes
Availability	It is the comparison between the number of hours that a machine is available to produce with the number of hours that it was programmed to produce.	1) Identifiable downtime; 2) Equipment failure; 3) Wastes due to adjustments and setups.
Performance	It is how much the machine produces compared to its nominal prodution rate.	1) Wastes due to lowered speed; 2) Unplanned downtimes (starvation and blocked downtimes).
Quality	It is the number of good pieces produced compared to the total number of pieces produced.	1) Quality loss; 2) Process wastes.

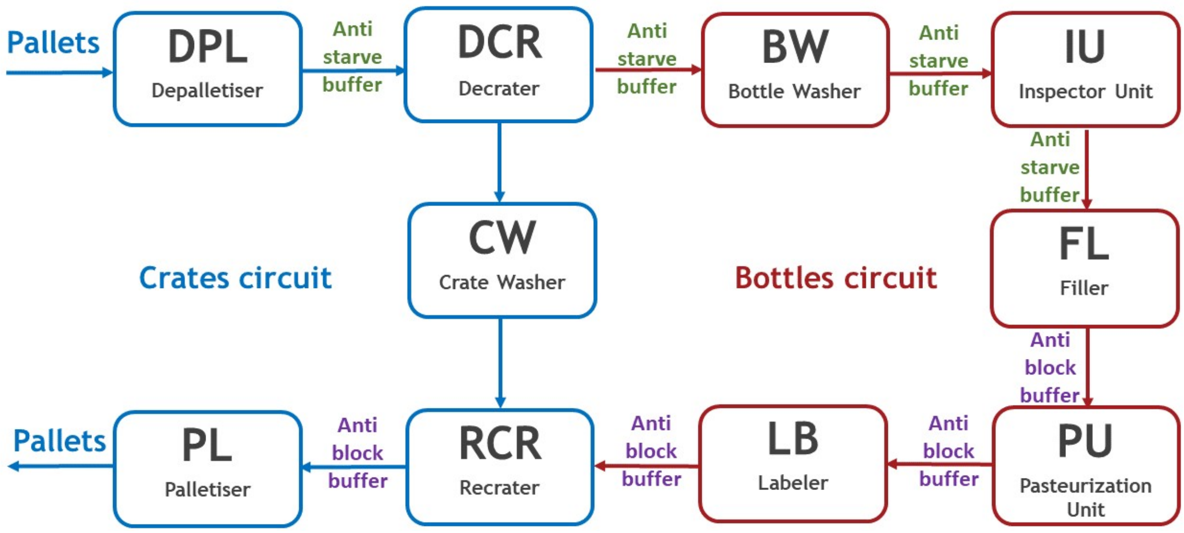
Source: CASTRO and ARAUJO, 2012

4.5 Buffer Parameters

As mentioned, the main objective of using the buffer strategy is to minimize the influence of failure behavior of the others machines on the core machine (usually the filler). There are two types of accumulation: dynamic and static. The first applies to conveyors located between machines and, the second occurs when a real buffer is placed between machines. Another name for static accumulation is accumulation tables.

For definition, a buffer located before core machine is a *anti starve buffer* and if a buffer is placed after core machine it is a *anti block buffer*. Figure 4.7 shows an example of a returnable bottle filling line with the description of each buffer.

Figure 4.7: Returnable bottle packaging line with buffers description



Another concept concerning buffers is *accumulation*. It refers to the time a machine can stop working without causing an avoidable downtime (starvation or blocking) on the others. To calculate this time the capacity of static and dynamic buffers should be considered.

4.5.1 Dynamic accumulation

Dynamic accumulation normally occurs in conveyors that connect two machines. The buffers of bottles and cans are a series of parallel chains, where some are for transportation and others for accumulation. For crates, cases and trays buffer the conveyors are normally one single chain and, the accumulation occurs when the space between containers is reduced.

Anti starve buffers

The main objective of an *anti starve* buffer is to prevent that downstream machine from starving due to a stop of the upstream equipment. Theoretically, the ideal state of these buffers are completely full, once they are located upstream the core machine.

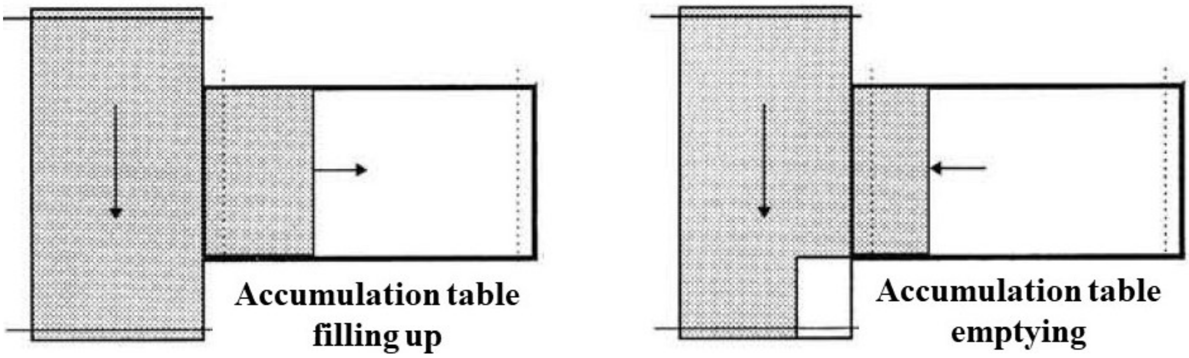
Anti block buffers

The main objective of an *anti block* buffer is to prevent the upstream machine from blocking due to a stop of the downstream equipment. Theoretically, the ideal state of these buffers are completely empty, once they are located downstream the core machine.

4.5.2 Static accumulation

Static accumulation occurs when besides a conveyor connecting two machines there is an accumulation table. It works similarly as a piston, when the buffer is full, it starts to accumulate and, when the buffer is no longer full it starts to empty. Figure 4.8 illustrates the piston movement of an accumulation table.

Figure 4.8: Accumulation table filling up and emptying

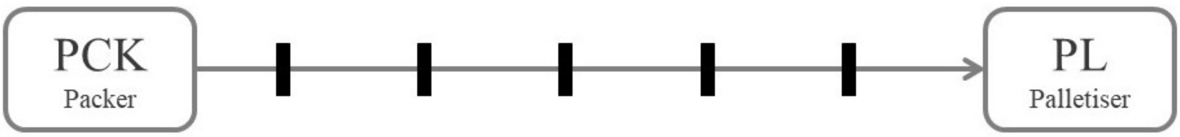


Source: Adapted from HÄRTE (1997)

4.5.3 Buffer instrumentation

Both dynamic and static accumulation are measured by sensors displayed through the whole conveyor. Figure 4.9 illustrates it.

Figure 4.9: Generic conveyor with sensors



We estimate how full/empty the conveyors are by verifying which sensor is activated.

In this chapter we described line, machine and buffer main definitions. They are important to understand how some parameters are calculated, such as TBF and TTR. Moreover, machine and buffer definitions are crucial to the parameters that are exposed on Chapter 5.

The next Chapter describes a literature review of filling line studies.

Chapter 5: Methodology

This chapter has six main sections. Section 5.1 describes all filling lines studied on this work. Section 5.2 describes how the data was obtained. Section 5.3 describes how the data was pretreated. Section 5.4 refers to RAM analysis. This section describes all analysis necessary to elaborate a complete RAM analysis for a returnable filling line. Sections 5.5 and 5.6 describe the rules of thumb development and test, respectively.

The brief description of all statistical tools used does not intend to be comprehensive. More detailed information can be found on statistical textbooks, such as Montgomery and Runger (2011).

5.1 Filling lines description

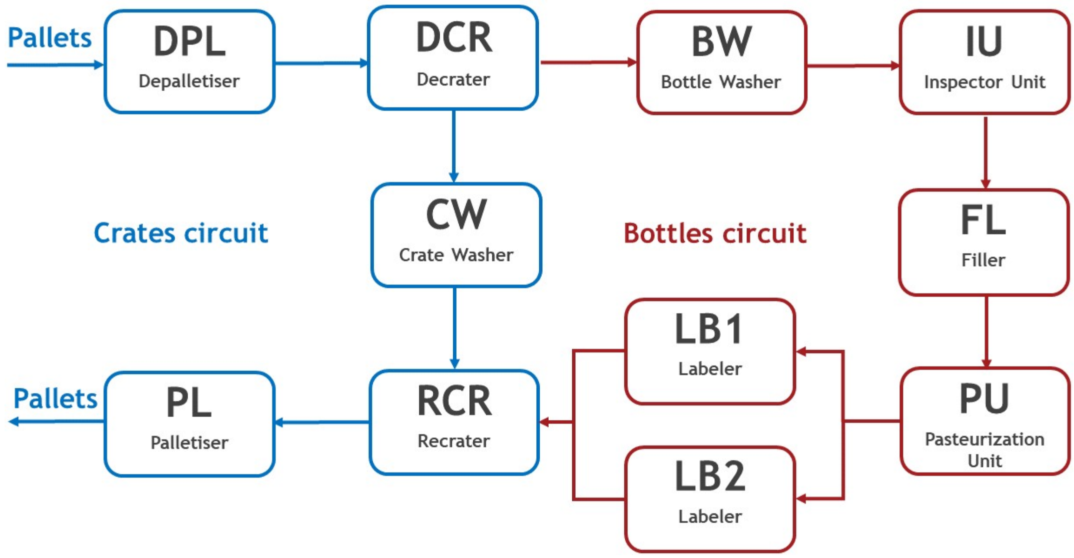
For this work, four different beer filling lines were selected: three returnable bottle lines and a can line (Lines A, B, C and D, respectively). All these lines belong to the same company and they are all located on Brazilian Southeast region. We chose them because these two types are very common, not only for beer lines, but also for soft drinks.

Due to confidentiality reasons, raw data and filling lines nominal speed and buffer capacity are not exposed.

5.1.1 Returnable filling lines

This study chose three returnable filling lines with the same layout and number of machines. Figure 5.1 shows a block diagram that represents all of them.

Figure 5.1: Block diagram for the returnable bottle filling line chosen.

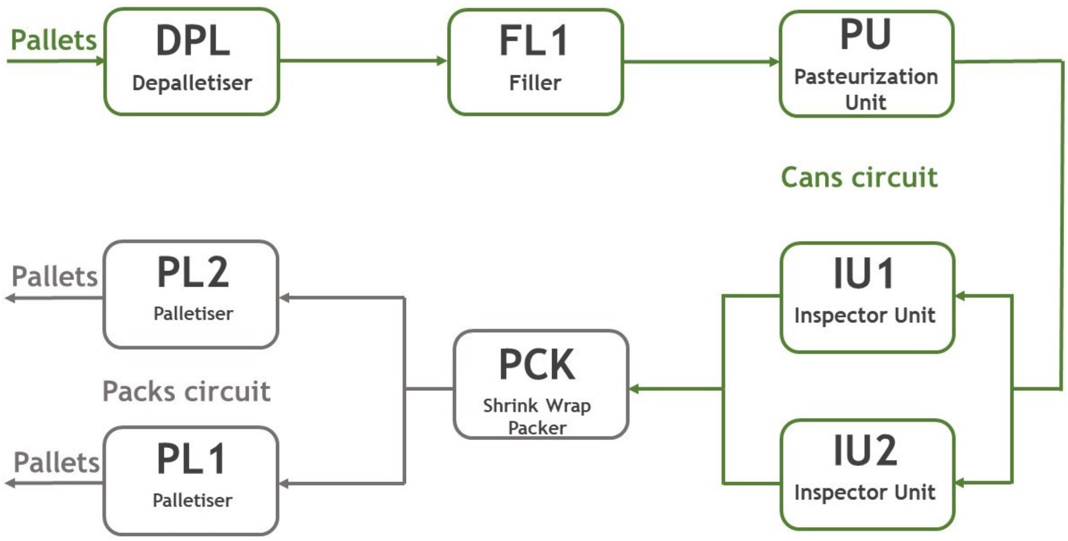


Lines A and C have the same filler nominal speed and produce the same type of product. Moreover, Line B presents a lower filler nominal speed, due to the bigger bottle size. Even though Lines A and C present the same filler nominal speed, they have considerable differences on buffer capacity.

5.1.2 Can filling line

The can line selected has two inspector unit and three palletisers, but palletiser 3 does not operate frequently. Thus, for all analysis that required palletisers evaluation, only the machines one and two were considered. Figure 5.2 illustrates this line layout.

Figure 5.2: Block diagram for Line D layout.

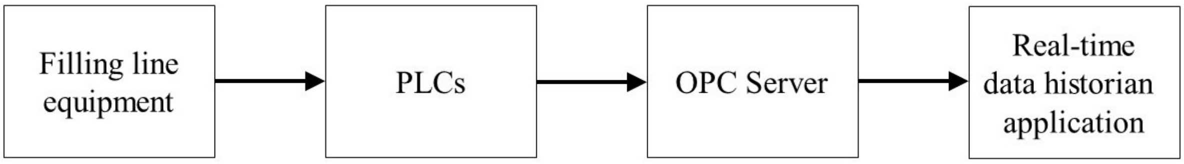


5.2 Data acquisition and evaluated period

All data used on this work was collected online from machine's PLCs (Programmable Logical Controller) through an OPC (Open Platform Communication) Server. A real time data historian application stored these data. Figure 5.3 illustrates this flux.

In addition, all data evaluated on this work have never been published before.

Figure 5.3: Data acquisition: block diagram



The variables collected are listed below:

- Product counter (for all equipment, except crate washer);
- Machine state (for all equipment, except crate washer);
- Line producing or not;

The variable *line producing* is defined as: true, when the line is actually producing, and false, when the line is shuttled down to maintenance, change product (setup), cleaning or any other activity to prepare the line to produce. We only considered in the analysis periods that the line were supposed to be producing (true state).

The time interval of data collection varied from 1 to 4 seconds. The same filling line could have had different frequencies of data collection through the whole period.

All evaluated filling lines operate 24h a day, 6 days a week. When the demand is very high (summer months - from December to February) they operate 7 days a week. Line A data were recorded from January to June 2019, covering 112 working days. Lines B, C and D data were recorded from February to March 2020, covering 14, 16 and 27 working days for each line, respectively.

5.3 Data pretreatment

All four fillings lines had their data pretreated. This methodology included filter out the events when the filling line was under a planned downtime. It was necessary because the acquired status variable did not identified when the equipment were at a *planned downtime*.

We treated the raw data using a set of scripts, developed to this specific purpose, in the language R. These scripts were run in the R package version 4.0.1. We decided to use this tool, due to its robustness to deal with a large (gigabytes) dataset.

The first step was to calculate all TBFs and TTRs for all four lines (as described on section 4.4.2). After that, TBFs and TTRs data were filtered based on the assumptions listed below:

1. TBF and TTR higher then 20000 s were eliminated;
2. TBF and TTR lower then 5 s were eliminated;
3. A failure event is considered only if it is higher then 5 s;

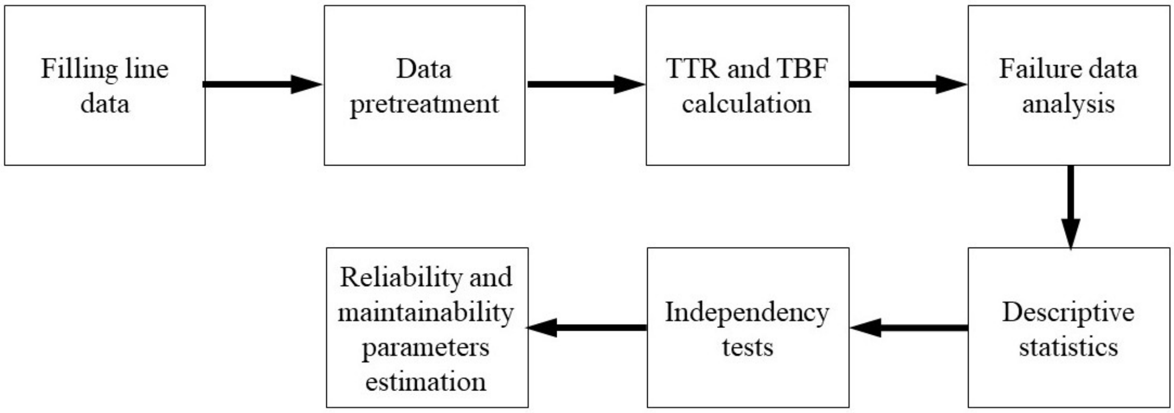
TBF and TTR events higher then 20000 seconds were disregarded, because they meant, most of the time, that the machine was turned off or the failure was considerably complicated to handle that it required a longer corrective maintenance. In other words, the failure event was a macrodowntime.

TBF and TTR events lower than 5 seconds were discharged, because most of them happened due a sensor issue. Moreover, this period of time is extremely fast that the machine is not able to stop completely, specially machines with long cycles, such as DPL, PL, DCR and RCR.

5.4 RAM (Reliability, Availability and Maintainability) analysis

Reliability Availability and Maintainability analysis was done only with Line A, due to its line type. This analysis was divided into several steps to better interpret the data. Figure 5.4 shows all steps developed in this section. The proposed methodology was based on the work of TSAROUHAS (2018).

Figure 5.4: Block diagram of all steps necessary to develop a reliability availability and maintainability analysis



Each step described of Figure 5.4 is detailed separately. TTR and TBF calculation and data pretreatment were already described on sections 4.4.2 and 5.3, respectively.

5.4.1 Failure data analysis

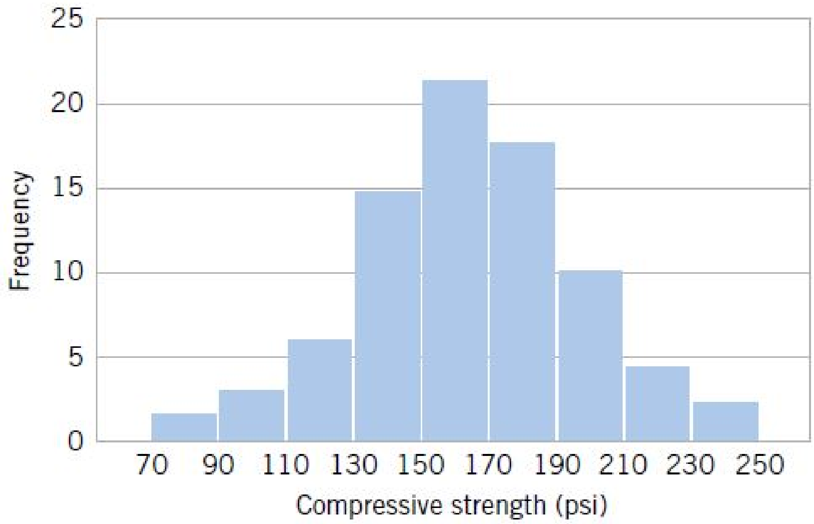
Line A failure data analysis aimed to evaluate the failure behavior of this line through histograms and Pareto diagrams. These analyses are qualitative tools. A brief description of them is exposed below.

Histogram

A histogram is the most common graph used to exhibit a frequency distribution. The main objective of evaluating a histogram is to have an idea of how often each different value (or a certain interval) occurs in a set of data. This kind of tool helps to visually identify which theoretical distribution best fit the data. Figure 5.5 shows an example of a histogram. This graph show the frequency distribution of a compressive strength for 80 aluminum lithium alloy specimens.

We built histograms for TBF and TTR of all Line A equipment.

Figure 5.5: Histogram of a compressive strength for 80 aluminum lithium alloy specimens.



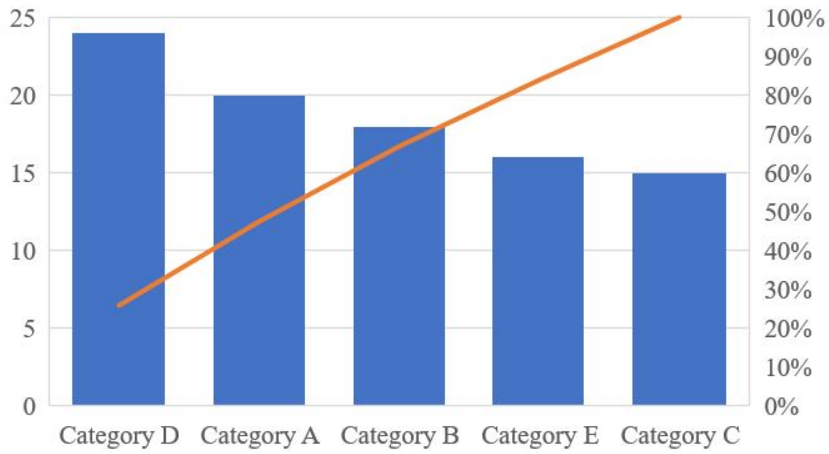
Source: MONTGOMERY and RUNGER (2011)

Pareto

A Pareto chart is a bar graph that aims to identify which situations are more significant to a determinate analysis. Each bar represents the frequency of each situation and, these bars are ordered from the highest to the smallest. Figure 5.6 shows a generic example of a Pareto chart.

In this work, we built two different Pareto charts. The first shows the number of failures of all equipment and the second the total time that each machine spent at failure status. From these graphs, we evaluated which machine failed more and which stayed more on failure status.

Figure 5.6: Generic Pareto chart.



Source: MONTGOMERY and RUNGER (2011)

5.4.2 Descriptive statistics of failure and recover data

The main objective to apply a descriptive statistics on TBF and TTR data is to identify and analyze the basic parameters. We did a quantitative analysis of the failure data for all Line A equipment. The parameters obtained were:

1. The number of events (N);
2. Mean, in seconds;
3. Standard Deviation (SD), in seconds;
4. Median, in seconds;
5. Minimum value (Min), in seconds;
6. Maximum value (Max), in seconds;
7. Skewness;
8. Kurtosis;
9. Coefficient of Variation (CoV).

Skewness is a measure of lack of symmetry. For a normal distribution the skewness is zero. Negative values of skewness indicate that the data are skewed left and, positive values values indicate that the analyzed data is skewed right (NIST, 2020a).

Kurtosis is a measure to verify if the data are heavy-tailed or light-tailed when compared to a normal distribution. The Kurtosis value for a normal distribution is 3. Thus, values above it can be considered heavy-tailed and below it light-tailed (NIST, 2020a).

The coefficient of variation (CoV) is defined as the ratio between the standard deviation and the mean. In other words, it shows the variability, relative to the mean (NIST, 2020b).

TBF and TTR trend analysis

The TBF and TTR trend graph consists of applying a moving average of 700 points through the whole data. The main objective of this analysis was to evaluate the variation of this moving average, to have an idea of its behavior through time.

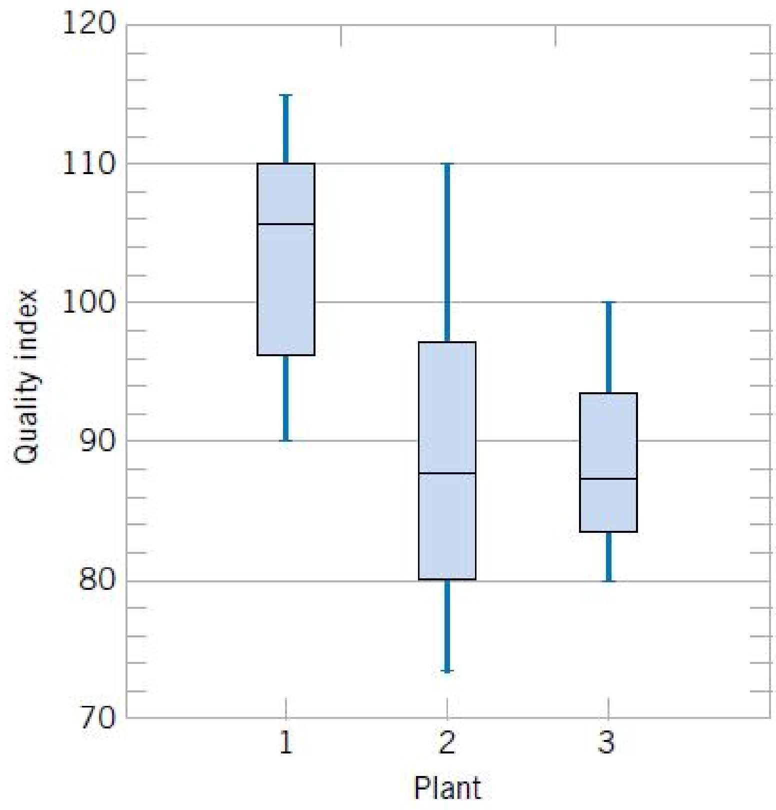
These graphs were visually inspected. We emphasized the moving average variability.

Box plot

A box plot is a graph that describes several features of data set, such as center, spread, symmetry and outliers simultaneously. It displays on a rectangular box (aligned either horizontally and vertically) the three quartiles, the minimum and the maximum. Figure 5.7 shows a comparison of three different box plots.

In this work, we built two different comparative box plots: one for TBF and another for TTR.

Figure 5.7: Example of comparative box plots of a quality index at three plants.



Source: MONTGOMERY and RUNGER (2011)

5.4.3 Independent and identically distributed analysis

The first step of reliability and maintainability analysis is the independent and identically distributed (IID) test. This step verifies if there is any intrinsic correlation between TBF and TTR events. In other words, IID analysis aims to evaluate if most of TBF or TTR events are aleatory.

To validate this hypothesis, we performed three tests: trend test, serial correlation and the relationship between TBF and TTR.

If any machine presents a correlation between TBF and TTR events, it is classified as a Nonhomogeneous Poisson Processes. In other words, the appropriate distribution is the power law process (TSAROUHAS, 2018). Thus, we do not need to test the machine data for several different theoretical probability distribution.

Trend test

The trend test includes plotting the cumulative failure number against the cumulative time between failures. If the test shows a straight line, it suggests that the analyzed data does not have a trend (TAHERI and BAZZAZI, 2016).

Serial correlation

The serial correlation test involves data pairs (X_i, X_{i-1}) from i varying from 1 to n, where n is the failure number. If the plot described shows points randomly distributed, it is another evidence that the data can be assumed as independent (TAHERI and BAZZAZI, 2016).

TBF and TTR correlation

The relationship between TBF and TTR is tested by plotting both parameters against each other (TSAROUHAS, 2018). If the data do not present a clear tendency, it indicates that there is not a correlation between TBF and TTR events.

5.4.4 Definition of the best theoretical probability distribution

We fitted five different theoretical distributions (exponential, Weibull, log-normal, gamma and normal) to TBF and TTR series by the maximum likelihood estimation method.

Moreover, we applied a goodness-of-fit test to identify the distribution that best fitted the failure data among those chosen. We selected Cramér-von Mises (CvM) goodness-of-fit test and, the procedure of it is described on Crow (1974).

To complement the goodness-of-fit test we selected other two criteria: Q-Q and P-P plot analysis. We made a brief description of each of them on the following sections.

Q-Q plot

The Q-Q plot (quantile-quantile plot) is a visual tool that helps to identify if a set of data came from some theoretical distribution. This kind of graph is a scatterplot of two sets of quantiles plotted against each other. When the result is close to a straight line, it indicates that both sets came from the same distribution.

P-P plot

The P-P plot (probability–probability plot) is a visual tool that helps to identify if a set of data came from some theoretical distribution. This kind of graph shows two cumulative density functions (CDFs) against each other. When the result is close to a straight line, it indicates that both sets came from the same distribution.

5.4.5 Reliability analysis

Reliability is the probability that a component or system operates without failure under a specified period and a certain condition. In other words, it is the probability that the component will survive at a given time (ESMAEILI, *et al*, 2011 and NIST, 2020c). Equation 5.1 describes mathematically this parameter (ESMAEILI, *et al*, 2011).

$$R(t) = 1 - F(t) \tag{5.1}$$

Where:

$R(t)$ - reliability function evaluated at time t, in hours;

$F(t)$ - cumulative failure distribution function;

We calculated the failure distribution function fitting TBF data.
Moreover, we calculated the reliability probability for all Line A equipment.

5.4.6 Hazard plots

The hazard rate (or failure rate), for a non repairable systems, is a rate per unit of time. In other words, it is the instant failure rate for the system at a determined time (NIST, 2020c). Equation 5.2 describes it mathematically.

$$h(t) = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{R(t)} \tag{5.2}$$

Where:

$h(t)$ - instantaneous conditional failure rate;

$f(t)$ - theoretical probability density function;

The Cumulative hazard function is the sum of all hazard rates, then:

$$H(t) = \int_0^t h(t) \tag{5.3}$$

Finally, Cumulative hazard plots are graphs of the cumulative hazard (Equation 5.3) versus time (NIST, 2020c).

We plotted the described hazard function for all Line A equipment. Afterwards, we compared the results to the bathtub curve. The objective of creating the hazard plots was to identify in which part of the bathtub curve the machine is.

The bathtub curve is a empirical model obtained by calculating the failure rate as units age over time. Its name is given due to its shape. Figure 5.8 illustrates a generic bathtub curve and, highlights its three parts: infant mortality, normal life and wear out phase.

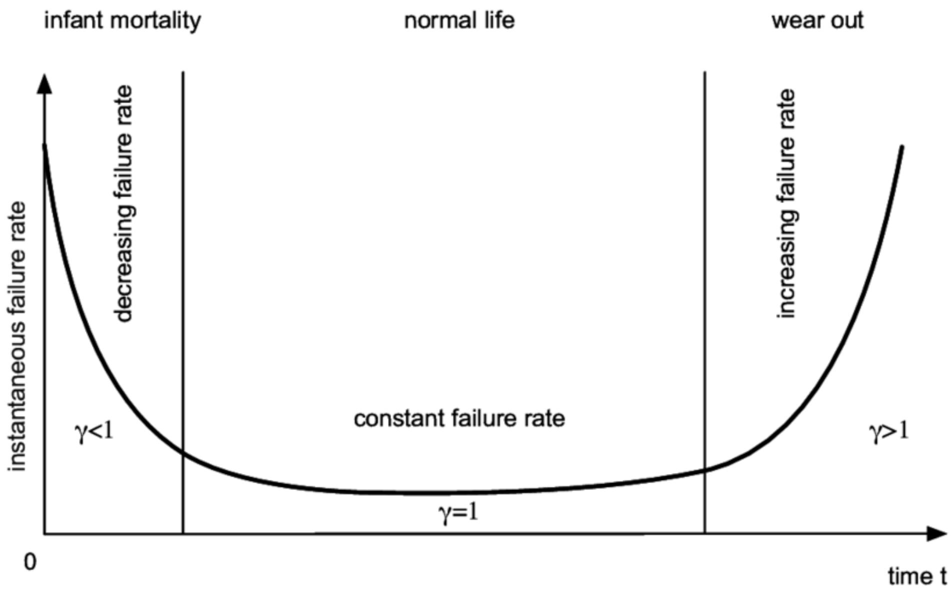


Figure 5.8: The bathtub curve (LU *et al.*, 2016).

The first region, named infant mortality period, occurs when a customer starts to use the product. It is characterized by a rapidly decreasing failure rate.

The intermediate region represents the period that the failure rate remains constant.

The last region represents the products that are used long enough, thus their failure rate begins to increase due to materials wearing out. That is why this region is called wear-out.

It is necessary to compare the hazard plots of each machine with the theoretical bathtub curve shape. This analysis allows us to identify if any machine is at wear-out stage, suggesting that it should be overhauled or replaced.

5.4.7 Maintainability analysis

Maintainability is the probability that a component or system will be restored to operational effectiveness under a specified period under a certain condition. In other words, maintainability is the probability to recover completely at a given time (TSAROUHAS, 2018). Equation 5.4 describes it mathematically.

$$M(t) = \int_0^t g(t) \tag{5.4}$$

Where:

$M(t)$ - maintainability function evaluated at time t in hours;

$g(t)$ - function that describes the time to recover data;

We calculated the time to recover distribution function fitting TTR data.

5.5 Rules of thumb: development

To develop some rules of thumb for filling lines, we evaluated line and buffer parameters of three different returnable bottle lines (Lines A, B and C). We selected these three lines, because they have the same layout. In other words, all three are returnable bottle lines with two labellers. Therefore, we could infer some general rules for each parameter without the effect of having different number and topology of machine on the line.

The line and buffer parameters calculations we used to develop the rules of thumb are described by Equations 5.5 to 5.8 (line parameters) and Equations 5.9 to 5.18 (buffer parameters).

Line parameters

Machine availability (equation 4.5) is the first parameter that needs to be calculated.

Afterward, we calculated the MER (mean efficiency rate) to identify which machine is the actual bottleneck considering only speeds and failure parameters (Equation 5.5). For parallel equipment, it is the sum of the MERs of all machine on this step.

$$\text{Mean Effective Rate (MER)}_{machine} = \eta_{machine} \cdot \frac{\text{Machine Nominal Speed}}{\text{Filler Nominal Speed}} \tag{5.5}$$

To estimate buffer strategy performance two line efficiency theoretical limits (upper and lower) were calculated. The lower limit consists of an hypothetical filling line with exactly the same number of machines and efficiencies, but without buffer. This means that every time a machine stops, the whole line stops too. This condition is called *zero-buffer limit*, and its calculation is expressed on Equation 5.6. On the other hand, the upper limit consists of another hypothetical filling line with the same number of machines and efficiencies, but with infinite buffer. In other words, the machines work completely independently from each other. This condition is called *infinite-buffer limit* and, it is calculated as expressed on Equation 5.7 (HÄRTE, 1997).

$$\text{Lower limit} : \eta_{line}^{0} = \min_{\text{machine}} C^{\text{machine}} \cdot \prod_{\text{machine}} \eta_{machine} \tag{5.6}$$

$$\text{Upper limit} : \eta_{line}^{\text{inf}} = \min_{\text{machine}} \text{MER}_{\text{machine}} \tag{5.7}$$

After calculating the upper and the lower limit of line efficiency, we calculated the buffer strategy performance through Equation 5.8. This parameter is defined as the percentage of the difference between the actual line efficiency and the lower limit and the difference between the infinite-buffer limit and the zero buffer limit (HÄRTE, 1997).

$$\beta = \frac{\eta_{line} - \eta_{line}^{0}}{\eta_{line}^{inf} - \eta_{line}^{0}} \tag{5.8}$$

Where η_{line} is calculated using Equation 4.5 and filler data, once it is the line core machine (HÄRTE, 1997).

To explore more the relationship between line efficiency and buffer strategy performance, we performed a sensibility analysis with Line A data. In this analysis, we varied line efficiency from the lower limit (20.9%, for Line A) to the upper limit (84.0%, for Line A). The results are shown on Figure 5.9.

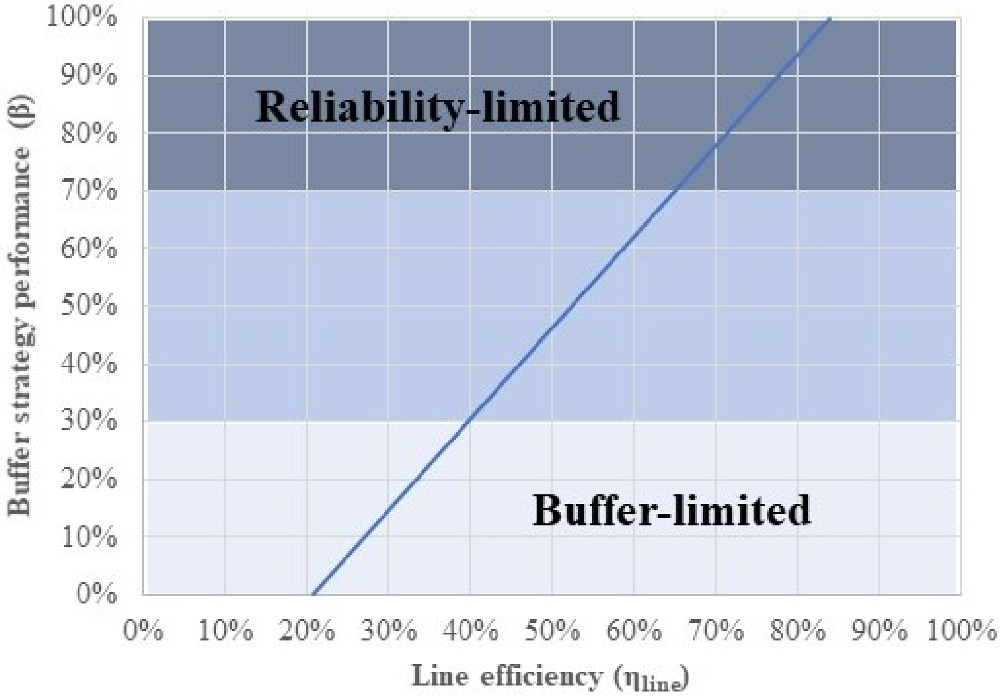


Figure 5.9: Graph of line efficiency *vs* buffer strategy performance

We suggest the existence of three different areas for the buffer strategy performance parameter: lower, intermediate and upper values, as seen in Figure 5.9.

The first area (lower values) varies from 0 to 30%, approximately. It suggests that when line efficiency is closer to the zero-buffer limit, the line bottleneck tends to be the size of buffers (it can be more than one buffer).

The intermediate area (intermediate values) varies from 30 to 70%, approximately. It is described as the biggest area and, there the line bottleneck is not clear. The most probable bottleneck for this kind of filling line is a mix of both problems: buffer sizes and machine reliability. When one of the problems is solved, or minimized, the second becomes more evident. In addition, when dealing with filling lines on the intermediate area is strongly advisable to carefully evaluate machines and buffer parameters to understand which kind of project has the highest return of investment.

Finally, the last area (upper values) varies from 70 to 100%, approximately. This area suggests that the line bottleneck is machine's reliability. Therefore, to increase line efficiency is necessary to carefully evaluate preventive maintenance schedule and promote studies to investigate the root cause of the most frequent failures for the most critical machine.

Regardless to how line efficiency is calculated, the criteria used to define each zone can be applied without changes.

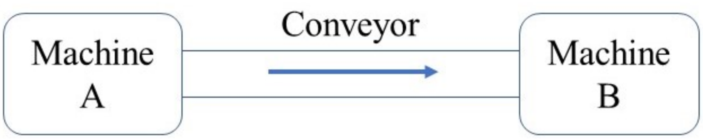
It is important to point out that the intervals suggested for each region are not fixed. For example, a line that presents a buffer strategy performance of 65%, probably is limited by machine reliability and not buffer size.

As seen, the buffer strategy performance (Equation 5.8) describes the buffer strategy efficiency as a whole. However, each buffer performance can be evaluated individually. The next section describes all buffer parameters calculated.

Buffer parameters

The buffer parameters listed in Equations 5.9 to 5.18 were developed by HAINES (1995) and HÄRTE (1997). Each parameter has a variation for *anti-starve* and *anti-block* buffers. The names of machines A and B are used as the reference on all buffer equations. Figure 5.10 shows these two hypothetical machines connected by a conveyor.

Figure 5.10: Two hypothetical machines connected by a conveyor



Source: Adapted from HÄRTE (1997)

Accumulation ratio (Equations 5.9 and 5.10) represents how fast a buffer decrease (for *anti-starve*) or increase (for *anti-block*) relatively to buffer accumulation capacity. The higher the accumulation ratio, less influence the machine A failures has on machine B (starvation scenarios) and less influence the machine B failures has on machine A (blockage scenarios).

$$\text{Accumulation ratio}_{\text{anti-starve}} = \frac{n}{\mathrm{C}_B^{nom} \cdot \mathrm{MTTR_A}} \tag{5.9}$$

$$\text{Accumulation ratio}_{\text{anti-block}} = \frac{n}{\mathrm{C}_A^{nom} \cdot \mathrm{MTTR_B}} \tag{5.10}$$

Nominal recovery ratio (Equations 5.11 and 5.12) is how a fast a buffer increases (for *anti-starve*) or decreases (for *anti-block*) relatively to buffer accumulation capacity. The higher the nominal recovery ratio more failures of machine A (starvation scenarios) or machine B (blockage scenarios) are covered due to machines' speed difference.

$$\text{Nominal recovey ratio}_{\text{anti-starve}} = \frac{\text{MTBF}_A \cdot (\text{C}_A - \text{C}_B^{nom})}{n} \tag{5.11}$$

$$\text{Nominal recovey ratio}_{\text{anti-block}} = \frac{\text{MTBF}_B \cdot (\text{C}_B - \text{C}_A^{nom})}{n} \tag{5.12}$$

Mean recovery ratio (Equations 5.13 and 5.14) have a similar physical meaning to the nominal recovery ratio. The only difference is that the nominal recovery ratio is relative to buffer accumulation capacity and the mean is relative to the consumption rate of containers (starvation scenarios) or to accumulation rate (blockage scenarios). The mean recovery ratio can also be calculated multiplying the accumulation ratio with the nominal ratio. As expected, the higher the mean recovery ratio better, because it suggests that the buffer is filling (*anti-starve* buffers) or emptying (*anti-block* buffers) in order to avoid unplanned downtime by starvation or blocking, respectively.

$$\text{Mean recovey ratio}_{\text{anti-starve}} = \frac{\text{MTBF}_A \cdot (\text{C}_A - \text{C}_B^{nom})}{\text{C}_B^{nom} \cdot \text{MTTR}_\text{A}} \tag{5.13}$$

$$\text{Mean recovey ratio}_{\text{anti-block}} = \frac{\text{MTBF}_B \cdot (\text{C}_B - \text{C}_A^{nom})}{\text{C}_A^{nom} \cdot \text{MTTR}_\text{B}} \tag{5.14}$$

Where:

C_A^{nom} - Machine A nominal speed;

C_B^{nom} - Machine B nominal speed;

C_A - Machine A maximum speed;

C_B - Machine B maximum speed;

n - Capacity in containers of the conveyor;

The next two parameters represent the efficiency of each buffer individually. The first parameter is calculated based on running time (Equations 5.15 and 5.16) and the second on number of events (Equations 5.17 and 5.18).

$$\eta_{buffer}^{AB} = \frac{\text{T}_{\text{STOP}}^{A} - \text{T}_{\text{STARVE}}^{B}}{\text{T}_{\text{STOP}}^{A}} \tag{5.15}$$

$$\eta_{buffer}^{BA} = \frac{\text{T}_{\text{STOP}}^{B} - \text{T}_{\text{BLOCK}}^{A}}{\text{T}_{\text{STOP}}^{B}} \tag{5.16}$$

$$\eta^{AB}_{buffer-events} = \frac{\text{Number of stops of machine A} - \text{Number of events machine B is starved}}{\text{Number of stops of machine A}} \tag{5.17}$$

$$\eta^{BA}_{buffer-events} = \frac{\text{Number of stops of machine B} - \text{Number of events machine A is blocked}}{\text{Number of stops of machine B}} \tag{5.18}$$

Where:

$\text{T}^{A}_{\text{STOP}}$ - Total stop time of machine A except when blocked by machine B. Examples: total time machine A is failed and starved;

$\text{T}^{B}_{\text{STARVE}}$ - Total time machine B is starved;

$\text{T}^{B}_{\text{STOP}}$ - Total stop time of machine B except when starved by machine A. Examples: total time machine B is failed and blocked;

$\text{T}^{A}_{\text{BLOCK}}$ - Total time machine A is blocked.

Parallel machine

In order to correct handle with parallel machine, some considerations should be made before calculating the previous buffer parameters:

Variables that should be summed:

- C^{nom} - Sum all nominal speeds for that step;
- N - Sum the capacity of all conveyors between the two machines;

Variables that should be averaged:

- $MTBF$, $MTTR$;
- T_{STOP}, T_{STARVE}, T_{BLOCK};
- Number of stops of machine X, Number of events machine X is blocked, Number of events machine X is starved;

5.6 Rules of thumb: test

Once the rules of thumb were developed based on returnable bottle line results, we verified its robustness testing them on a filling line with different layout. Thus, a can line (Line D) was chosen to have its line and buffer parameters evaluated through the rules of thumb proposed.

Chapter 6: Results and Discussion

This chapter presents and discusses the results achieved by applying the methodology described on the previous chapter.

Section 6.1 describes Line A RAM analysis. Sections 6.2 and 6.3 deal with rules of thumb development and testing, respectively. In addition, Section 6.4 summarizes the main improvement opportunities that we found for all four lines evaluated, and we also explain some restrictions for the rules of thumb developed.

6.1 RAM (Reliability, Availability and Maintainability Analysis) analysis

RAM analysis was divided into seven sections: failure data analysis (6.1.1), descriptive statistics of failure and recover data (6.1.2), independent and identically distributed analysis (6.1.3), definition of the best theoretical probability distribution (6.1.4), hazard plots (6.1.5), reliability analysis (6.1.6), maintainability analysis (6.1.7) and RAM analysis sum up (6.1.8).

6.1.1 Failure data analysis

Failure data analysis of Line A aimed to evaluate the failure behavior of this line through histograms and Pareto diagrams.

Line A is subjected to preventive and corrective maintenance programs. The first type is scheduled and normally occurs once a week. As expected, this kind of maintenance aims to prevent breakdowns and failures. Some actions that are considered as preventive maintenance are: greasing, oil change and pieces replacement. These actions are required in order to keep and/or increase the reliability of all line equipment. On the other hand, corrective maintenance occurs when a machine needs an emergency repair in order to keep producing.

Line A was designed based on the V-graph theory, thus the core machine for this line is the filler (bottleneck by design). As Line A production is measured on the filler, the reliability analysis for this machine is extended to the whole line.

Figures 6.1 and 6.2 show the histograms of failure for the filler, Figures 6.3 and 6.4 for bottle washer and Figures 6.5 and 6.6 for pasteurization unit. The histograms for the other machines are in **Appendix A**.

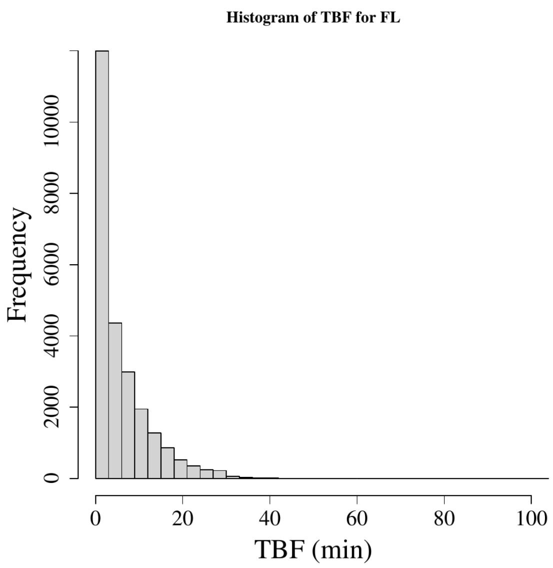


Figure 6.1: Histogram of TBF data for Line A filler.

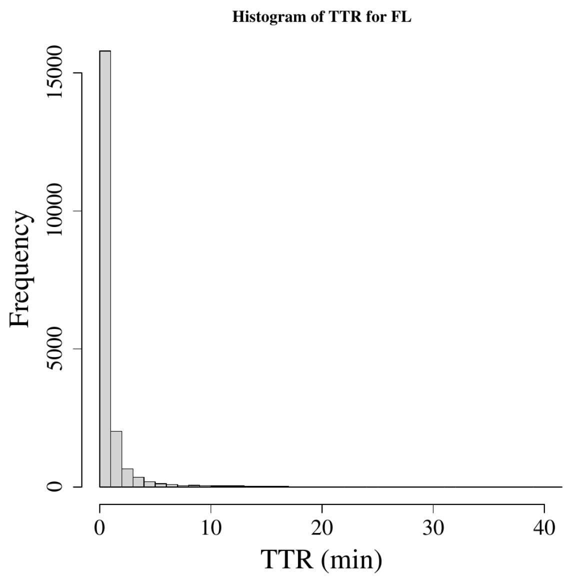


Figure 6.2: Histogram of TTR data for Line A filler.

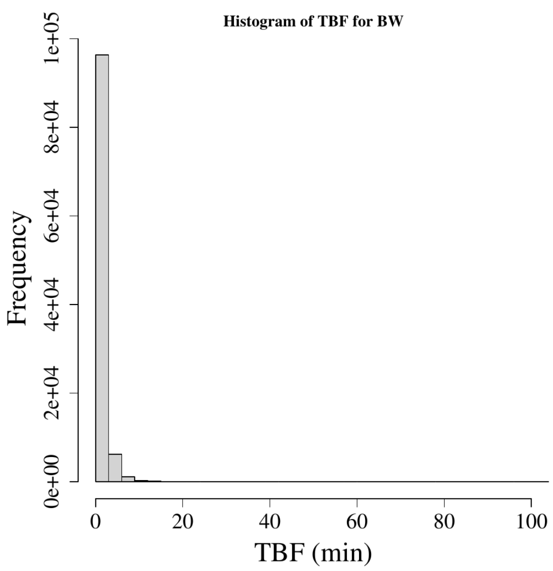


Figure 6.3: Histogram of TBF data for Line A bottle washer.

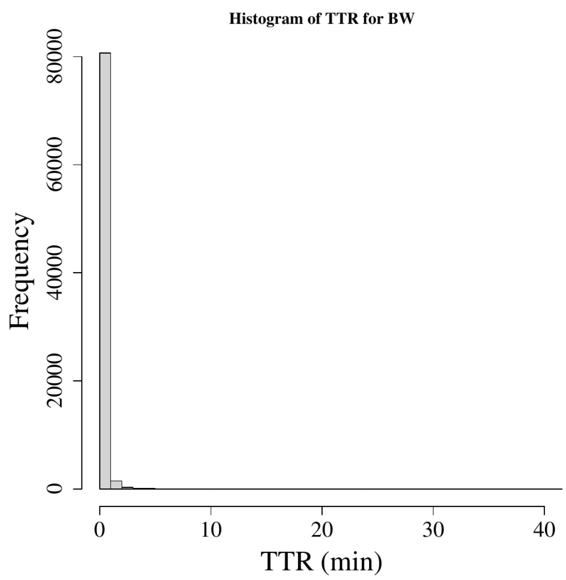


Figure 6.4: Histogram of TTR data for Line A bottle washer.

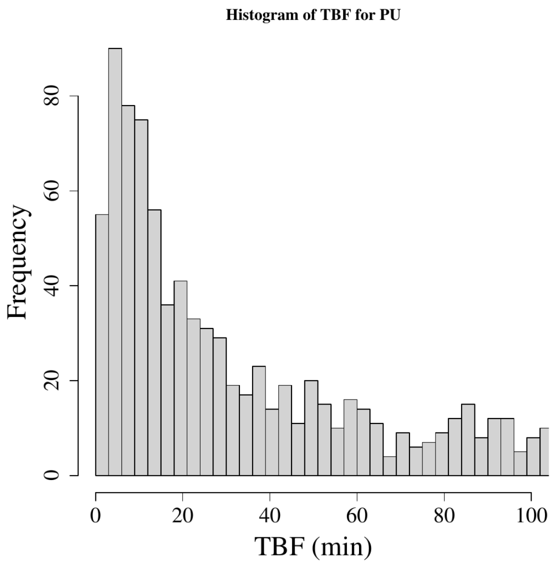


Figure 6.5: Histogram of TBF data for Line A pasteurization unit.

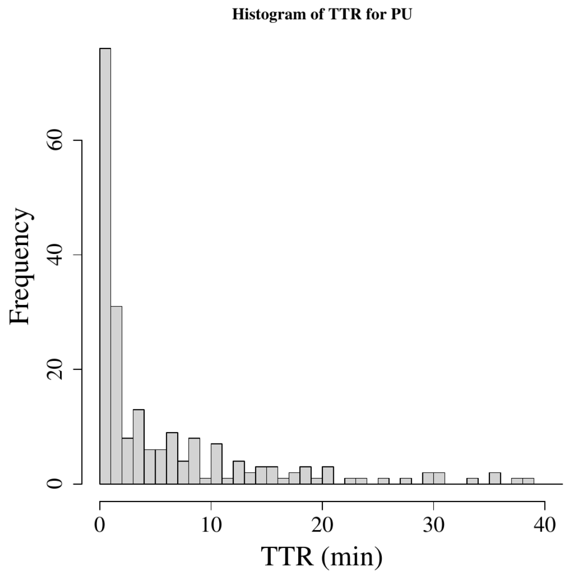


Figure 6.6: Histogram of TTR data for Line A pasteurization unit.

TBF and TTR histograms show a shape of right tailed distribution. Comparing Figures 6.1 and 6.2 with the other machines available on Line A (except BW and PU), we observe that the data have similar characteristics.

Considering the filler TBF histogram (Figure 6.1) almost all events last between 0 to 30 minutes. On the other hand, TTR events (Figure 6.2) are much shorter, having most of its events between 0 to 5 minutes. In other words, even though most of machines fail with high frequency, most of these events are very short.

We verified a different behavior when we compared the filler to the bottle washer (Figures 6.3 and 6.4) and to the pasteurization unit histograms (Figures 6.5 and 6.6). Bottle washer presents a failure behavior more intense, in other words, with higher number of failure events. But, they are considerably shorter when compared to the filler.

Most of bottle washer TBFs events lasted less than 5 minutes, while its TTR most frequent events lasted almost 1 minute. This implies that although the bottle washer fails with more frequency, when compared to the filler, it also recovers much faster (almost 5 times faster). We observed the opposite behavior in the pasteurization unit results. For this machine, there is a considerable reduction on the number of failure events, but with longer duration (considering only 90% of the events).

Another interesting point when comparing TBF histograms for these three machines is the dispersion of TBF values for PU. Its values are considerably higher when compared to the other two and, there are a considerable number of events with duration longer than 20 minutes. This kind of event is not observed for the other two machines.

We evaluated the failure frequency and the total time on the *failed* state for the whole Line A through two Pareto diagrams. The first graph (Figure 6.7) considers the total number of failure events and the second (Figure 6.8) considers the total time (in hours) of each machine on the status *failure*.

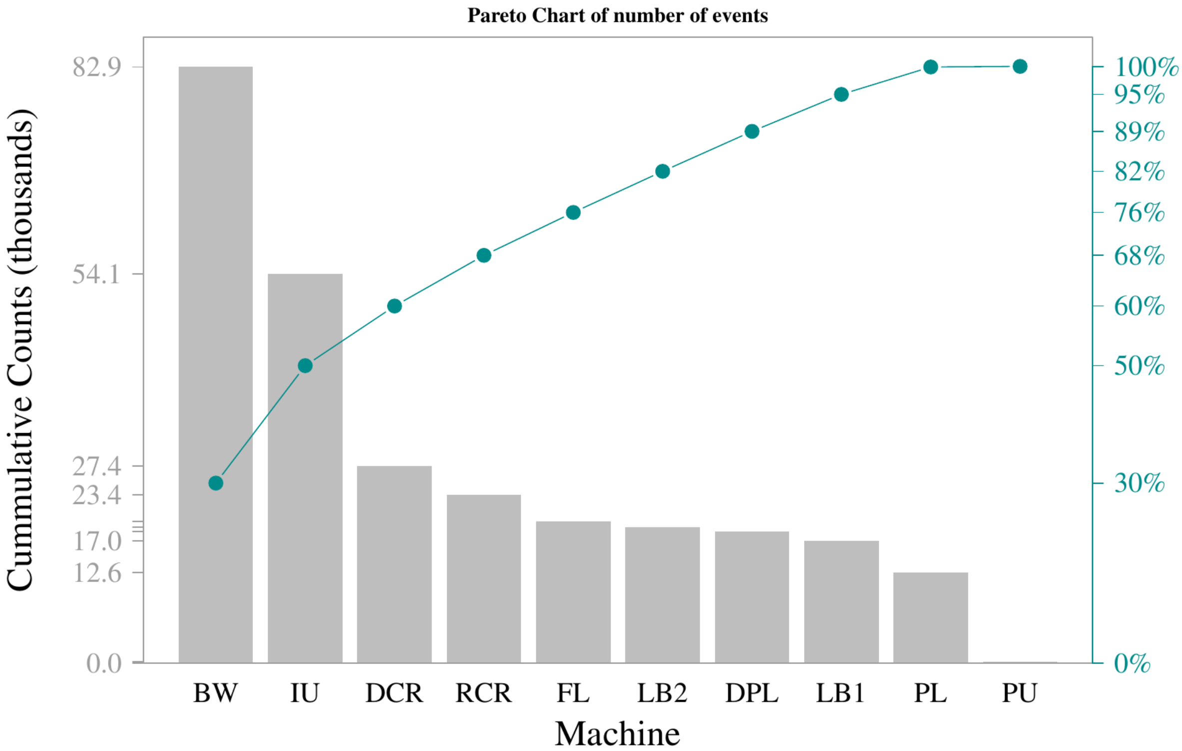


Figure 6.7: Pareto diagram for the number of failure events.

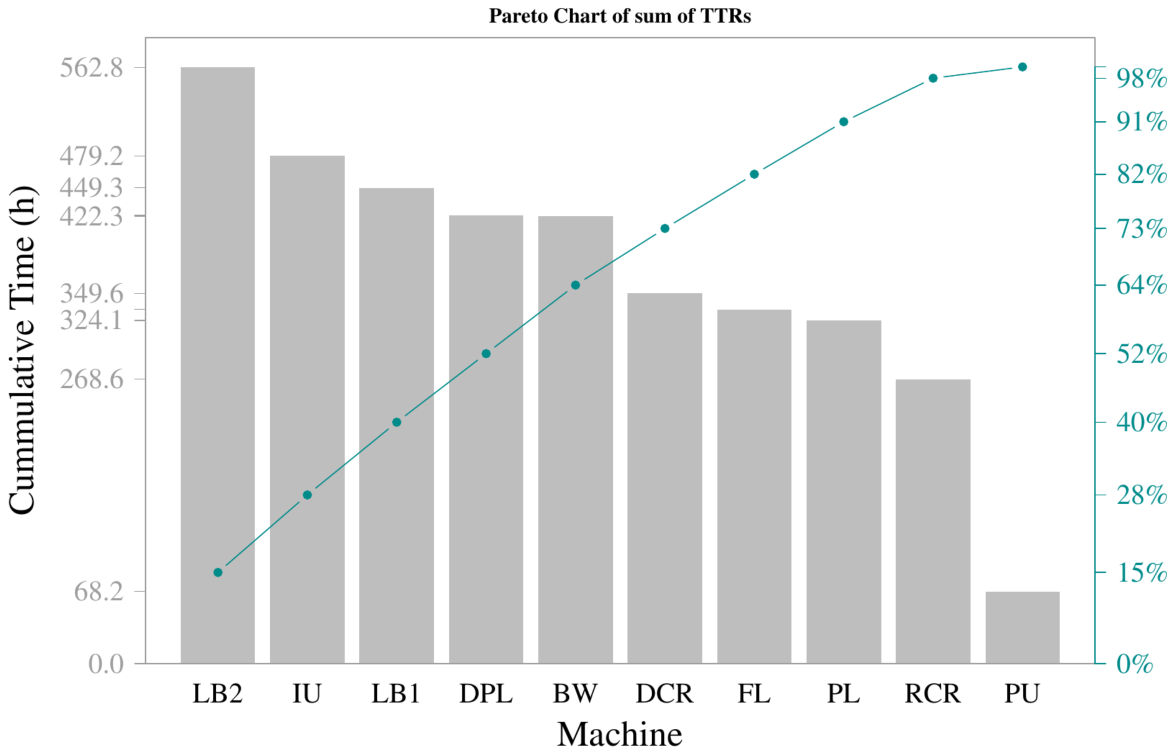


Figure 6.8: Pareto diagram for the total time on the status *failure*.

The bottle washer is the machine with the highest number of failure events. Although, evaluating the hours spent at the *failed* status, the labeller 2 presents the most relevant contribution (15% of the total failure time). This means that even though the bottle washer fails more, the duration of these events are much shorter, when compared to the other machines. The opposite behavior occurs with the depalletizer and the labellers 1 and 2. All these equipment present a considerable low number of failure events, but the highest total of hours on *failed* status.

In addition, Figure 6.8 shows that only four machines are responsible for more than 52% of the total hours on *failure* status, they are: labeller 2, inspector unit, labeller 1 and depalletiser.

6.1.2 Descriptive statistics of failure and recover data

Tables 6.1 and 6.2 show Line A results for the descriptive statistics tests. In addition, we calculated the availability [1] for every machine and, the results are available in Table 6.2.

[1] See Equation 4.6

Table 6.1: Descriptive statistics of TTR parameter for each machine of Line A

	Machine	N	Mean (s)	SD (s)	Median (s)	Min (s)	Max (s)	Skewness	Kurtosis	CoV
1	DPL	18299	83	226	43	6	10239	21.01	652.23	2.72
2	DCR	27433	46	124	23	6	5244	19.68	583.30	2.70
3	BW	82889	18	53	11	6	4553	36.41	2201.18	2.88
4	IU	54057	32	89	16	6	5666	25.75	1079.75	2.79
5	FL	19666	61	170	21	6	5263	11.18	203.35	2.77
6	PU	235	1044	2217	188	6	14412	3.64	15.04	2.12
7	LB1	17008	95	215	42	6	5207	10.20	158.52	2.26
8	LB2	18948	107	296	42	6	17770	21.14	887.53	2.77
9	RCR	23386	41	68	25	6	3457	14.17	415.31	1.64
10	PL	12646	92	119	63	6	2433	5.85	59.82	1.29

Table 6.2: Descriptive statistics of TBF parameter for each machine of Line A

	Machine	N	Mean (s)	SD (s)	Median (s)	Min (s)	Max (s)	Skewness	Kurtosis	CoV	Availability
1	DPL	18912	429	626	186	6	7396	3.08	14.53	1.46	0.84
2	DCR	27810	302	469	129	6	9739	4.15	31.85	1.55	0.87
3	BW	104184	75	289	39	6	19502	41.24	2129.95	3.85	0.80
4	IU	51492	152	194	88	6	3599	3.52	22.59	1.27	0.83
5	FL	24939	339	402	197	6	4064	1.98	5.57	1.19	0.85
6	PU	1100	4173	4764	2059	13	19850	1.45	1.29	1.14	0.80
7	LB1	15920	505	787	208	6	12496	3.63	22.02	1.56	0.84
8	LB2	17039	448	745	169	6	15216	4.25	35.39	1.66	0.81
9	RCR	25245	344	512	161	6	7658	3.75	23.12	1.49	0.89
10	PL	14013	606	967	206	6	14268	3.32	17.05	1.60	0.87

In Tables 6.1 and 6.2 the N (number of TBF or TTR samples) values were expected to be the same, because every failure event generates a TBF and TTR. In this study they are different because the data analyzed had been filtered (see Section 5.3 to check all the criteria used).

Comparing all TTR mean values, pasteurization unit is the machine that takes a longer time to recover from a failure (almost 18 minutes). Contrarily, the bottle washer is the one that recovers faster (18 seconds). In addiction, for TTR data, all equipment presented a positive value for skewness and kurtosis values above 3, which implies that all of them are skewed right and heavy-tailed.

Another interesting observation is the variability of the TTR data. It is expressed by the coefficient of variation. For almost all machines (except the recrater and palletizer) this parameter is higher than 2, which suggests a high variability.

Comparing all TBF mean values, pasteurization unit showed itself as the most reliable machine of Line A, taking almost 70 minutes to fail. On the opposite hand, the bottle washer is the less reliable, taking less than 2 minutes to fail. Analyzing the skewness and the kurtosis of the TBF data the same pattern observed for TTR is verified. The only exception is the pasteurization unit, which has a kurtosis value below 3 for TBF. As a consequence, it is the only machine that can be considered light-tailed.

Moreover, coefficient of variance for TBF set of data presented values around 1.5, which suggests a lower variance when compared to TTR data.

Finally, the pasteurization unit presented the lowest availability. It implies that this machine is only capable to operate 80% of its uptime (time available to run), due to its failures.

To complement TBF and TTR descriptive statistics analysis, we built a chart with TBF and TTR data and a moving average of 700 points. For the sake of simplicity, only three TBF and TTR trends were exposed here: the filler (Figures 6.9 and 6.10), bottle washer (Figures 6.11 and 6.12) and recrater (Figures 6.13 and 6.14). The graphs for the other machines are in **Appendix B**.

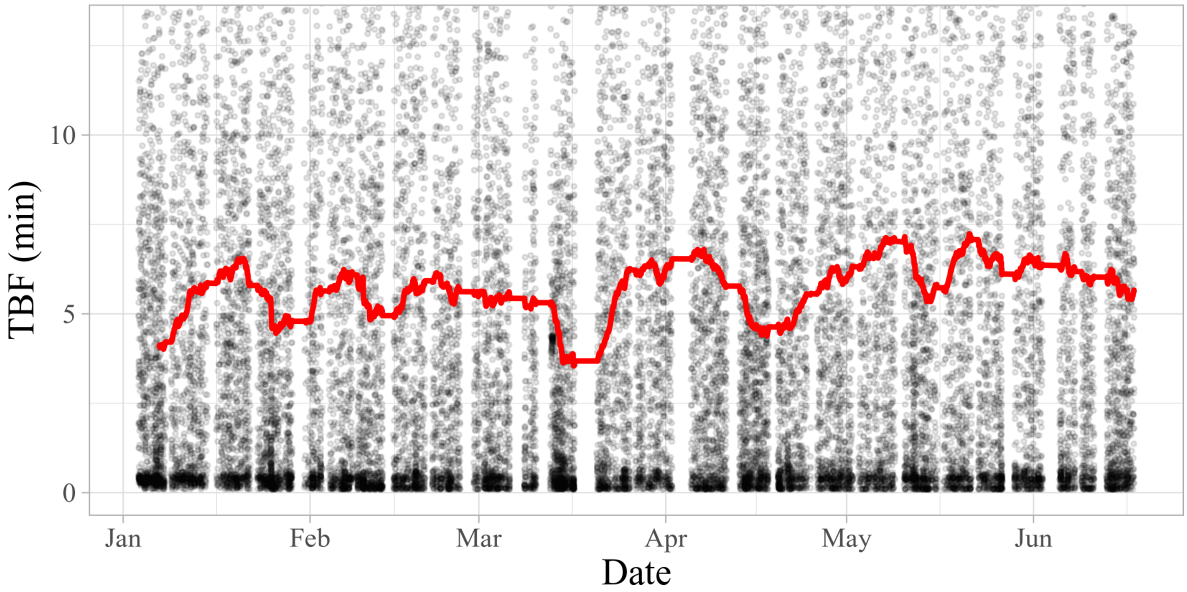


Figure 6.9: Filler TBF trend chart.

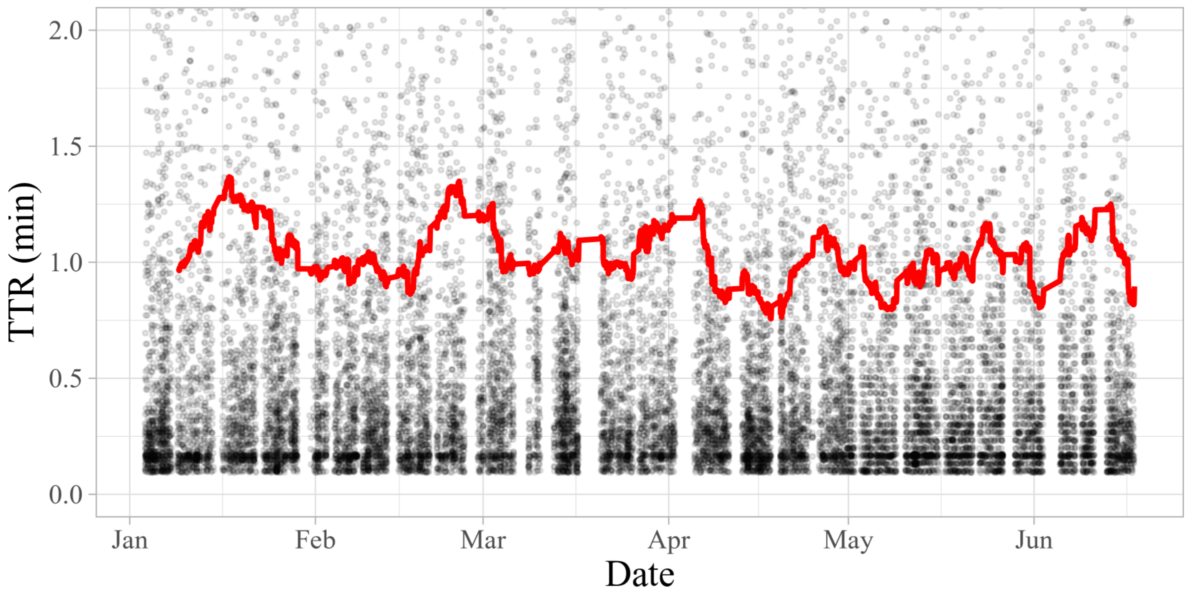


Figure 6.10: Filler TTR trend chart.

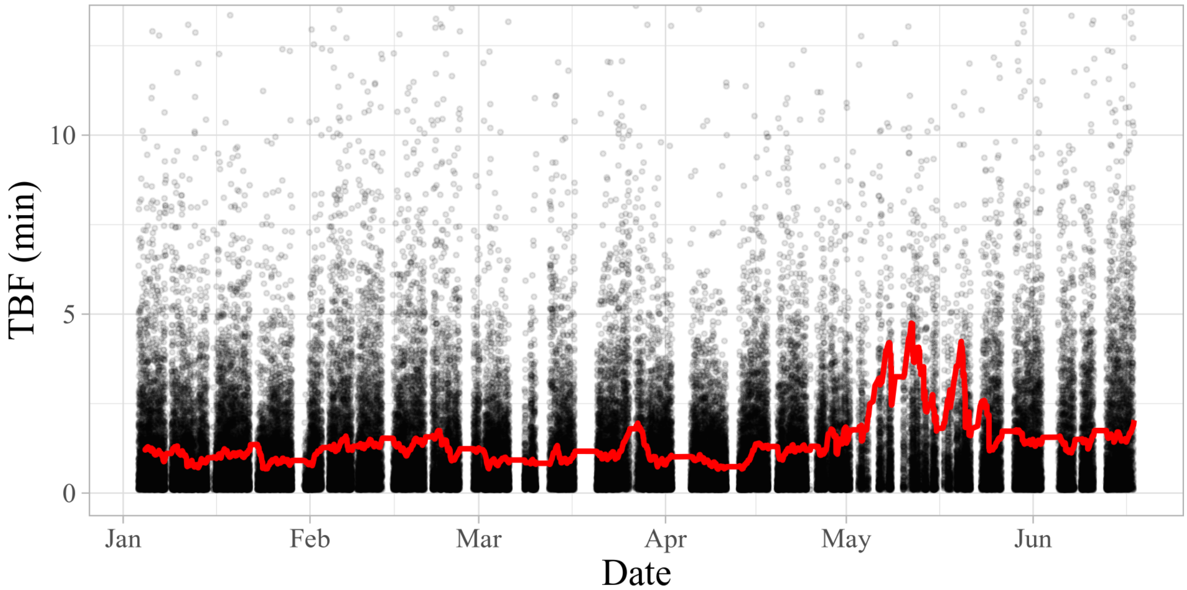


Figure 6.11: Bottle Washer TBF trend chart.

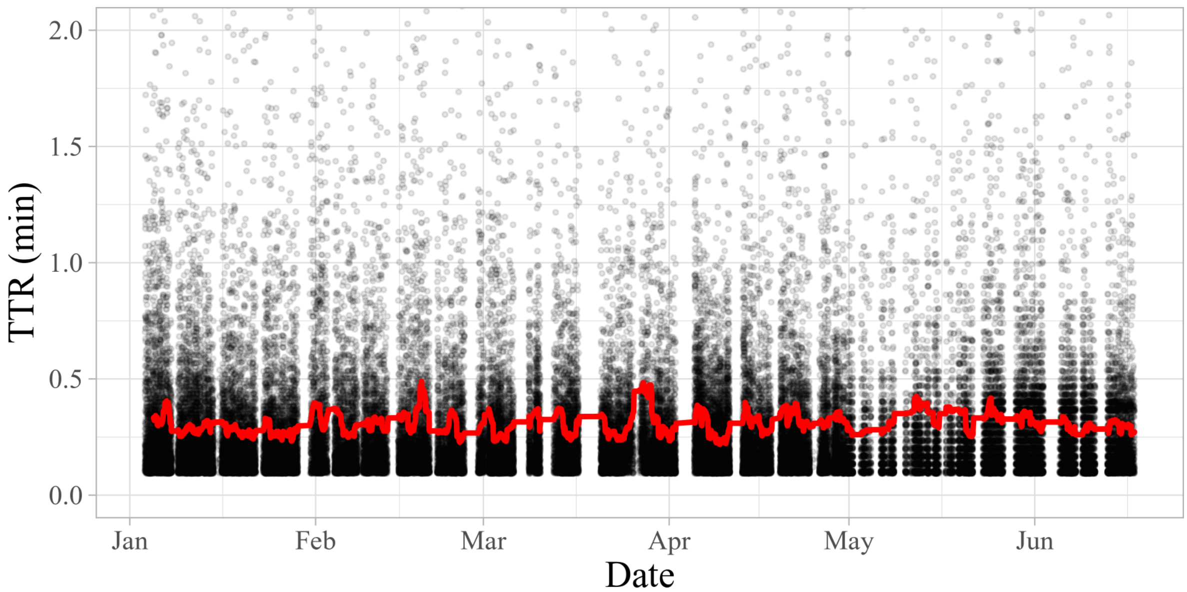


Figure 6.12: Bottle Washer TTR trend chart.

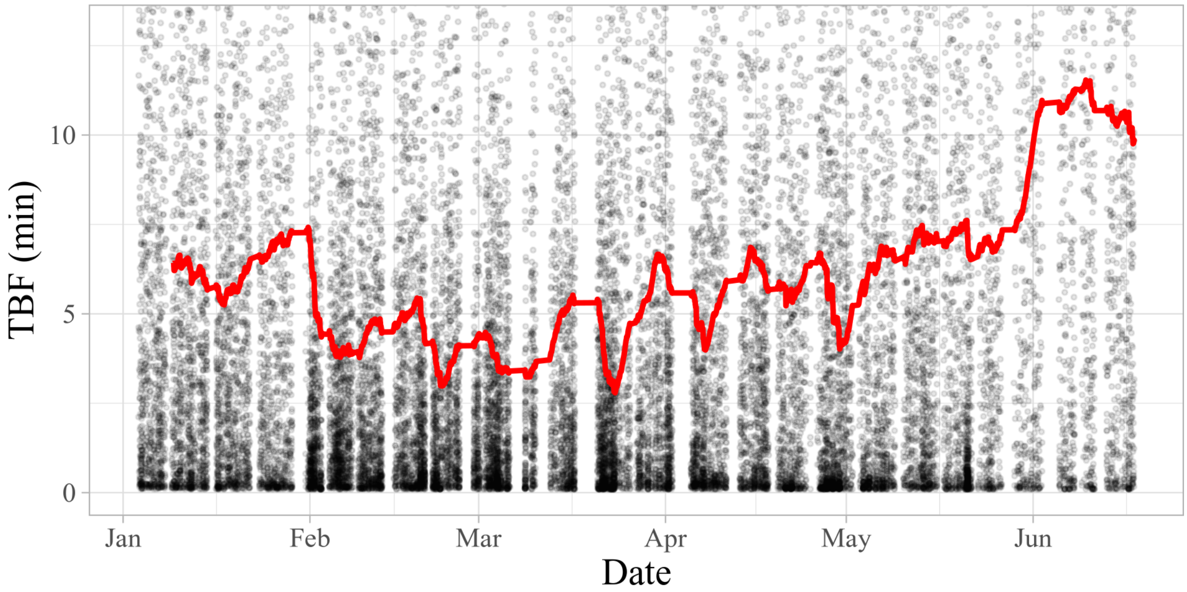


Figure 6.13: Recrater TBF trend chart.

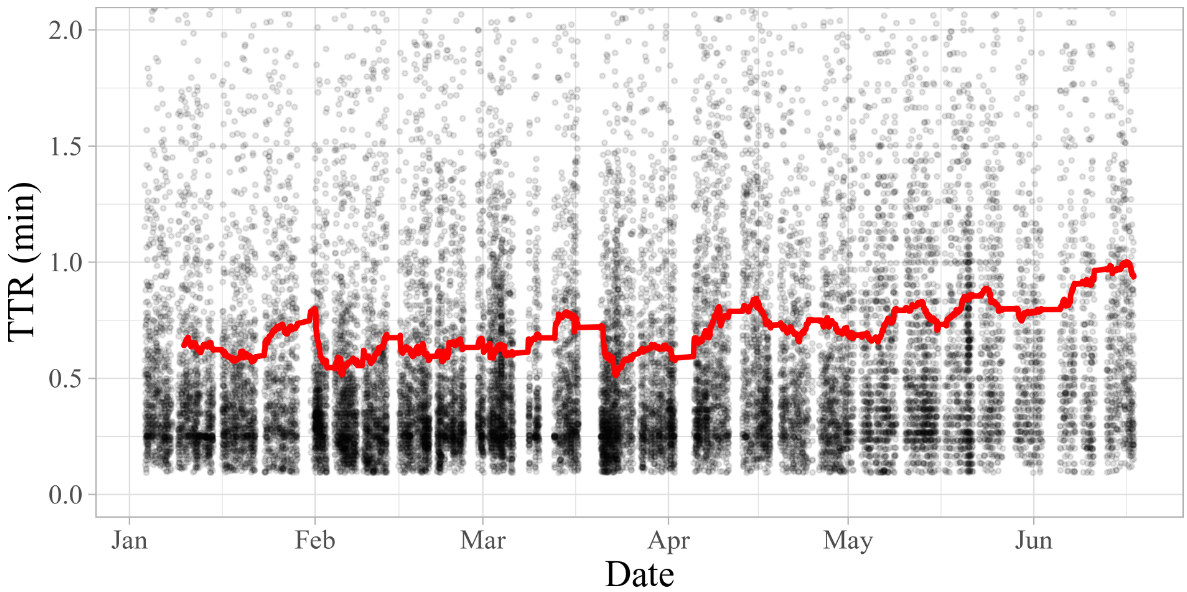


Figure 6.14: Recrater TTR trend chart.

All TBF and TTR trends, except recrater TBF, present a similar behavior, even though the nature of these equipment are considerably different.

The moving average of most of these machines varied within 1 minute interval for TBF trends and 0.5 minute for TTR trends during the analyzed period. The exceptions are: the bottle washer TBF trend during May and almost all recrater TBF trend.

Differently from the others, RCR TBF trend presents a higher variation and its moving average indicates a increasing tendency. In addition, recrater TBF graph suggests that this machine maintenance had been improving over the six month analyzed.

Aiming to assess the data variability, we constructed a box plot (Figures 6.15 and 6.16) for each Line A machine. To improve the visualization, all outliers were suppressed from the graphs. In addition, some of Pasteurization Unit results had to be suppressed to avoid distortion on the other machines, that is the reason the PU's forth quartile does not appear in both figures.

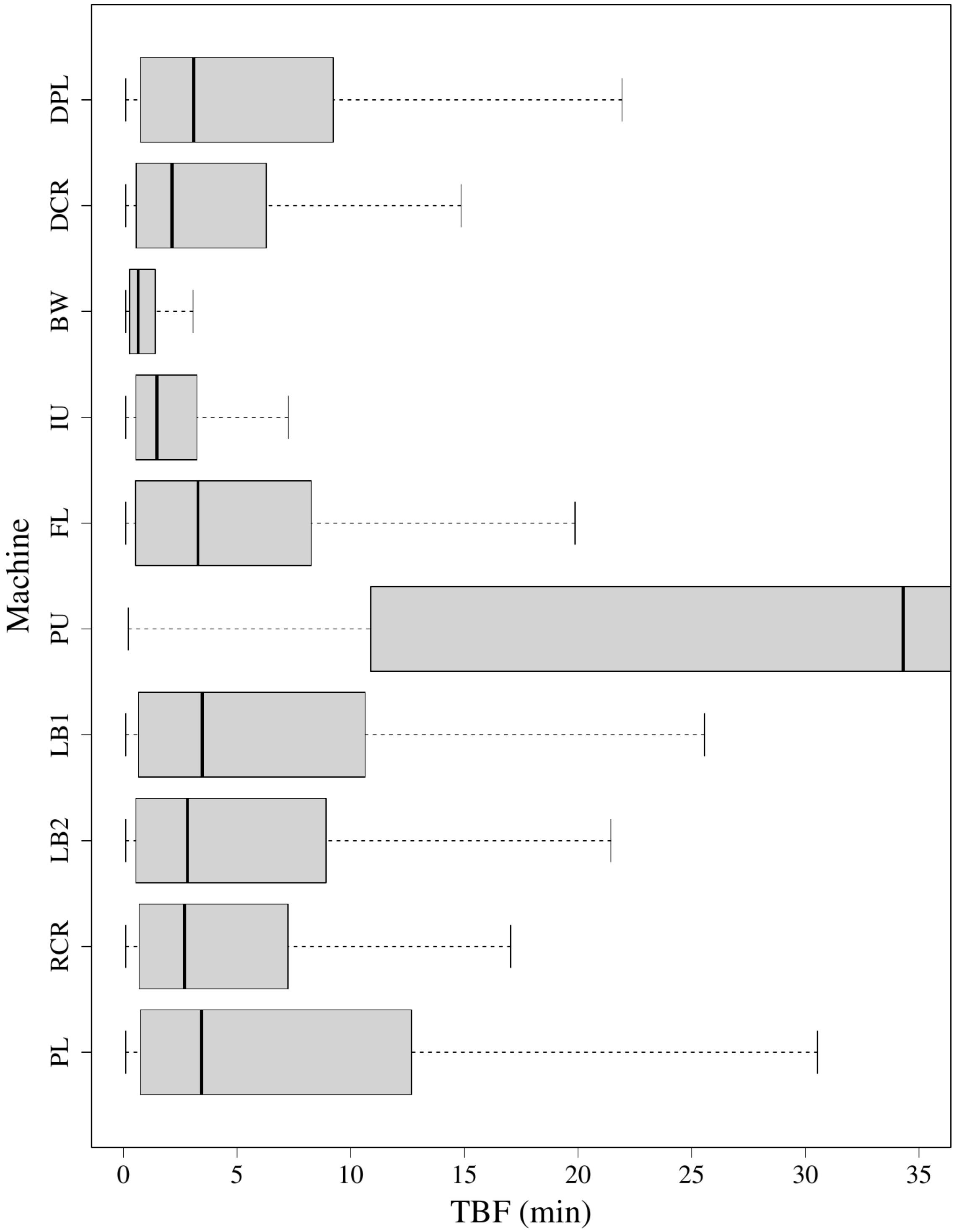


Figure 6.15: Boxplot diagram for TBF parameter for all Line A equipment.

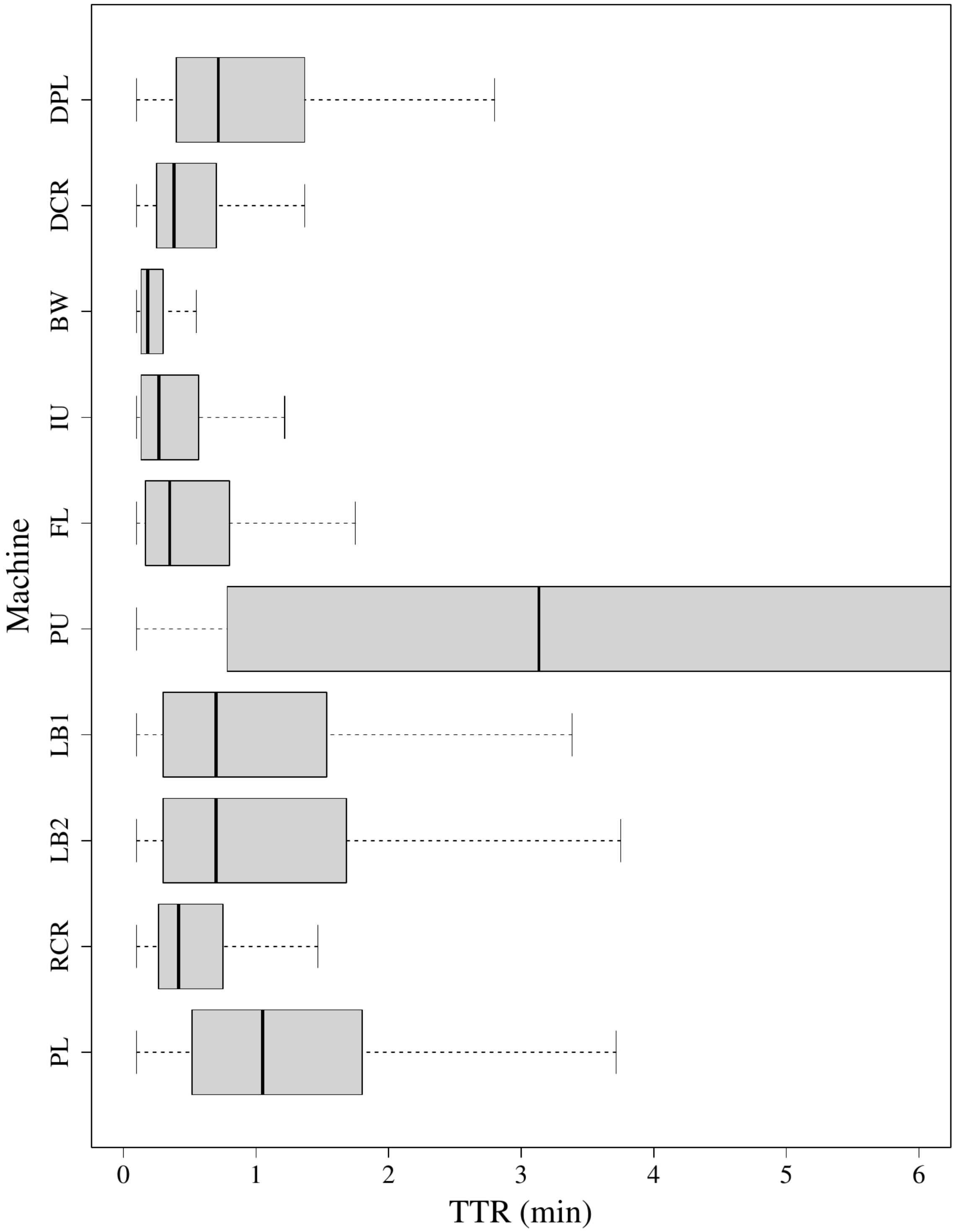


Figure 6.16: Boxplot diagram for TTR parameter for all Line A equipment.

Pasteurization unit box plots are considerably longer when compared to the other pieces of equipment. In addition, all graphs have the distance between the third quartile and the median considerably greater than the distance between the median and the first quartile. This observation corroborates that these distributions are right tailed and with high variance.

6.1.3 Independent and identically distributed analysis

In order to validate the IID hypothesis and to continue reliability and maintainability analysis, three tests were performed: trend test, serial correlation and the relationship between TBF and TTR.

All Line A equipment presented very similar results, except the Filler. Thus, the filler and labeller 1 were exposed as examples. The graphs for the other machines are shown in **Appendix C**. Figures 6.17 to 6.24 illustrate the results of trend tests, serial correlation tests and relationship between TBF and TTR for both FL and LB1.

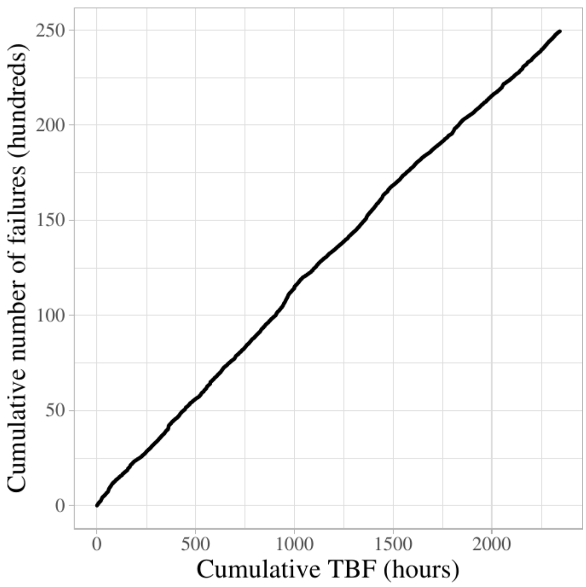


Figure 6.17: Line A filler trend test for TBF data.

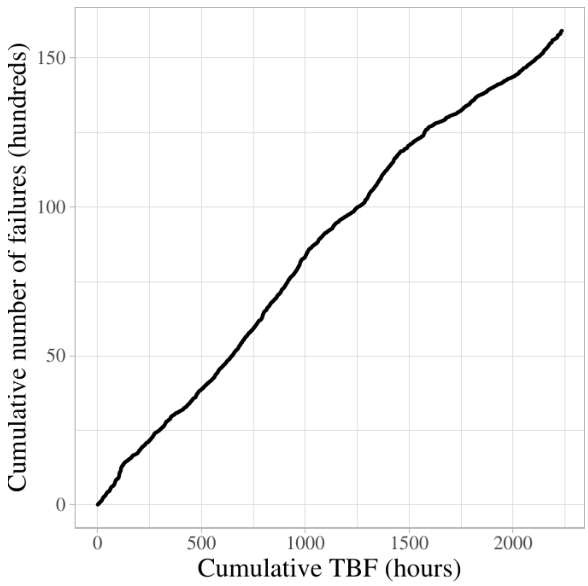


Figure 6.18: Line A labbeller 1 trend test for TBF data.

The data is free of trend, as trend test graphs for filler and labeller 1 showed a straight line.

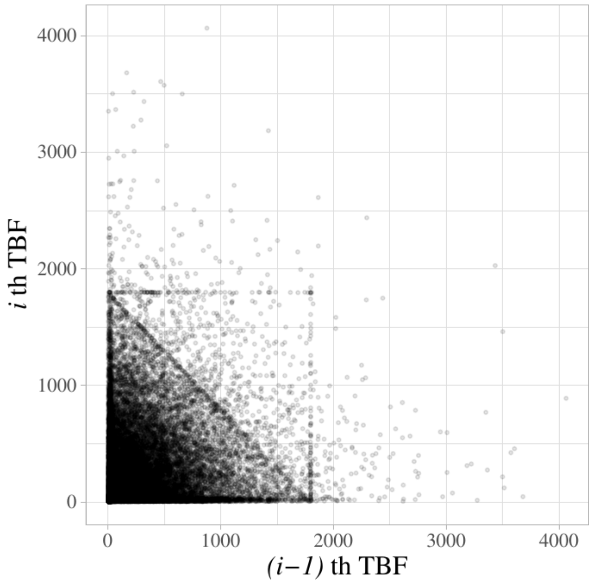


Figure 6.19: Line A filler serial correlation for TBF data.

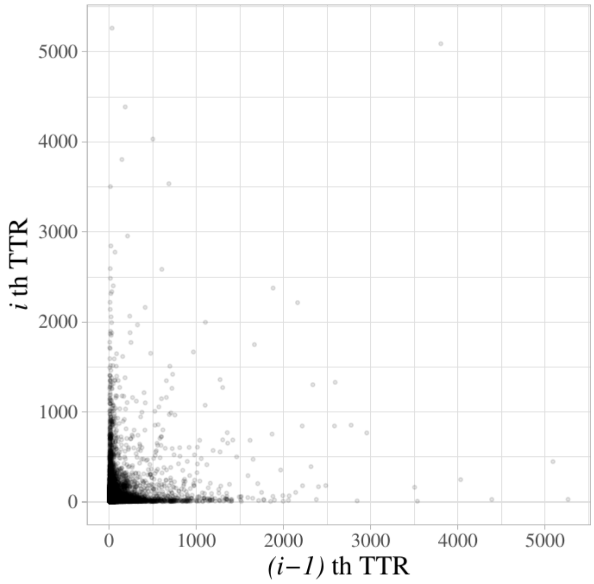


Figure 6.20: Line A filler serial correlation for TTR data.

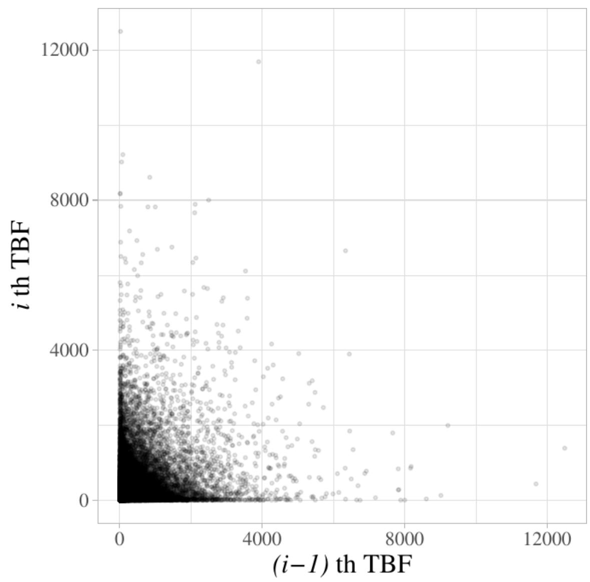


Figure 6.21: Line A labbeller 1 serial correlation for TBF data.

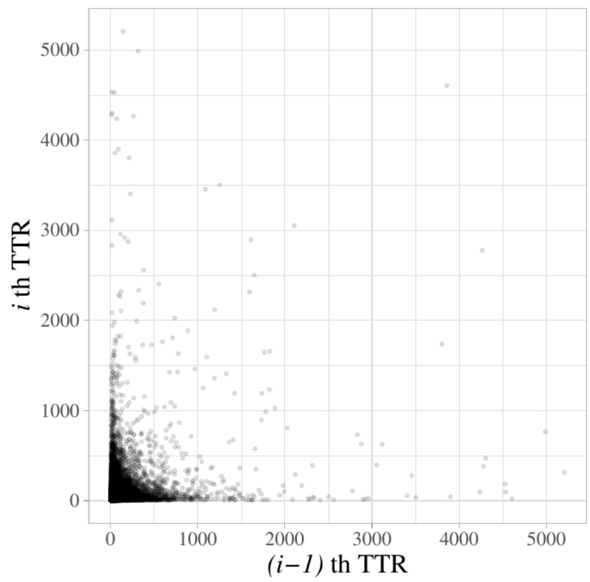


Figure 6.22: Line A labbeller 1 serial correlation for TTR data.

The serial correlation test for TTR of both machines and TBF of LB1 clearly does not present a tendency, since the data is randomly scattered. On the other hand, even though TBF serial correlation test for FL also presents a random scattered result for the most part of data, but an anomalous square shape is observed in Figure 6.19. It is related to how line running status was implemented. It considered that the line was not running when the filler was failed for more than 30 minutes and more than half of line machines are also failed. Thus, the acquired data became "polluted".

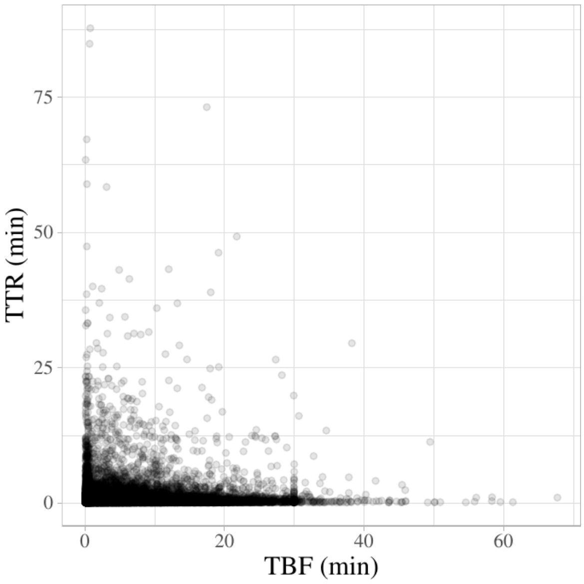


Figure 6.23: Line A filler TBF vs TTR correlation test.

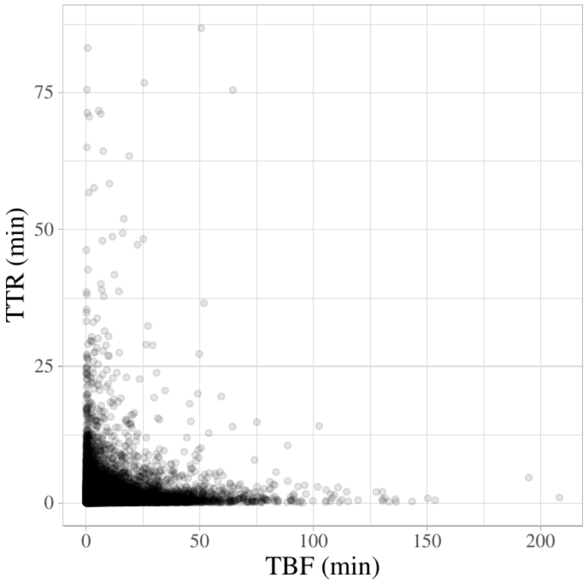


Figure 6.24: Line A labeller 1 TBF vs TTR correlation test.

The TBF and TTR for the filler and labeller 1 do not present an intrinsic correlation between them, as the data is clearly randomly scattered.

In conclusion, all equipment TBF and TTR data can be considered independent and identically distributed. Thus, it is possible to test several theoretical statistical distribution on each of them.

6.1.4 Definition of the best theoretical probability distribution

The TBF and TTR data of all Line A machines were tested for five different theoretical probability distributions. The results are shown in Tables 6.3 and 6.4. To complement Cramér-von Mises statistical tests, Q-Q plot and P-P plot charts for all equipment were built and are in **Appendix D**. The plots for bottle washer, the filler and the pasteurization unit (Figures 6.25 to 6.36) were further analyzed in this section, because they showed particular results that required a deeper analysis.

Table 6.3: Cramer von Mises statistics for TBF data of all Line A equipment

Machine	Exponential	Weibull	Log-normal	Normal	Gamma	Best fit	shape	scale	meanlog	sdlog
DPL	213.84	11.06	19.97	340.49	21.18	Weibull	0.72	341.39	-	-
DCR	305.95	11.70	25.10	536.76	79.05	Weibull	0.72	239.32	-	-
BW	442.44	180.15	30.61	4843.70	16636.15	Log-normal	-	-	3.66	1.08
IU	96.98	20.16	26.86	745.27	102.39	Weibull	0.90	143.73	-	-
FL	165.71	35.52	78.29	261.13	41.27	Weibull	0.77	291.07	-	-
PU	6.44	1.15	0.93	13.89	1.81	Log-normal	-	-	7.54	1.45
LB1	228.81	8.67	26.12	304.94	19.29	Weibull	0.66	373.07	-	-
LB2	299.00	12.86	20.88	373.21	55.62	Weibull	0.66	322.87	-	-
RCR	223.36	8.39	26.55	453.60	50.86	Weibull	0.74	280.87	-	-
PL	273.51	12.74	14.51	291.87	23.06	Weibull	0.64	431.26	-	-

Table 6.4: Cramer von Mises statistics for TTR data of all Line A equipment

Machine	Exponential	Weibull	Log-normal	Normal	Gamma	Best fit	meanlog	sdlog
DPL	118.86	89.58	5.81	759.80	1864.58	Log-normal	3.83	0.96
DCR	285.52	250.41	58.86	1206.00	2935.03	Log-normal	3.28	0.87
BW	1076.13	1082.02	259.16	4090.55	11071.16	Log-normal	2.54	0.67
IU	379.76	305.17	107.96	2266.34	5885.26	Log-normal	2.89	0.92
FL	445.43	161.06	50.90	877.40	1809.30	Log-normal	3.26	1.09
PU	11.67	0.74	0.37	8.11	3.13	Log-normal	5.35	1.86
LB1	182.06	55.52	5.32	594.04	957.30	Log-normal	3.78	1.15
LB2	270.16	57.96	7.70	746.69	1642.53	Log-normal	3.81	1.21
RCR	146.84	140.02	28.55	666.43	947.77	Log-normal	3.32	0.80
PL	19.47	17.52	5.42	221.43	131.62	Log-normal	4.06	0.97

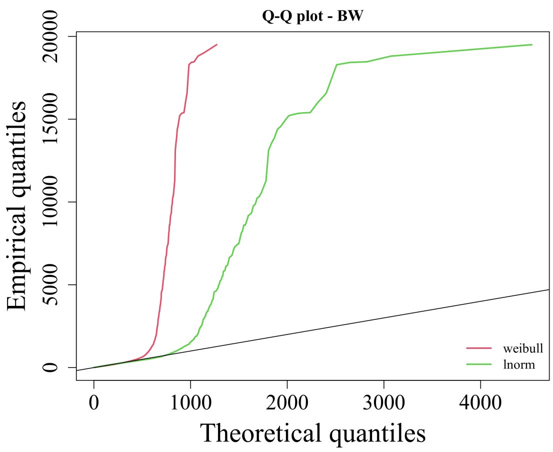


Figure 6.25: Q-Q plot for the bottle washer TBF data - comparison between Log-normal and Weibull.

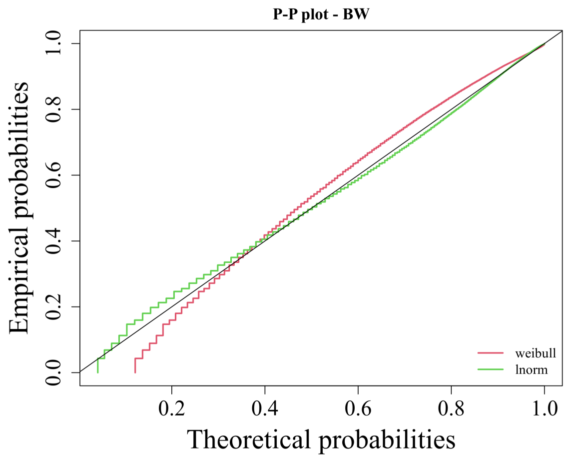


Figure 6.26: P-P plot for the bottle washer TBF data - comparison between Log-normal and Weibull.

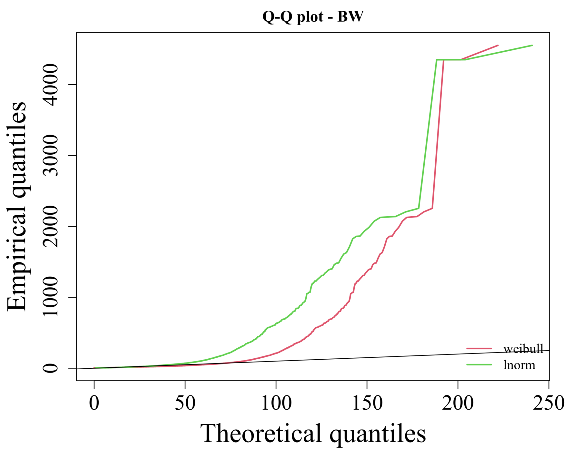


Figure 6.27: Q-Q plot for the bottle washer TTR data - comparison between Log-normal and Weibull.

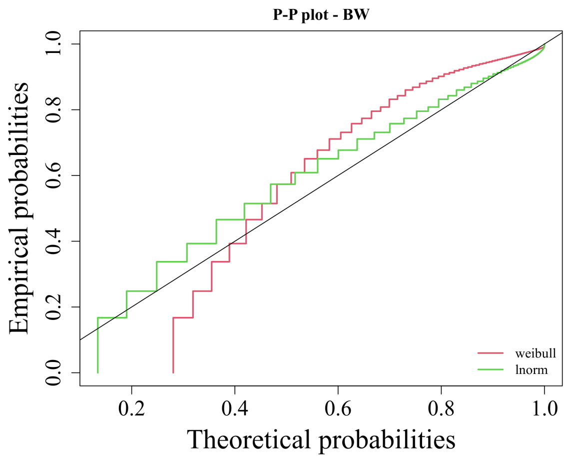


Figure 6.28: P-P plot for the bottle washer TTR data - comparison between Log-normal and Weibull.

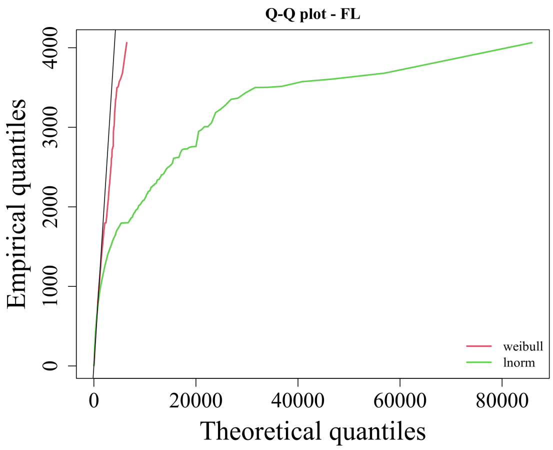


Figure 6.29: Q-Q plot for the filler TBF data - comparison between Log-normal and Weibull.

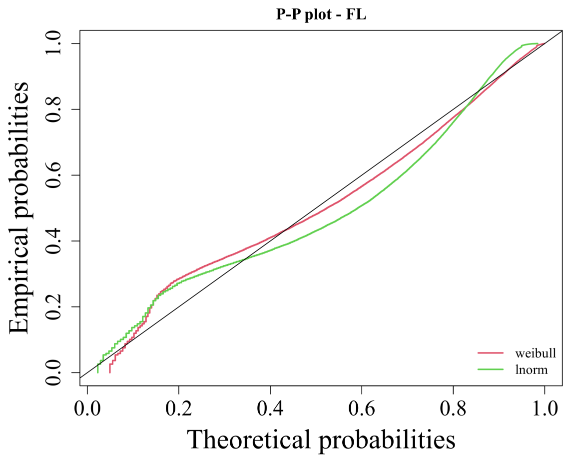


Figure 6.30: P-P plot for the filler TBF data - comparison between Log-normal and Weibull.

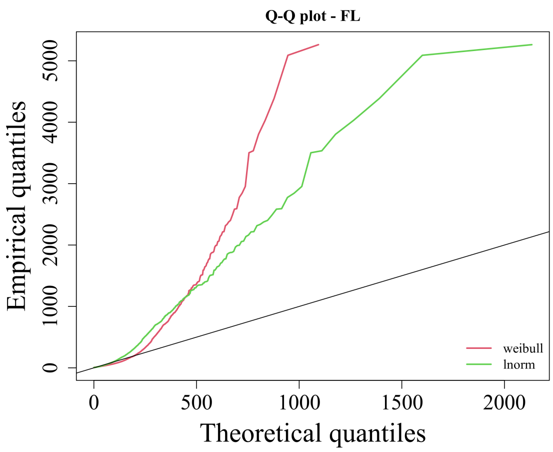


Figure 6.31: Q-Q plot for the filler TTR data - comparison between Log-normal and Weibull.

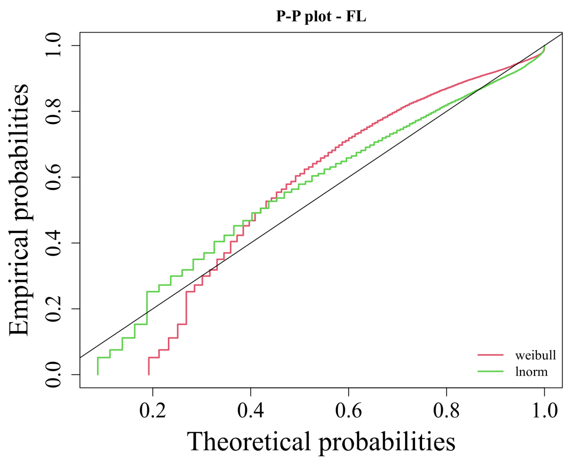


Figure 6.32: P-P plot for the filler TTR data - comparison between Log-normal and Weibull.

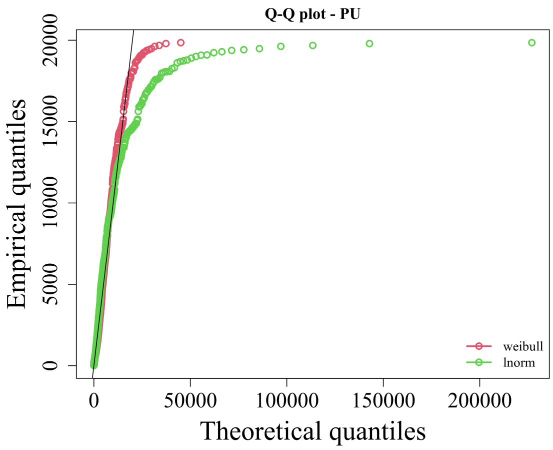


Figure 6.33: Q-Q plot for the pasteurization unit TBF data - comparison between Log-normal and Weibull.

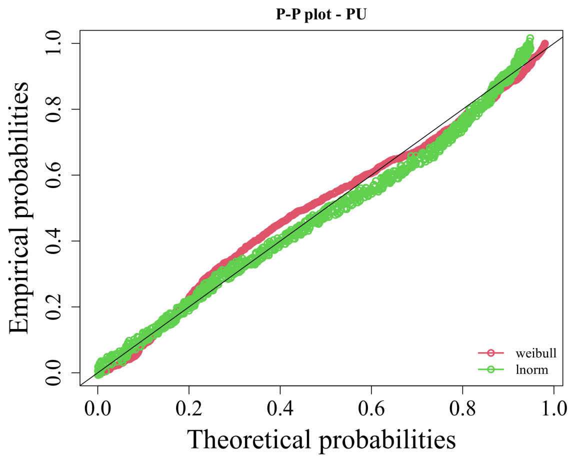


Figure 6.34: P-P plot for the pasteurization unit TBF data - comparison between Log-normal and Weibull.

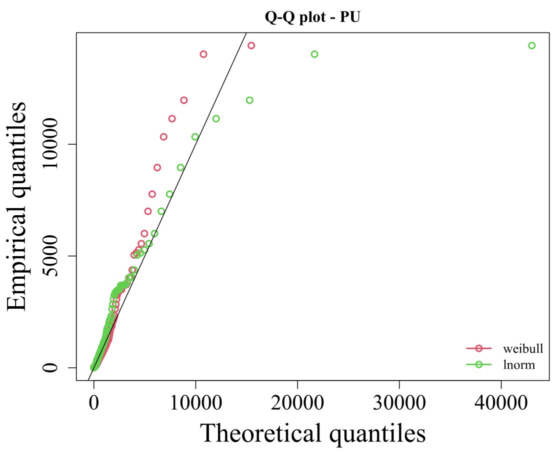


Figure 6.35: Q-Q plot for the pasteurization unit TTR data - comparison between Log-normal and Weibull.

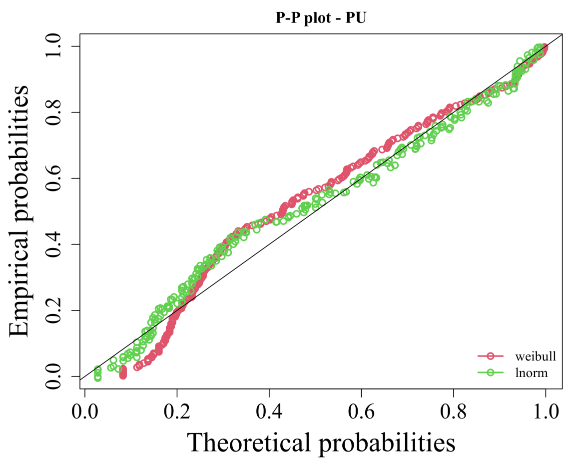


Figure 6.36: P-P plot for the pasteurization unit TTR data - comparison between Log-normal and Weibull.

Weibull distribution was the best fit for almost all equipment TBF data, the only two exceptions were the bottle washer and the pasteurization unit. The best fit for these two machines was Log-normal. On the other hand, all equipment presented Log-normal as the best distribution for TTR data.

We discussed the combination between Cramér-von Mises, Q-Q and P-P plot results of each machine selected separately.

Bottle Washer

Bottle washer Q-Q plot for TBF data showed that Weibull and Log-normal distributions for values above 1000 do not represent well the analyzed data. But, when comparing both distributions, Log-normal presents closer values for the interval between 500 to 1000. Moreover, observing P-P plot, Log-normal clearly represents better the data, specially between 0.4 to 1.0.

Similarly to TBF results, TTR Q-Q plot points out that Weibull distribution would represent better the data. Contrarily, P-P plot shows that Log-normal is the best option for this data.

Filler

Contrarily to the bottle washer, the filler Q-Q plot for TBF data presented a good result for Weibull distribution. But, P-P plot showed that values between 0.1 and 0.4 have higher divergence from Weibull distribution. Even though Weibull results are better when compared to Log-normal distribution.

Filler TTR data shows similar results for Q-Q and P-P plot when compared to TBF data, but in this case, the best distribution was Log-normal. Similarly to BW TTR results, Q-Q plot shows that for values higher than 300 both distributions presented difficulties to predict the data.

Pasteurization Unit

Differently of bottle washer and the filler, the pasteurization unit presented similar results for both theoretical probability distributions. For TBF Q-Q plot, the best distribution would be Weibull, but for P-P plot Log-normal represents better the data. Therefore, for this machine TBF data Log-normal was chosen as the best function, however Weibull would also generate good results.

Similarly to PU TBF data, TTR Q-Q and P-P plot present a similar result for both distributions, but this time the two plots are consistent with each other. Even though they are very similar, Log-normal presented a slight better result on both charts. Thus, it was selected as the best distribution for PU TTR data.

Combining all statistical tests performed for the three machines selected, Log-normal distribution was elected as the best for all data, except filler TBF. Even though for PU TBF data Weibull distribution would also present a satisfactory prediction, Log-normal was chosen due to its positive result on P-P plot and Cramér-von Mises tests.

6.1.5 Hazard plots

Once the best theoretical probability distribution for TBF and TTR data of all Line A equipment were identified, we were able to built the hazard plot. Again, three machines were chosen to be analyzed to avoid redundant information. For this topic the decrater, the filler and the palletiser were selected. Figures 6.37, 6.38 and 6.39 show the results for each of them, respectively. The hazard plot for the other machines are in **Appendix E**

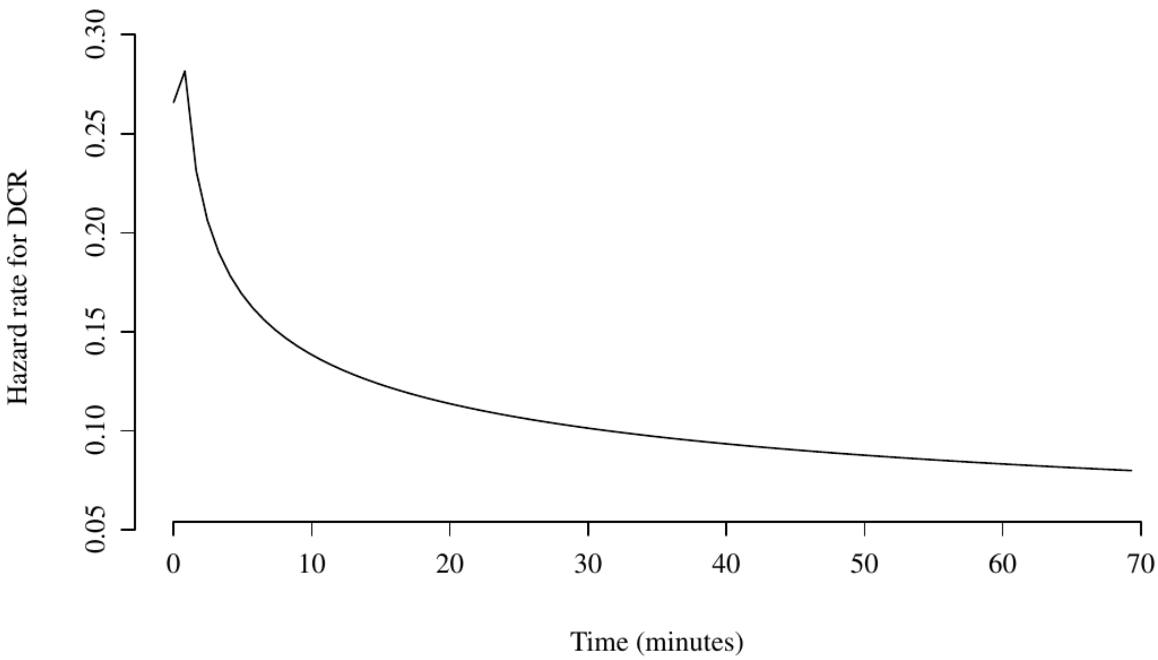


Figure 6.37: Decrater hazard function.

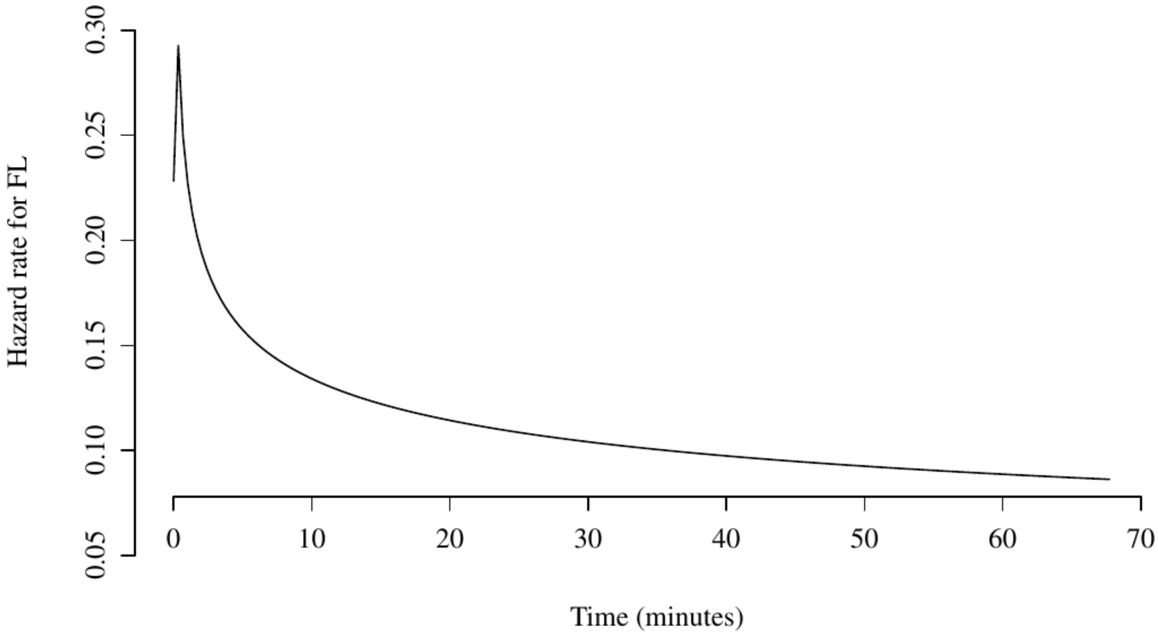


Figure 6.38: Filler hazard function.

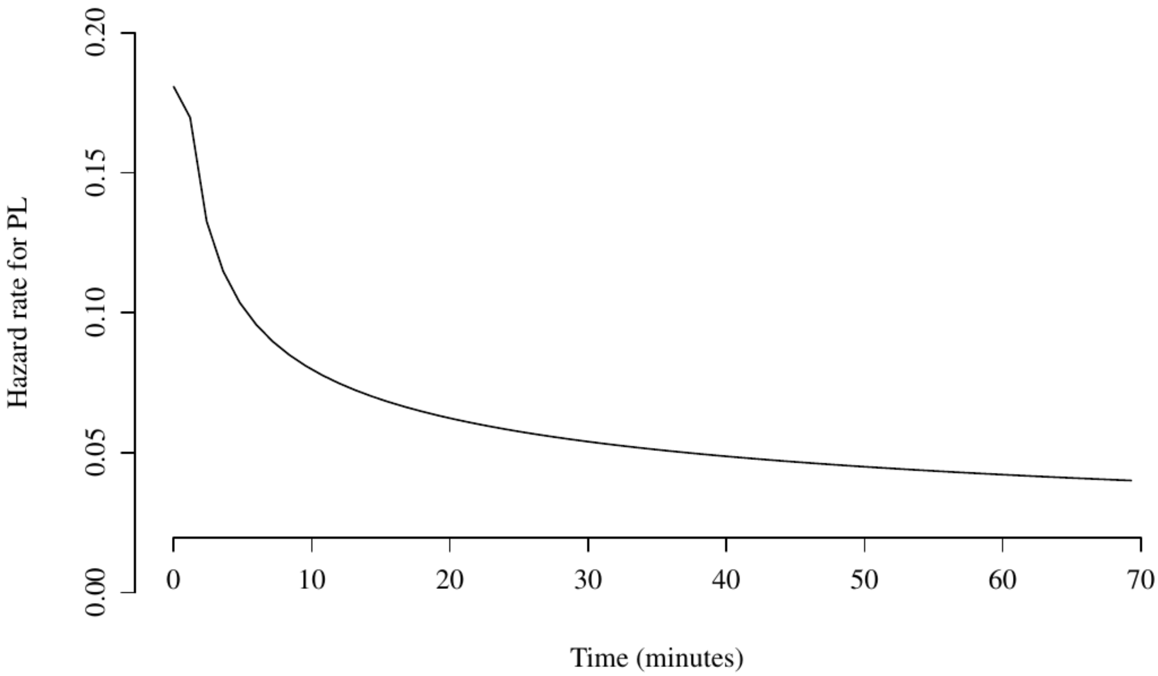


Figure 6.39: Palletiser hazard function.

Comparing the bathtub curve with the three hazard plots exposed, we noticed that none of them are at the wear out stage of the bathtub curve. As none of the hazard plots for Line A machines presented an ascendant curve, this analysis did not point out that any machine specifically would have its preventive maintenance routine reviewed or be replaced.

In addition, the hazard plot results suggest that the evaluated data do not include macrostops. Moreover, most of the studied microdowntimes are concentrated on less than 5 minutes. These events usually are recovered by a simple operational intervention, for example: unblock tumbled containers.

6.1.6 Reliability analysis

The reliability analysis was divided into two parts: evaluation of reliability curves and their relationship among all line pieces of equipment.

The first part aimed to compare the reliability probability of two different distributions: Weibull and log-normal with a empirical curve obtained from the data. The machines chosen for this analysis were the filler, pasteurization unit and labeller 1. Figures 6.40, 6.41 and 6.42 show their the results, respectively. Again, only three machines were elected to be analyzed to avoid unnecessary repetition. The graphs for the other machines are in **Appendix F**.

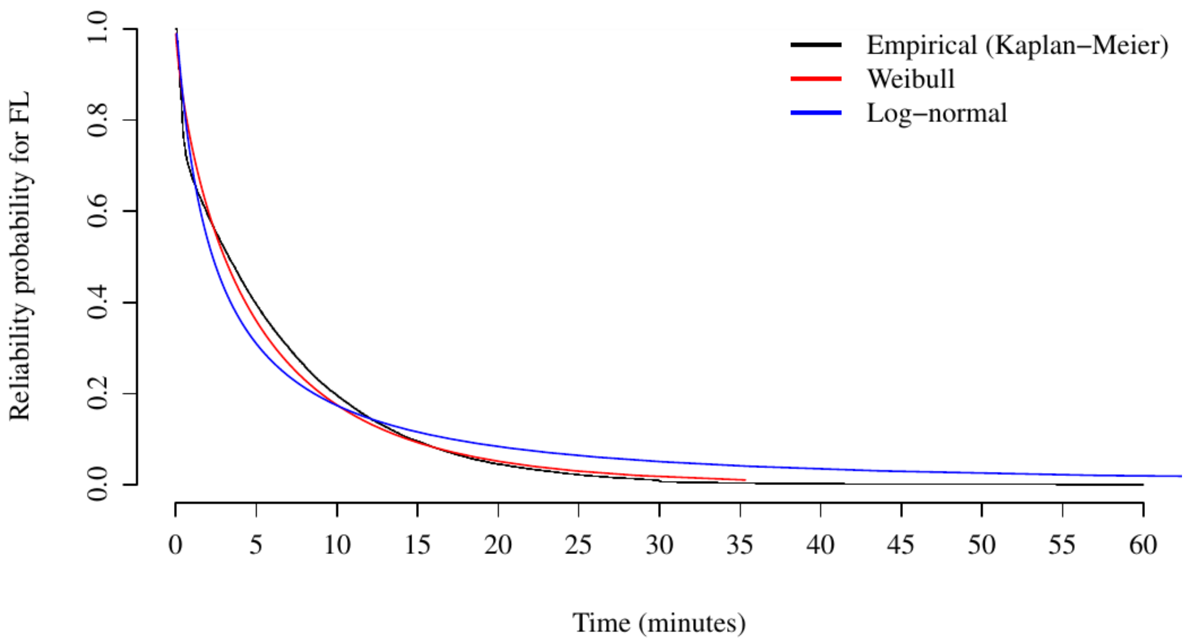


Figure 6.40: Filler reliability plot.

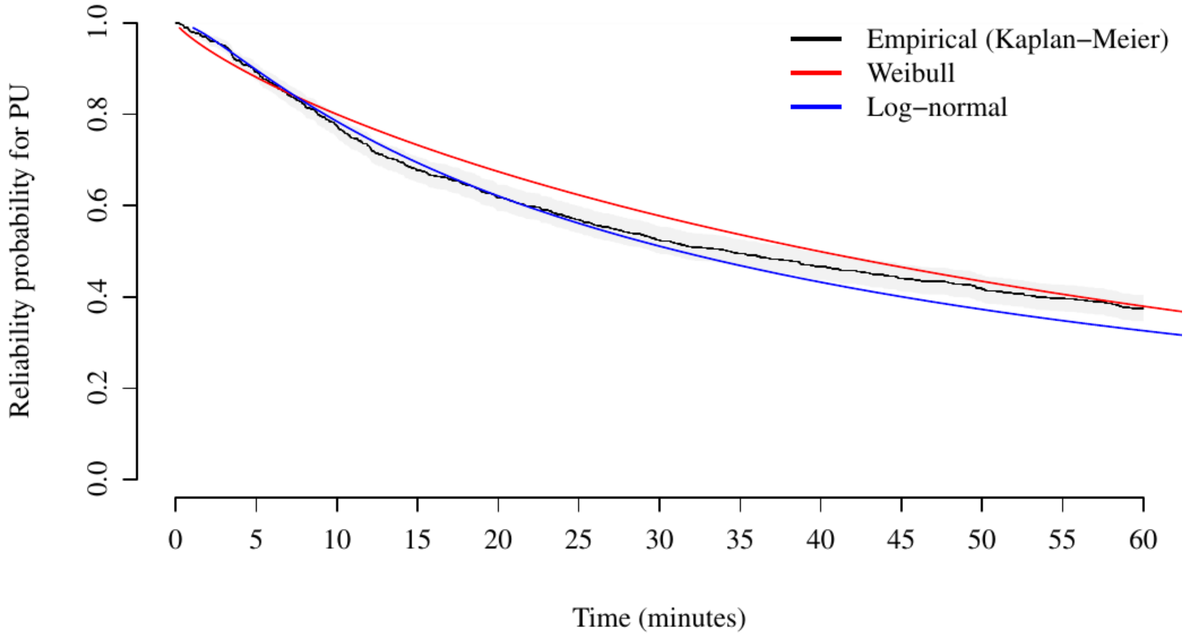


Figure 6.41: Pasteurization unit reliability plot.

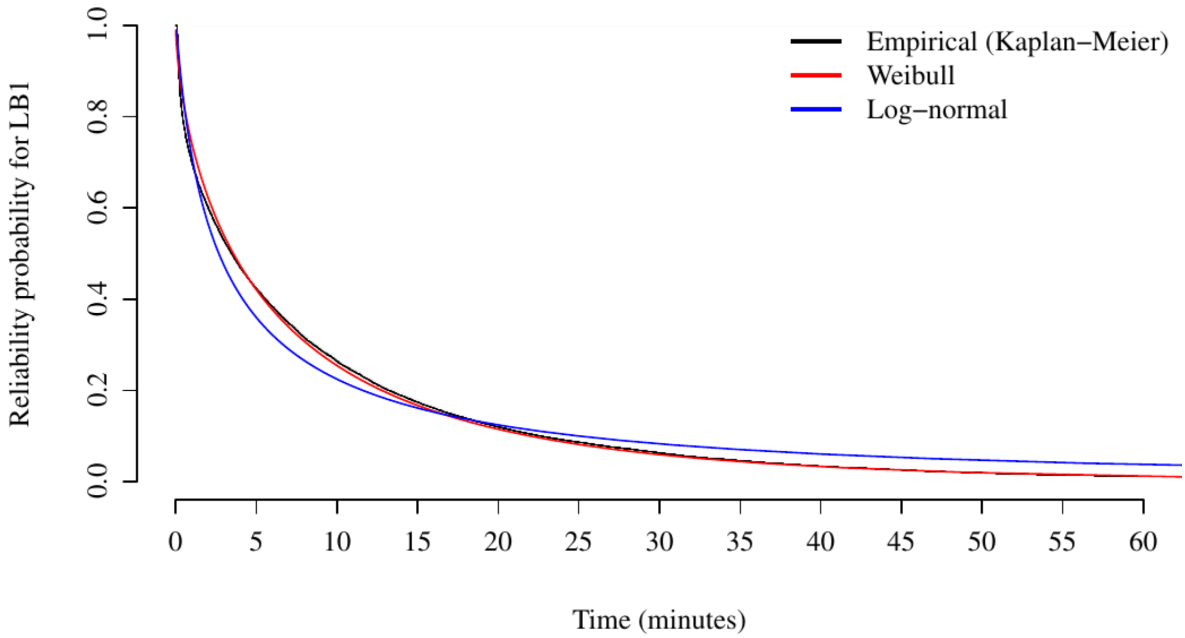


Figure 6.42: Labeler 1 reliability plot.

Since reliability probability is calculated using TBF data of each machine, we expected that Weibull distribution would better represent the filler and labeller 1 and log-normal the pasteurization unit.

Filler and labeller 1 are better represented by Weibull distribution, but for pasteurization unit this relationship is not obvious. Log-normal represents better this machine data until 30 minutes, approximately. Moreover, Weibull distribution represents better values above 50 minutes. This mixed result for PU was expected, due to Q-Q plot results. But, on reliability probability plot is clear that even though Weibull distribution represents better some PU data, log-normal describes better the major part. Therefore, this test corroborates to log-normal choice as the best distribution for PU TBF data.

The second reliability analysis consists of interpreting Line A reliability diagram, which is shown in Figure 6.43.

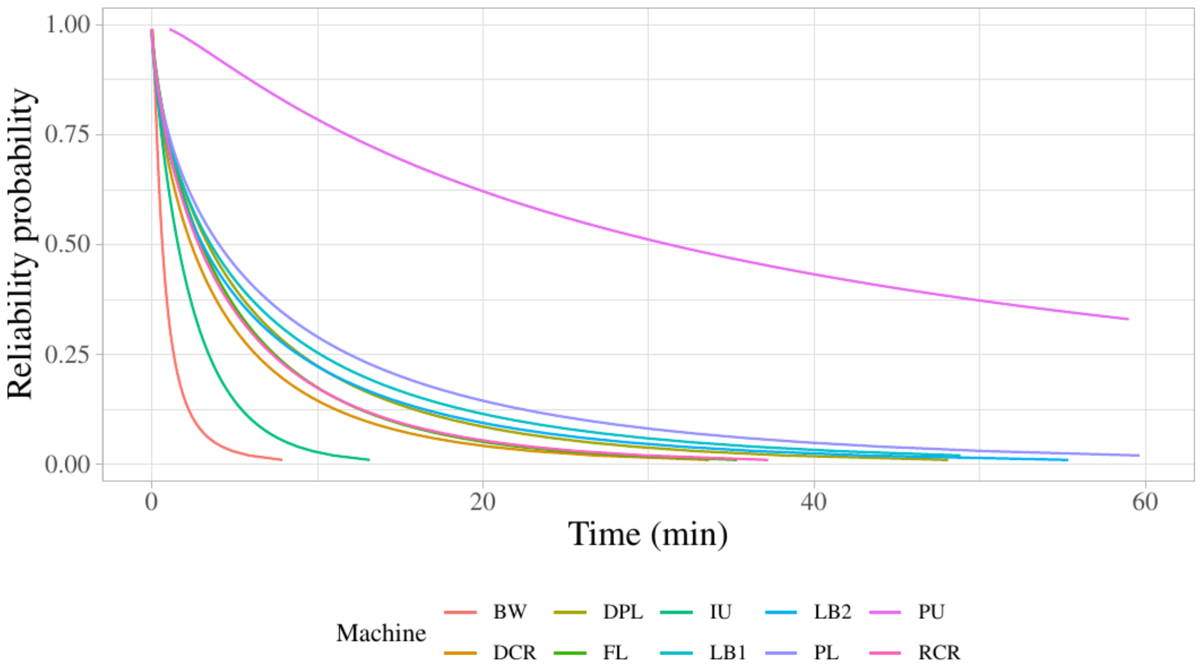


Figure 6.43: Line A reliability diagram.

Line A reliability diagram shows that some Line A machines have considerable different reliability probability tendencies. For instance, comparing the bottle washer, the palletiser and the pasteurization unit curves, we verified that to achieve a probability to survive of 50% a maintenance should be carried out on the first 2, 7 and 33 minutes, respectively. This result suggests that the bottle washer and the inspector unit demand a high intervention level, which is not desirable. Thus, it is suggested that the preventive maintenance should be reviewed to focus on bottle washer and inspector unit.

6.1.7 Maintainability analysis

Maintainability analysis consisted of interpreting maintainability diagram (Figure 6.44) .

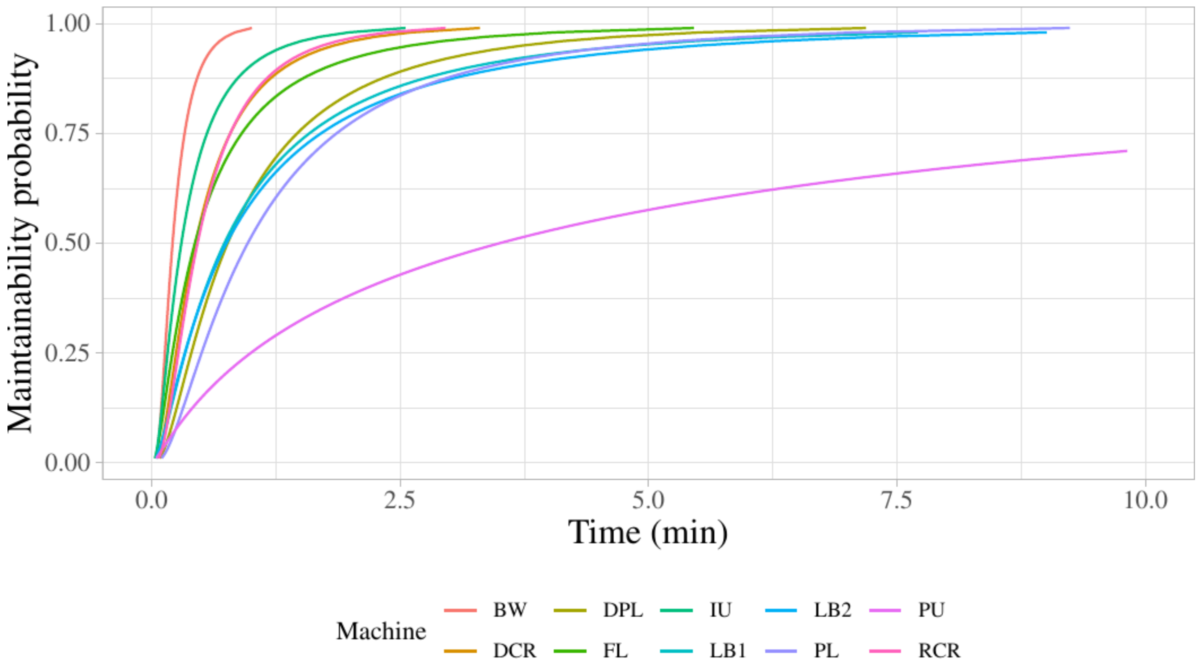


Figure 6.44: Line A maintainability diagram.

Observing maintainability diagram, we noticed that all equipment presented a similar maintenance probability distribution. The only exception is the pasteurization unit.

PU presents the lowest maintainability curve due to its high MTTR mean. Thus, to improve this machine maintainability, it is necessary to investigate the root cause of PU major failures in order to reduce MTTR mean.

Moreover, the maintainability graph suggests that there is a 90% chance that any Line A equipment failure (except PU) would be recovered within 6.5 minutes, approximately.

In conclusion, from maintainability analysis, we observed that the pasteurization unit should have its preventive maintenance reviewed, in order to reduce its mean time to recover.

6.1.8 RAM analysis - sum up

Combining reliability and maintainability results, we verified that three different machines should have their preventive maintenance reviewed: bottle washer, inspector unit and pasteurization unit.

In order to fully understand the main impact of these three machine failures on line efficiency, we evaluated the propagation of their failures down to the filler. A crucial element for this kind of analysis is buffer efficiency. Thus, Line A buffer efficiencies and other line and buffer parameters were evaluated.

6.2 Rules of thumb: development

To develop rules of thumb for filling lines, we analyzed and discussed line and buffer parameters of three returnable bottle lines: Line A, B and C.

We selected these three lines due to their layout similarity. They are returnable bottle lines with two labellers. It was necessary to choose three filling lines to have a better idea of how each studied parameter behaves.

Each line was evaluated separately to evidence the improvement opportunities of each of them. Afterwards, their results were compared and then the rules of thumb were proposed.

6.2.1 Line A

Line parameters

The first step to identify the actual line bottleneck is to calculate the M.E.R. (Equation 5.5) for each equipment. The results are disposed in Figure 6.45.

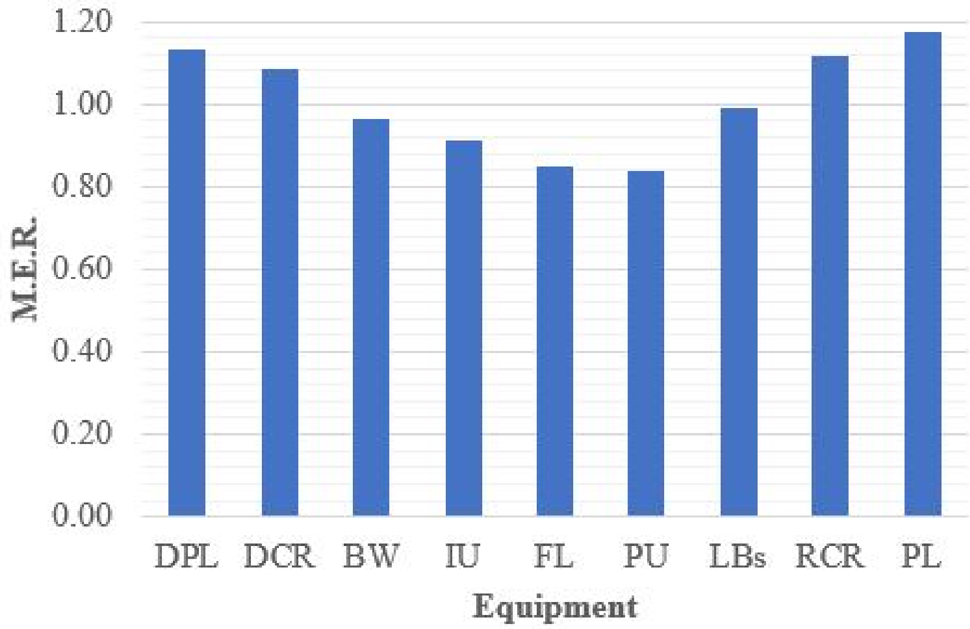


Figure 6.45: M.E.R. of all Line A equipment

Figure 6.45 shows that Line A original shape of the V-graph is preserved, even though the bottle washer presented a lower availability than the filler.

Figure 6.46 was built to understand what is impairing the filler, and consequently, the line production. It shows a column graph with all Line A equipment divided by the percentage that each of them spent at each status (running, failed, starved and blocked).

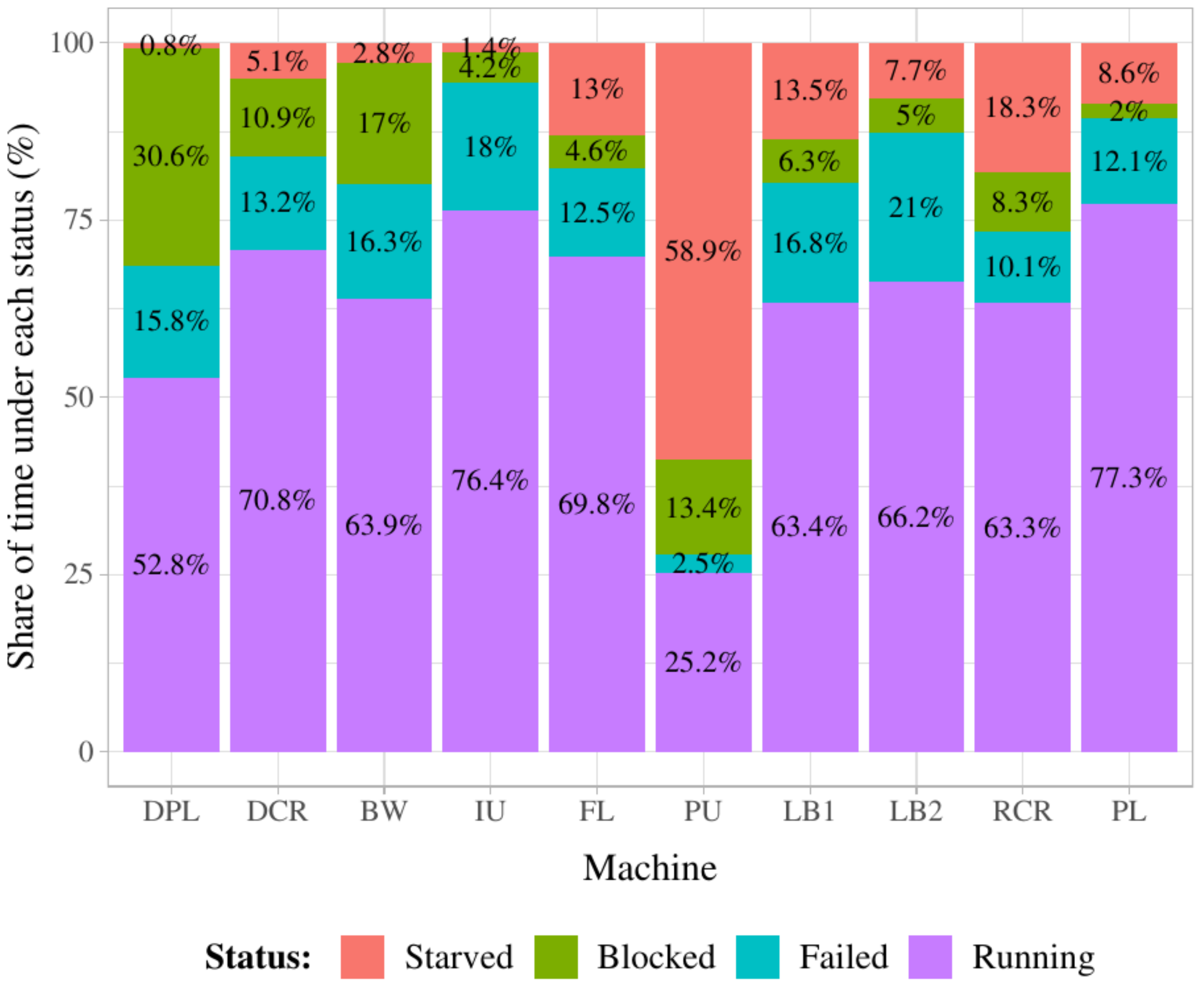


Figure 6.46: Column graph of Line A equipment divided by each status (running, failed, starved and blocked)

Analyzing Figure 6.46, it is clear that all machines (except PU) spend more than 10% of their actual production time failed. This is very negative for line efficiency, due to intrinsic losses by the failure itself and their propagation. In other words, if most of machines have a high failure frequency it is more probable that the other pieces of equipment increase their number of hours under starvation or blocked status.

In addition, even thought the filler presents a high percentage under the failed status the highest contribution for its unplanned downtime is the starved events. As the main problem of the filler, and consequently of the line, is starvation it indicates that the machines and buffers upstream the filler should be investigated.

Figure 6.46 analysis suggests that the main points that are impacting on Line A efficiency is the filler and inspector unit failure events. To have a clear understating if the actual bottleneck of this line is machine reliability or buffer sizes we calculated the zero buffer and infinite buffer limit efficiencies. Line efficiency and its upper and lower buffer limits were calculated as described in Equations 4.1, 5.6 and 5.7, respectively. Buffer strategy performance was also calculated based in Equation 5.8. The results are expressed in Table 6.5.

Table 6.5: Line A results for line efficiency, upper and lower buffer limits and buffer strategy performance.

Parameter	Value (%)
Line efficiency (η_{line})	69.9
Lower Limit (η_{line}^{0})	20.9
Upper Limit (η_{line}^{inf})	84.0
Buffer strategy performance (β)	77.6

Line A efficiency is closer to upper than lower limit, as expressed by a high buffer strategy performance (β). It suggests that the existing buffers are effectively contributing to line efficiency, otherwise line efficiency would be closer to 21% (lower buffer limit). Consequently, this parameter suggests that increasing buffer size is not going to have a positive impact on line efficiency.

Buffer parameters

The buffer parameters calculated were: accumulation ratio (Equations 5.9 and 5.10), nominal recovery ratio (Equations 5.11 and 5.12), mean recovery ratio (Equations 5.13 and 5.14), and buffer efficiency - time based (Equations 5.15 and 5.16) and events based (Equations 5.17 and 5.18). Table 6.6 shows the results.

Table 6.6: Line A buffer parameters results.

Conveyor	Type of buffer	Accumulation ratio	Nominal recovery ratio	Mean recovery ratio	η_{buffer}
DPL-DCR	Anti-starve	2.77	0.15	0.41	0.70
DCR-BW	Anti-starve	8.91	0.03	0.27	0.85
BW-IU	Anti-starve	26.39	0.01	0.37	0.92
IU-FL	Anti-starve	16.94	0.03	0.48	0.32
FL-PU	Anti-block	0.48	0.42	0.20	0.56 [2]
PU-LBs	Anti-block	5.12	0.13	0.67	0.45
LBs-RCR	Anti-block	15.87	0.02	0.35	0.69
RCR-PL	Anti-block	2.56	0.21	0.53	0.42

Observing the accumulation ratio alone, the conveyor FL-PU is the only one whose value is below 1. This parameter indicates that the pasteurization unit stays a considerable time failed, and the filler fills the buffer quicker than the PU recovers itself.

Combining this result with PU MTTR (17 min), it suggests that FL-PU buffer can be considered small. However, considering that a buffer main function is to prevent machine microdowntimes (less than 5 minutes), FL-PU is not necessarily a small buffer, once PU needs (on average) 17 minutes to recover from a failure. Thus, PU failures can be considered breakdowns and are not supposed to be covered by buffers.

As nominal recovery ratio represents the ability of the equipment to recover from its own failures relative to buffer size, the higher this parameter, the better. Line A lowest nominal recovery ratio are: 0.01 (BW-IU), 0.02 (LBs-RCR) and 0.03 (DCR-BW and IU-FL). It suggests that BW, DCR, IU and RCR take some time to recover from their failures (when compared to their buffer capacities). Otherwise speaking, nominal recovery ratio suggests that these equipment have difficulties to fill (DCR, BW and IU) and to empty (RCR) the related buffers.

[2] As PU MTTR is higher than 5 minutes, the events-based efficiency was used.

The higher the mean recovery ratio, the higher the rate that the buffer fills up (*anti-starve buffers*) or empties (*anti-block buffers*). Disregarding FL-PU, the conveyors that present the lowest values of this parameter are DCR-BW, LBs-RCR and BW-IU, respectively. Considering only this parameter, it indicates that LBs probably stop frequently by blockage, and BW and IU stop by starvation very frequently and/or that the related buffers are constantly empty (DCR-BW and BW-IU) or full (LBs-RCR).

The lowest value for buffer efficiency based on hours is IU-FL with 32%. It indicates that every minute that the IU stops, the filler starves 40 seconds. To make the matter worst, the filler is the core machine, thus every time it stops, overall line efficiency decreases.

According to Härte (1997), buffer efficiency events-based is more representative when there is a considerable number of macrodowntimes. This characteristic is identified by observing MTTR values. Machines that have a MTTR higher then five minutes should consider the efficiency events-baseds, instead of time-based. Pasteurization unit is the only machine on this condition for Line A. Therefore, FL-PU buffer efficiency time-based was not considered.

Considering all buffer parameters described, we selected three conveyors as the main points of improvement, they are: IU-FL, BW-IU and RCR-PL. The first buffer presented the lowest value of buffer efficiency. The conveyor BW-IU showed the lowest value of nominal recovery ratio and the third lowest for mean recovery ratio. Finally, the RCR-PL presented the second lowest value for buffer efficiency and accumulation ratio.

To clearly illustrate the relationship between buffer efficiencies and the time under each not-running status, we built a column chart (Figure 6.47). It was obtained multiplying each status share (shown on Figure 6.46) by the respective machine speed divided by the filler speed, as illustrated in Equation 6.1.

$$\text{Speed relative to filler}_{\text{status}}^{\text{machine}} = \text{Time share}_{\text{status}}^{\text{machine}} \cdot \frac{\text{Machine nominal speed}}{\text{Filler nominal speed}} \qquad (6.1)$$

All the filler avoidable downtime events (starvation and blocked) should be explained by other machine failure. If the equipment is located upstream, it would cause a starved event. But, if the machine is located downstream it would cause a blockage event on the filler. If no buffer would exist between the equipment, every failure would stop the core machine, resulting in an avoidable downtime. Thus, the buffer efficiency shows how effective the respective buffer is. In other words, it illustrates the percentage of time that the machine stayed on a not-running status, due to the stop of the other. It is true for any pair of machines with a buffer between them. For example, the depalletiser failures and starvation events are responsible for all decrater starvation occurrences (6.3% of its running time). In this particular case, the buffer DPL-DCR avoided 69.7% of the possible starvation events.

The buffer efficiencies and their influences on the respective machines are illustrated in Figure 6.47.

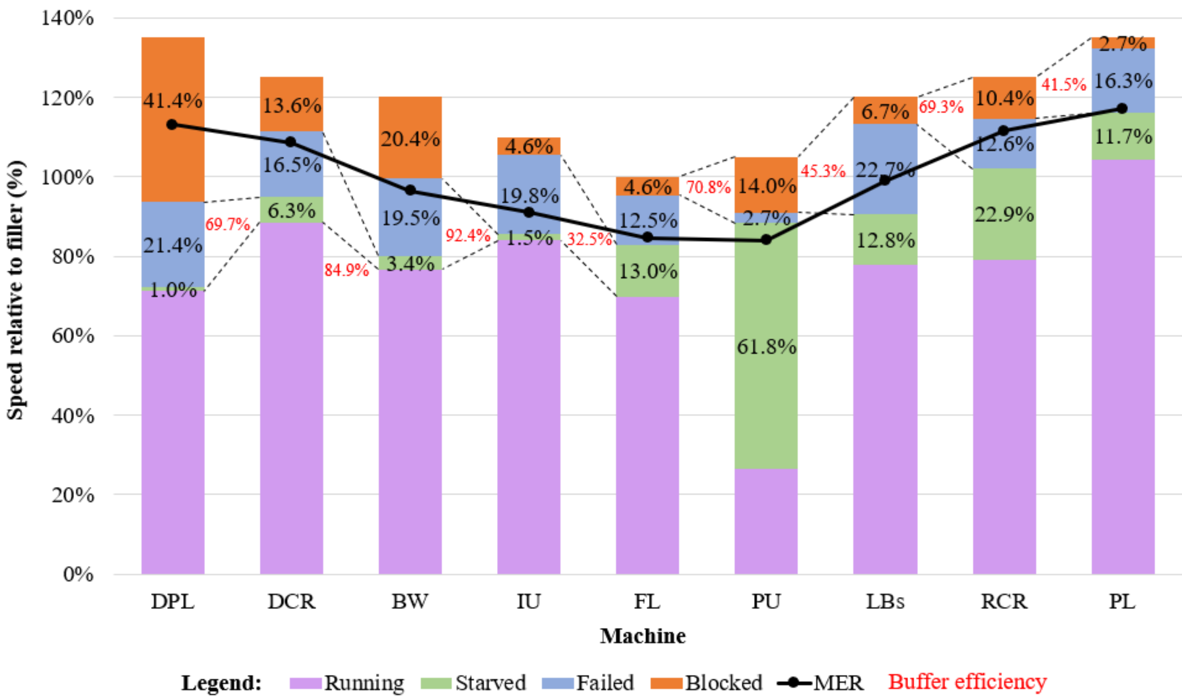


Figure 6.47: Column graph of Line A equipment divided by each status (running, failed, starved and blocked), M.E.R. and buffer efficiencies.

Figure 6.47 shows that the filler starvation events are directly related to: inspector unit failures and low IU-FL buffer efficiency. Therefore, to improve line efficiency we could review inspector unit preventive maintenance routine and/or increase IU-FL buffer size.

Comparing DPL , DCR, BW and IU unplanned downtime percentage, the inspector unit is the equipment with the highest share of their time on failed status, even though the depalletiser presented the highest total downtime. Although the failure rates are high for all these equipment, the starvation percentage is considerably low. For example, the highest percentage under starved status belongs to the decrater, and it represents only 5.1% of its total time. This low time under starvation status suggests that the main reason for the filler starvation events is the failures of the inspector unit. Thus, to improve line efficiency it is recommended to focus on the filler and inspector unit preventive maintenance.

Comparing the buffer analysis outcomes with Figure 6.47 we concluded that the results achieved are consistent. Buffer analysis selected two conveyors upstream the filler, as the highest points with potential improvement (IU-FL, and BW-IU). This result converges with the fact that the filler spends 13% of its actual production time starved. In addition, RCR - PL was the other buffer selected by buffer analysis. Probably, the low efficiency of this buffer contributes to the number of hours that the filler spend at blocked status.

Even thought some conveyors were elected with improvement potential, only one of them (IU-FL) suggested that a size increase would result in line efficiency upgrade. But, focusing on upgrading inspector unit maintenance policy would also contribute for line efficiency. Thus, for Line A the actual bottleneck is machine reliability, with focus on the filler and the inspector unit.

6.2.2 Line B

Line Parameters

Firstly, Line B had MTBF, MTTR and availability calculated for all equipment. Table 6.7 shows the results.

Table 6.7: Line B MTBF, MTTR and availability data.

Machine	MTBF (s)	MTTR (s)	Availability
DPL	179	26	0.88
DCR	821	54	0.94
BW	246	33	0.88
IU	312	21	0.94
FL	1122	114	0.91
PU	1060	51	0.95
LB1	612	89	0.87
LB2	723	102	0.88
RCR	490	61	0.89
PL	396	40	0.91

The filler is the equipment with the highest MTBF ($\sim$ 19 min) and MTTR ($\sim$ 2 min). It means that this equipment takes longer to fail, but it is considerably slow to recover itself [3], suggesting that the failures that occur are more complex. On the opposite hand, the depalletiser presents the lowest MTBF ($\sim$ 3 min) and the second lowest MTTR (26 s). In other words, this equipment failures more often, but its recovery is fast.

All Line B equipment present a similar availability. If only the first significant figure would be considered, almost all equipment would have the same availability (0.9). The only exception would be the pasteurization unit. It suggests that there is not a huge difference between the equipment failure behavior.

Secondly, M.E.R (Equation 5.5) was calculated for all equipment. Figure 6.48 illustrates the results.

[3] Comparatively to the other equipment.

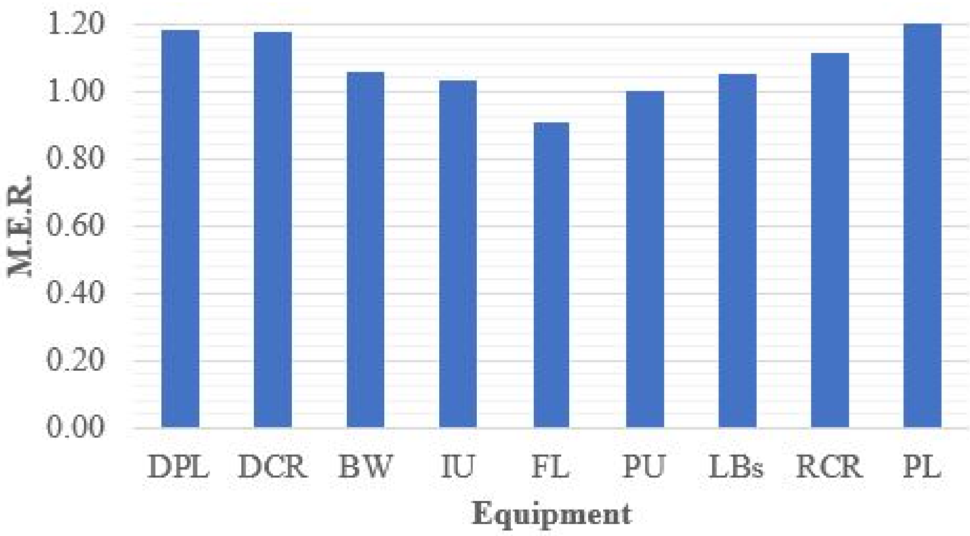


Figure 6.48: M.E.R. of all Line B equipment

Similarly to Line A, Line B also preserves its V-graph format. Even with labeller 1 presenting the lowest availability, and the filler the third highest. To have a better idea of what is impairing the filler (line core machine), we built a column chart (Figure 6.49) with the percentage of the time that each equipment spent at each status (running, failed, starved and blocked).

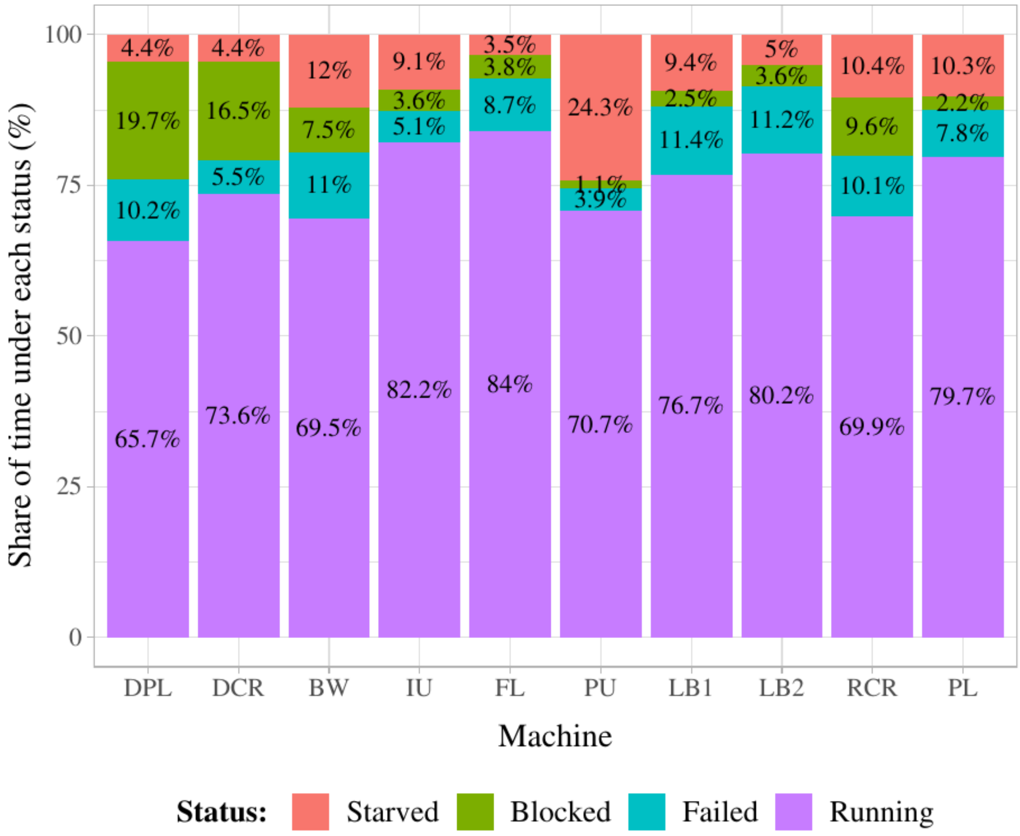


Figure 6.49: Column chart of Line B equipment divided by each status (running, failed, starved and blocked)

Comparing the percentage of time that each equipment spend failed, we verified that only five of them (DPL, BW, LBs and RCR) spend more than 10% of their time in this status, with a maximum of 11.4%. It suggests that Line B has less intrinsic stops, and, consequently, less probability of adjacent machines to stop by starvation and blocked.

Analyzing the filler percentages, the major contribution of its unplanned downtime is the intrinsic failures, followed by blocked and starvation. The difference between the last two are only 0.3% (pp), which suggests that, in practice, these causes have almost the same impact on line efficiency.

The next step on building the rules of thumb is to calculate line efficiency and its zero and infinite buffer limits. These results are presented in Table 6.8.

Table 6.8: Line B results for line efficiency, upper and lower buffer limits and buffer strategy performance.

Parameter	Value (%)
Line efficiency (η_{line})	84.0
Lower Limit (η^{0}_{line})	41.4
Upper Limit ($\eta^{\inf}_{line}$)	90.8
Buffer strategy performance (β)	86.2

Line B efficiency presents a higher value of buffer strategy performance, when compared to Line A. It indicates that, probably, the main actual bottleneck is only machines reliability and not buffer size. In addition, Line B presents higher values of all parameters presented in Table 6.8. It suggests that the preventive maintenance programmed of Line B is more efficient when compared to Line A.

Buffer parameters

For Line B, we calculated the following buffer parameters: accumulation ratio (Equations 5.9 and 5.10), nominal recovery ratio (Equations 5.11 and 5.12), mean recovery ratio (Equations 5.13 and 5.14), and buffer efficiency considering hours (Equations 5.15 and 5.16) and considering events (Equations 5.17 and 5.18). Table 6.9 shows the results.

Table 6.9: Line B buffer parameters results.

Conveyor	Type of buffer	Accumulation ratio	Nominal recovery ratio	Mean recovery ratio	η_{buffer}
DPL-DCR	Anti-starve	11.61	0.05	0.56	0.70
DCR-BW	Anti-starve	12.93	0.05	0.63	-0.21
BW-IU	Anti-starve	12.80	0.05	0.67	0.61
IU-FL	Anti-starve	39.59	0.04	1.50	0.75
FL-PU	Anti-block	14.41	0.07	1.04	0.21
PU-LBs	Anti-block	9.22	0.11	1.00	0.92
LBs-RCR	Anti-block	15.28	0.02	0.33	0.85
RCR-PL	Anti-block	5.27	0.15	0.79	0.03

All Line B conveyors presented an accumulation ratio below 5.0, which is very positive. In addition, it suggests that all machines MTTRs are considerably short when evaluated proportionally to adjacent machines consumption and buffer size.

As the nominal recovery ratio describes how fast a machine is able to catch up its own failures (relatively to the buffer size), higher this parameter, better. Most of Line B equipment presents similar values for nominal recovery ratio (around 0.05). The only exceptions are: LBs-RCR (0.02), FL-PU (0.07), PU-LBs (0.11) and RCR-PL (0.15). These results indicates that the machines which tend to suffer from blocked events are the labellers, as the recrater presents a low consumption rate when compared to buffer size.

The mean recovery ratio represents how fast a equipment is able to refill (anti-starve buffers) or empty (anti-block buffers) relatively to the adjacent machine consumption (anti-starve buffers) or filling rate (anti-block buffers). LBs-RCR presents the lowest value of mean recovery ratio. This result suggests that the recrater appears to have difficulties to catch up its own failures. It corroborates to the nominal recovery ratio analysis.

As none Line B machines present a MTTR higher than 5 minutes, we calculated only buffer efficiencies hours-based on this analysis.

The two lowest values of buffer efficiency for Line B are: DCR-BW (-0.21) and RCR-PL (0.03). The negative value for DCR-BW conveyor means that the bottle washer spent more time starved than the decrater spent failed and starved. As the decrater can also be blocked by the crates circuit, it suggests that a considerable number of the blocked events could have been caused by a problem on it, and/or the buffer of this circuit is small. On the other hand, the conveyor RCR-PL does not present a negative value, but a very small one. It indicates that almost all PL stops (by blocked or failure) stops RCR. It is a clear indication that this buffer is small.

Comparing the main results for all buffer parameters, three conveyors can be highlighted: DCR-BW, LBs-RCR and RCR-PL.

Due to DCR-BW buffer efficiency negative value, we identified a possible anomaly. Since this problem is probably associated with the crate circuit, the other buffer parameters were not able to identify the phenomenon. In other words, the decrater spent a considerable amount of time blocked because of the crate circuit causing starvation on the bottle washer.

Nominal and mean recovery rate values for LBs-RCR suggested that the recrater consumption rate could be considered small, when compared to the buffer capacity or the labellers filling up rate. But, combining these results with buffer efficiency (0.85), we concluded that this buffer size is sufficient. The lack of blocked events for labellers and LBs-RCR high buffer efficiency corroborate to this conclusion.

The criteria used to select the buffer RCR-PL was its low buffer efficiency. In addition, this conveyor presented the lowest value of accumulation rate. Therefore, combining these two parameters, we concluded that increasing the size of this conveyor, recrater blocked events could be reduced.

To clearly illustrate the relationship between buffer efficiencies and the time under each not-running status we built a column chart (Figure 6.50). It is similar to what we did for Line A.

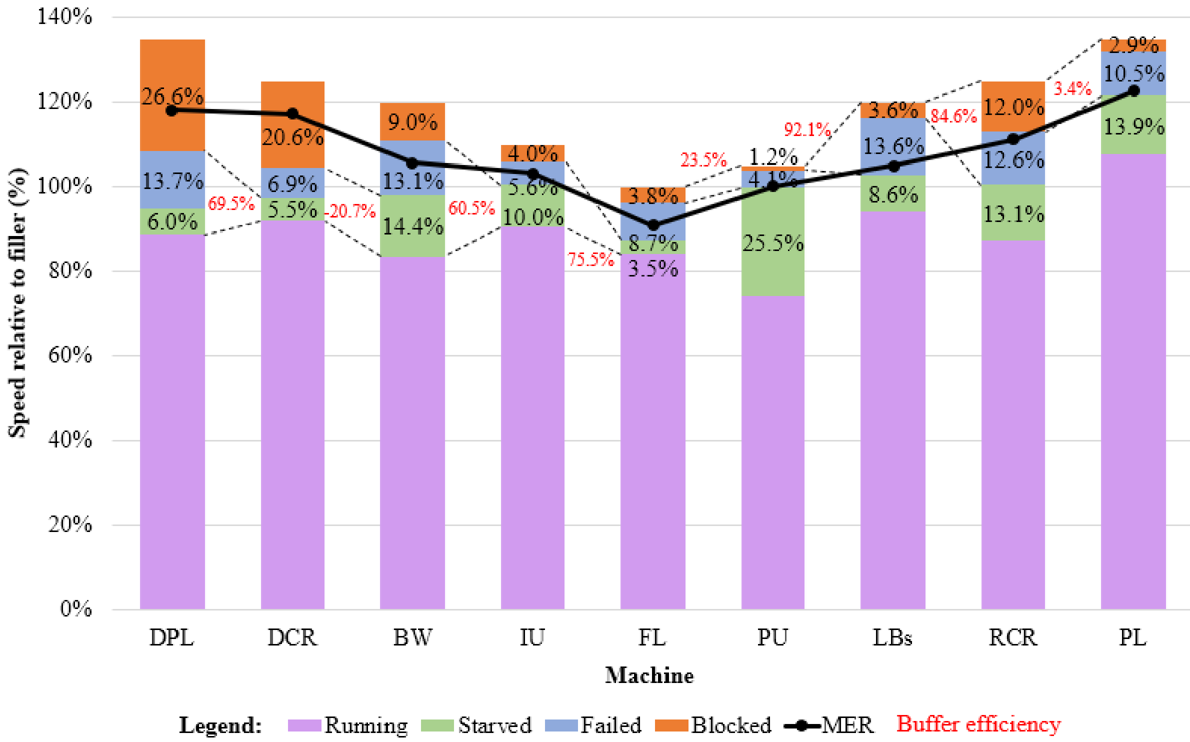


Figure 6.50: Column graph of Line B equipment divided by each status (running, failed, starved and blocked), M.E.R. and buffer efficiencies.

Figure 6.50 shows that there are several reasons for the filler avoidable downtime (starvation and blocked events). We analyzed each type of occurrence separately.

Analyzing IU, BW and DCR starved percentages and IU-FL, BW-IU and DCR-BW buffer efficiencies, we verified that the bottle washer starved events are propagated until the filler. This phenomenon occurred even with considerable high buffer efficiencies for BW-IU and IU-FL conveyors. Although the BW starvation events seem to be the major cause for the filler starvation events, DCR major problem is blocked. It suggests that the crate circuit is impairing the decrater to run, which increases bottle washer starvation events. To worsen the situation, BW has a considerably higher percentage on failed status. It contributes for the propagation of the starvation events until the filler.

Similar to starvation analysis, the machines percentages downstream the filler were evaluated. Even though the labellers present the highest time on failed status, their downtime events do not seem to be propagating to the machine upstream them. The main evidences are: pasteurization unit low time on blocked status and high PU-LBs buffer efficiency. Thus, the two main reasons for the filler blocked events are the PU failures and low FL-PU buffer efficiency.

Considering Figure 6.50 analysis, Line B actual bottlenecks are: the filler and pasteurization unit reliability, and the dynamics of the crate circuit.

Combining Figure 6.50 and buffer parameters analysis, we concluded that to increase Line B efficiency machine reliability and buffer size should be combined.

The machines that are directly impairing line efficiency are: the filler, bottle washer and pasteurization unit. If BW failure events decrease, probably starvation events on the filler would also decrease. The same logic can be applied for pasteurization unit failures, as they have a negative influence on the number of blockage events.

The buffer improvement opportunities for Line B: improve crate circuit dynamics to decrease the number of decrater blocked events and increase RCR-PL buffer size. In Line B, the crate circuit dynamics is manually controlled by operators. In other words, the circuit buffers are small, therefore it is necessary to take off and to replace the crates on the circuit depending on line demand. A possible solution for this problem is to create some alarms to help operators to act when needed and/or increase the size of the buffers involved.

Some newest returnable bottle lines have a crate magazine that automatically takes off or replace crates for crate circuit when needed. This technology can be considered an alternative for Line B, but it usually is considerably expensive and demands a large footprint.

6.2.3 Line C

Line Parameters

Firstly, we calculated MTBF, MTTR and availability for all Line C equipment. Table 6.10 shows the results.

Table 6.10: Line C MTBF, MTTR and availability data.

Machine	MTBF (s)	MTTR (s)	Availability
DPL	307	83	0.79
DCR	468	31	0.94
BW	238	33	0.88
IU	518	24	0.96
FL	1185	137	0.90
PU	4148	176	0.96
LB1	461	70	0.87
LB2	445	66	0.87
RCR	573	26	0.96
PL	107	18	0.85

Line C most reliable equipment is the pasteurization unit. This machine presents the highest MTBF and availability, but it also has the highest MTTR. In other words, it fails less, but it takes longer to recover when compared to the other equipment. On the opposite hand, the palletiser presents the lowest MTBF and MTTR. Even thought the PL has the lowest values for these two parameters, the machine with the lowest availability is the depalletizer.

Considering only availability values, we noticed that the machine upstream the filler present lower availability values. Thus, it is expected that Line C presents more production loss associated with starvation than blocked events.

Secondly, we calculated the M.E.R. (Equation 5.5) for all Line C equipment. Figure 6.51 shows the results.

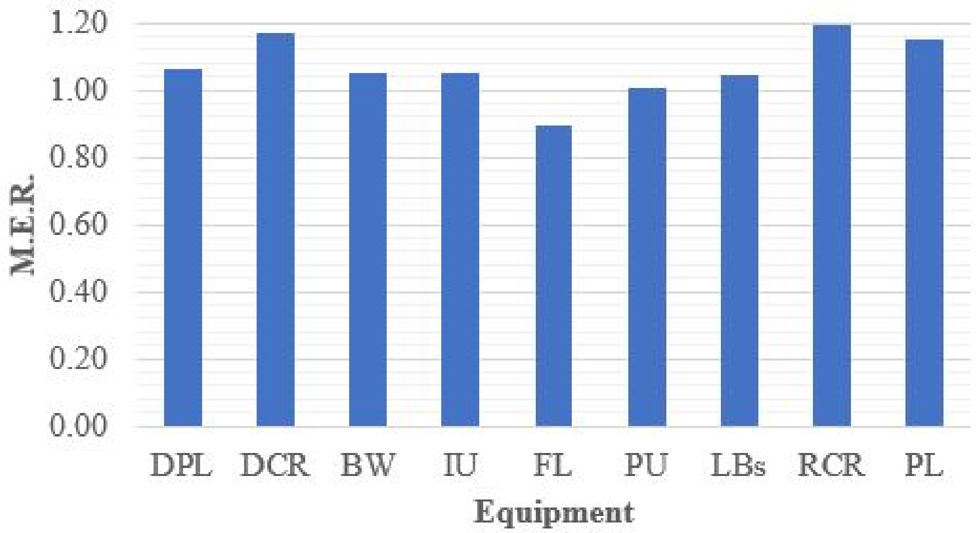


Figure 6.51: M.E.R. of all Line C equipment

Differently from Lines A and B, Line C does not present a clear V-graph shape. The machines that are causing this distortion are the depalletiser and the palletizer. These two machines present the two lowest availability, resulting in a lower M.E.R. when compared to the other equipment. To have a better idea of what is impairing the filler (line core machine) we built a column chart (Figure 6.52) with the percentage of the time that each equipment spent at each status (running, failed, starved and blocked).

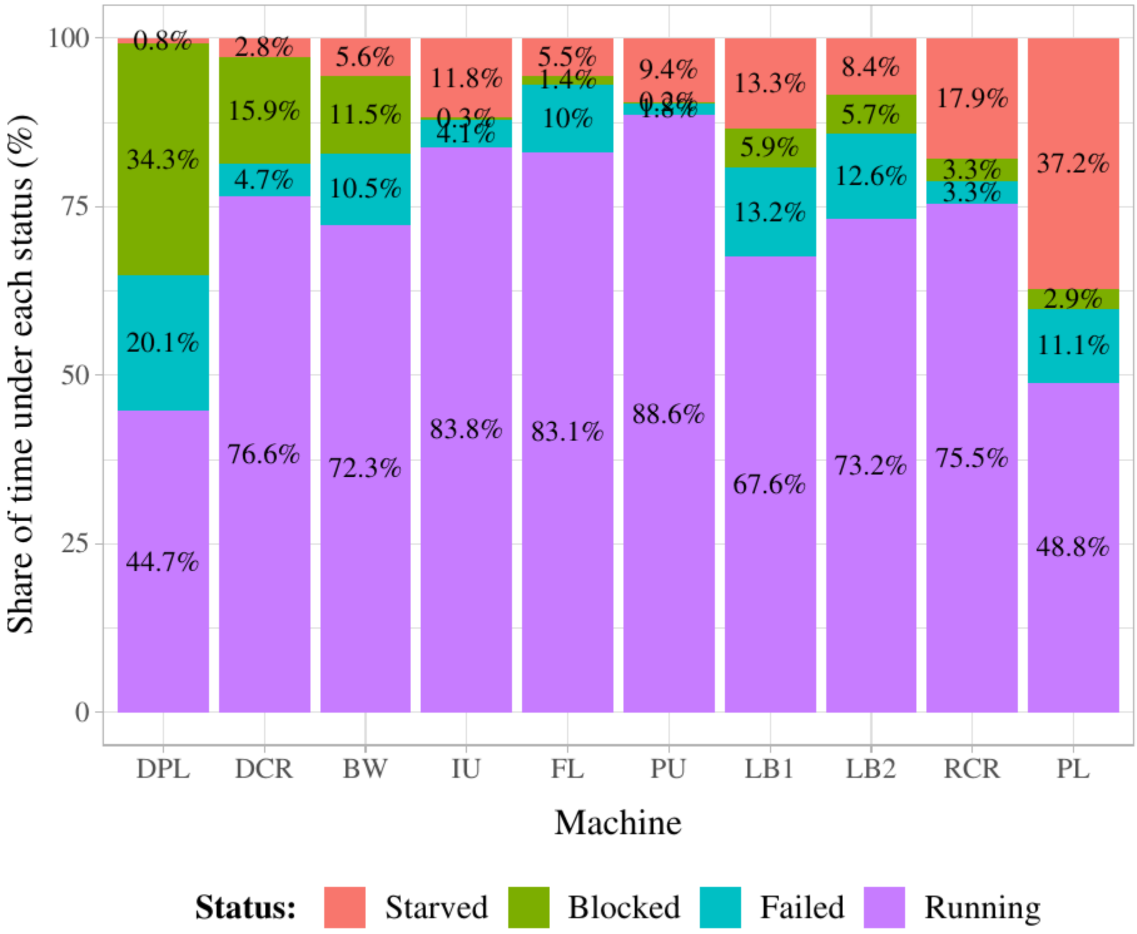


Figure 6.52: Column chart of Line C equipment divided by each status (running, failed, starved and blocked)

Comparing Line C equipment share, the depalletiser and the labellers are the machines with the highest percentage on the failed status. Although these machines present the highest percentage on failed status, if starvation and blocked percentages are summed up, their contribution becomes higher than the failures themselves.

Analyzing only the filler shares, we verified that the main cause of not-running events are the failures, followed by starvation and blocked events. To minimize failure events it is necessary to investigate the effectiveness of preventive maintenance and the root cause of the most frequent failures.

The next step is to calculate: line efficiency and Line C zero and infinite buffer limits. Table 6.11 shows the results.

Table 6.11: Line C results for line efficiency, upper and lower buffer limits and buffer strategy performance.

Parameter	Value (%)
Line efficiency (η_{line})	83.1
Lower Limit (η_{line}^{0})	37.7
Upper Limit ($\eta_{line}^{\inf}$)	89.7
Buffer strategy performance (β)	87.3

Line C presents the highest line efficiency when compared to Line A and B. This line efficiency is closer to its upper limit, as expressed by the high value of buffer strategy. It is expected that Line C actual bottleneck would be machine reliability due to its high value for buffer strategy performance.

Buffer Parameters

The buffer parameters calculated for Line C were: accumulation ratio (Equations 5.9 and 5.10), nominal recovery ratio (Equations 5.11 and 5.12), mean recovery ratio (Equations 5.13 and 5.14), and buffer efficiency considering hours (Equations 5.15 and 5.16) and considering events (Equations 5.17 and 5.18). Table 6.12 shows the results.

Table 6.12: Line C buffer parameters results.

Conveyor	Type of buffer	Accumulation ratio	Nominal recovery ratio	Mean recovery ratio	η_{buffer}
DPL-DCR	Anti-starve	3.73	0.08	0.30	0.87
DCR-BW	Anti-starve	14.23	0.04	0.62	0.25
BW-IU	Anti-starve	12.34	0.04	0.54	0.27
IU-FL	Anti-starve	18.19	0.14	2.53	0.65
FL-PU	Anti-block	2.46	0.48	1.18	-0.32
PU-LBs	Anti-block	9.51	0.10	0.95	1.00
LBs-RCR	Anti-block	21.64	0.04	0.91	0.12
RCR-PL	Anti-block	16.21	0.03	0.47	0.76

The conveyor FL-PU presented the lowest accumulation ratio value for Line C. Combining this result with PU MTTR ($\sim$ 3 min), it indicates that the pasteurization unit has difficulties to return from a failure. Even though its failures can still be considered microdowntimes (MTTR is below 5 min), the conveyor may have been sized considering a lower value.

The nominal recovery ratio results pointed out four different conveyors: RCR-PL (0.03), DCR-BW (0.04), BW-IU (0.04) and LBs-RCR (0.04). This parameter is associated with the refilling (anti-starve) or consumption (anti-block) rate relative to buffer size. Therefore, a low nominal recovery ratio means that the machine MTBF is low and/or that its filling or consumption rate is low when compared to buffer size. The first case (low MTBF) applies for the palletiser (RCR-PL buffer) and bottle washer (BW-IU buffer). These two machines presented the lowest two MTBF values. On the other hand, decrater (DCR-BW buffer) and recrater (LBs-RCR buffer) belong to the second category, as their MTBF values are high when compared to the other Line C equipment.

The mean recovery rate describes how fast a buffer is able to refill relatively to its consumption rate (anti-starve buffers) or to be consumed relatively to its refilling rate (anti - block buffers). Line D lowest values for this parameter are DPL-DCR (0.30) and RCR-PL (0.47). These low values are associated to low MTBF for DPL and PL. In addition, DPL presented a high MTTR, which also helps to reduce the parameter.

Line C four lowest buffer efficiencies are: FL-PU (-0.32), LBs-RCR (0.12), DCR-BW (0.25) and BW-IU (0.27). Each of them were discussed separately:

FL-PU

This conveyor presented a negative value of buffer efficiency, mostly due to pasteurization unit MTTR. In other words, the PU takes a long time to recover ($\sim$ 3 min). This time, by definition still is a microdowntime [4]. Even if we considered this conveyor with macrostops, and we used the efficiency in events instead, its value would still be very low (0.04). These results suggest that the conveyor FL-PU is small for the current condition. Thus, to reduce filler blocked events we suggest to increase buffer size and/or improve PU maintainability to reduce its MTTR.

[4] According to Härte (1997) a macrodowntime is above 5 min.

LBs-RCR

The conveyor LBs-RCR presents the second lowest value of buffer efficiency. It indicates that this conveyor is small, because only 12% of RCR stops by blocked and failure were covered. In addition, a problem on crate circuit is possibly worsening this phenomenon. It would generate starvation events that are independent of the labellers. In other words, it is possible that the RCR would be stopped by crates starvation and, simultaneously, the labellers would be blocked.

DCR-BW

The buffer DCR-BW has a similar behavior of LBs-RCR. In other words, the majority of DCR stops (by starvation and failure) generate starvation events on the bottle washer. Another similarity is the possibility of the negative influence of the crate circuit on this buffer efficiency. It is not evident as Line B, however this phenomenon should not be neglected. The described crate circuit anomaly refers to the decrater being blocked by the crate circuit (crate washer failure and/or crates accumulation on decrater's crate exit conveyor), causing starvation on the bottle washer.

BW-IU

Similarly to FL-PU, this low buffer efficiency suggests that this conveyor presents an improvement opportunity. This parameter indicates that every minute that the bottle washer stops, the inspector unit stops almost 45 seconds. Therefore, increasing BW-IU buffer size would help to reduce IU starvation events. Another possibility is to improve BW reliability to increase its mean MTBF.

To clearly illustrate the relationship between buffer efficiencies and the time under each not-running status we built a column chart (Figure 6.53). It is similar to what we did for Line A and B.

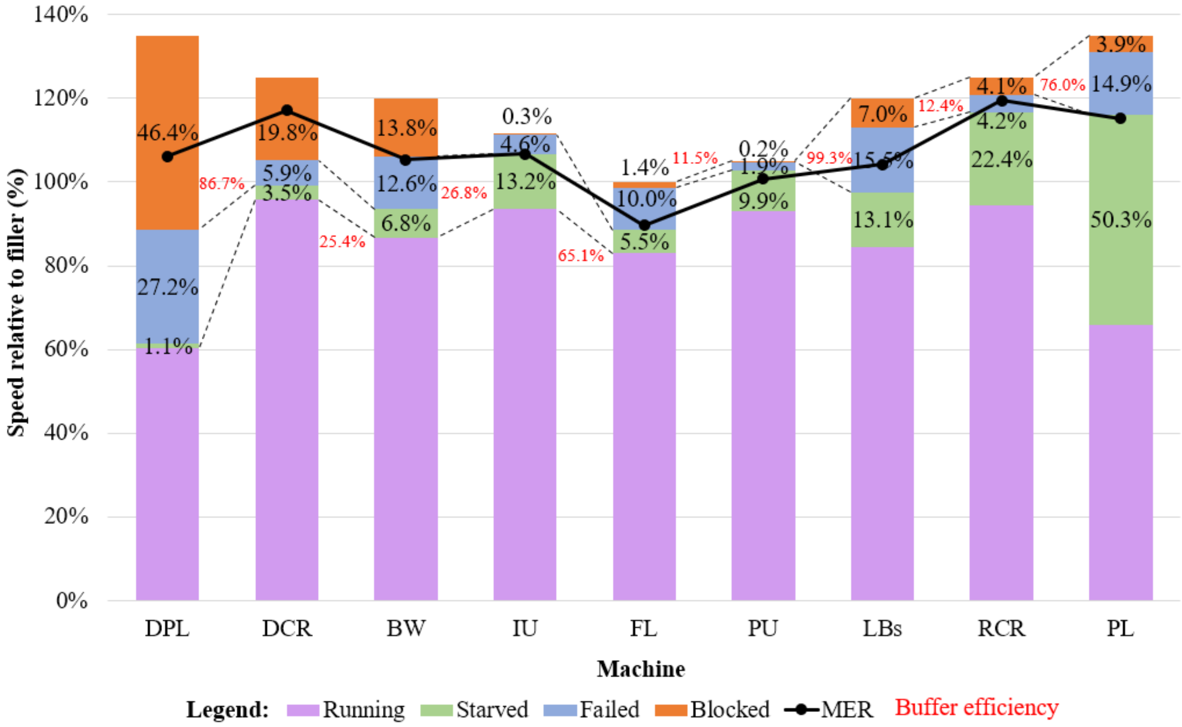


Figure 6.53: Column graph of Line C equipment divided by each status (running, failed, starved and blocked), M.E.R. and buffer efficiencies.

Figure 6.53 shows that the filler starvation events have more impact on line efficiency then blocked occurrences. Event though starvation scenarios are more relevant, we analyzed both of them.

The inspector unit presented the highest (13.2%) starvation percentage among DCR, BW and IU, followed by the bottle washer (6.8%) and the decrater (3.5%). The starvation percentages increase from DCR to BW may have three causes: DCR failures or blocked events related to crate circuit and/or low DCR-BW buffer efficiency (25.4%). Even though the starvation percentage increases 3.3% pp comparing DCR and BW, it is much more expressive when we compare IU and BW (6.4% pp). The main two reasons for this increase are: BW failures and low BW-IU buffer efficiency (26.8%). Thus, to decrease filler starvation events, it is recommended to carefully evaluate bottle washer reliability and/or increase BW-IU buffer size.

Making a similar analysis for blocked events, the pasteurization unit seems to be responsible for almost all filler blocked occurrences. It suggests that the buffer between the PU and the FL is small and/or the pasteurization unit MTTR is considerably high for the actual FL-PU buffer size.

Considering Figure 6.53 analysis, Line C actual bottlenecks are: the bottle washer, the filler and pasteurization unit reliability, and the size of the buffer FL-PU.

Combining Figure 6.53 and buffer parameters analysis, we concluded that the filler, bottle washer and pasteurization unit should have their preventive maintenance reviewed. It aims to increase these machines reliability. In addition, the conveyors FL-PU and BW-IU presented an improvement opportunity, due to their low nominal ratios and buffer efficiencies.

It is important to point out that improving BW and PU reliability a positive impact would already be seen on buffer parameters. Thus, it is necessary to carefully analyze all possible opportunities and choose the one that is easier and/or cheaper to be implemented.

6.2.4 Comparison between Lines A, B and C

After evaluating each returnable bottle line, we compared their results aiming to identify some "rules of thumb" to quickly evaluate improvement opportunities on filling lines. The comparison was divided into line and buffer parameters.

Line Parameters

The first parameter compared was M.E.R. Figure 6.54 illustrates a chart with all equipment from the three filling lines.

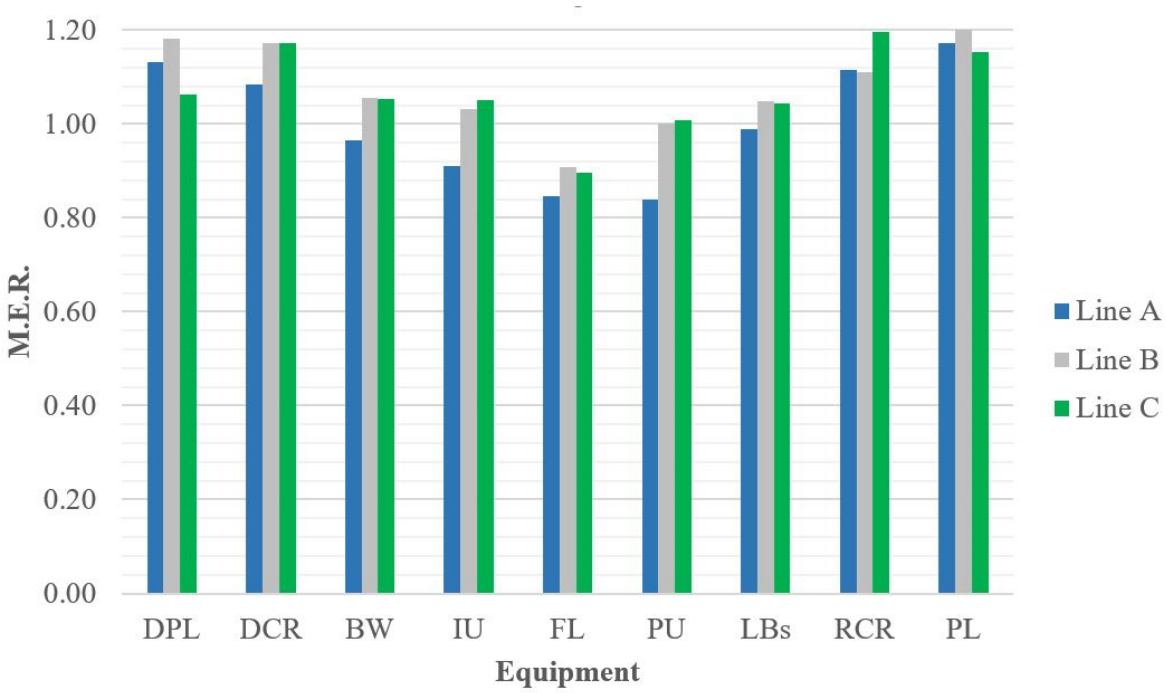


Figure 6.54: M.E.R. chart of Lines A, B and C.

Line A presents the lowest M.E.R. value for almost all equipment, the only two exceptions are the depalletiser and palletiser. Moreover, Lines B and C present similar values, the only three main exceptions are DPL, RCR and PL. Hence, considering only M.E.R., it is expected that Lines B and C present similar problems, and Line A equipment reliability should be deeply investigated.

Buffer strategy performance was the second parameter compared. Figure 6.55 shows line efficiency, upper and lower buffer limit of all three returnable bottle lines.

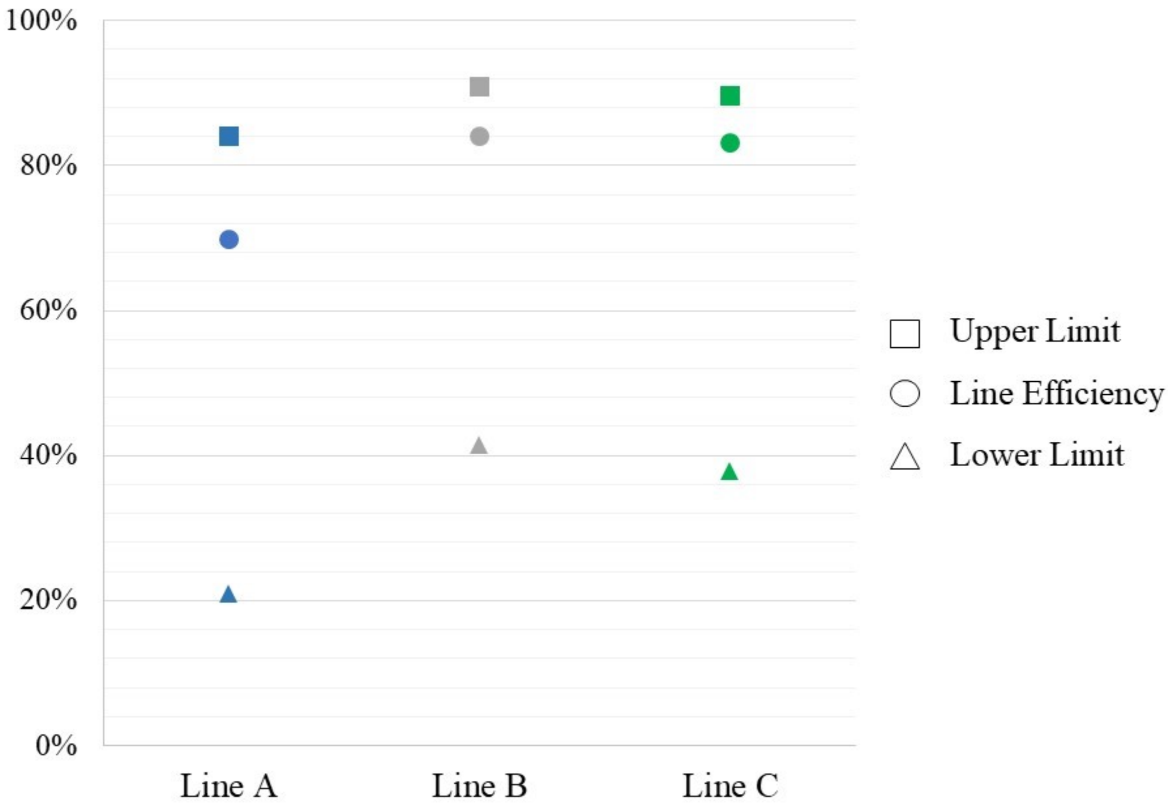


Figure 6.55: Chart comparing upper and lower buffer limits and line efficiency of Lines A, B and C.

However Line B presents the highest values of all buffer strategy performance indicators, Line C also presents high values. On the other hand, Line A has not only the lowest values, but they are considerably more spread when compared to Lines B and C. These two lines present line efficiencies much closer to upper limit, which suggests that their improvement opportunities tend to be more scarce.

The third parameter evaluated was the percentage of time that each filler spent on each status (failed, starved, blocked and running). Figure 6.56 illustrates these data through a bar chart.

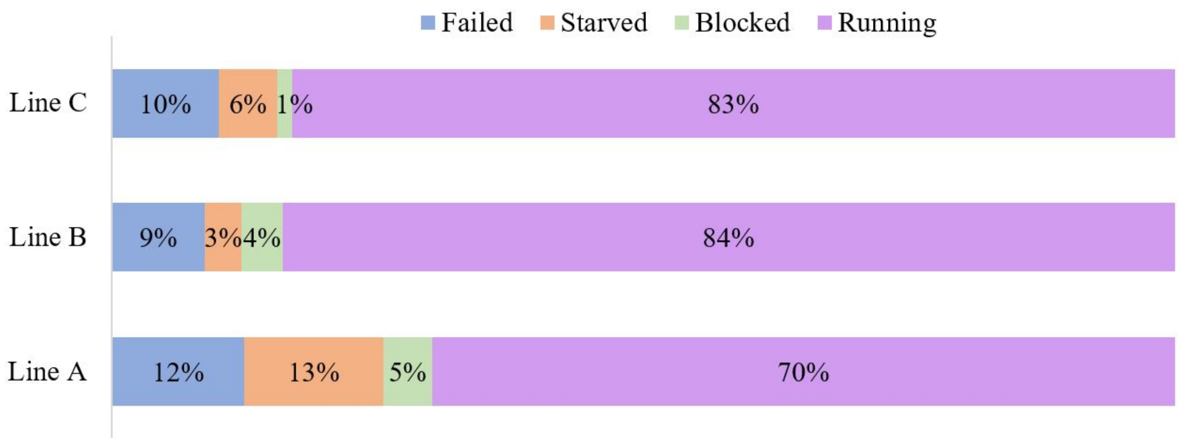


Figure 6.56: Bar chart comparing the percentage that each filler spent on each status (failed, starved, blocked and running)

As expected, Line A filler presents the lowest time on status running among the three lines. In addition, Lines B and C have similar values between them. Nevertheless the total time failed is considerably high (above 5%) for all lines, Line A highest share of not-running status is starved and not failed as the other two.

Moreover, starvation events appear to be an improvement opportunity for all three returnable bottle lines. Even though Line B has slight more time spent on blocked than starvation events.

Buffer Parameters

We calculated the following buffer parameters for all returnable bottle lines: accumulation ratio (Equations 5.9 and 5.10), nominal recovery ratio (Equations 5.11 and 5.12), mean recovery ratio (Equations 5.13 and 5.14) and buffer efficiency time-based (Equations 5.15 and 5.16).

The first parameter analyzed was accumulation ratio. Table 6.13 shows all three lines results.

Table 6.13: Accumulation ratio results for Lines A, B and C.

	Accumulation ratio		
Conveyor	**Line A**	**Line B**	**Line C**
DPL-DCR	2.77	11.61	3.73
DCR-BW	8.91	12.93	14.23
BW-IU	26.39	12.80	12.34
IU-FL	16.94	39.59	18.19
FL-PU	0.48	14.41	2.46
PU-LBs	5.12	9.22	9.51
LBs-RCR	15.87	15.28	21.64
RCR-PL	2.56	5.27	16.21

Comparing all three lines results and combining them with the conclusions drawn for each line, we conclude that buffers that present an accumulation value lower than 6.0 should be further evaluated, for example machines as for their MTBFs and MTTRs and/or the current buffer size. This result indicates a small buffer size and/or high values of MTTR[5] for adjacent machines.

Contrarily, very high values (above 20) should also be observed. This result is a consequence of a mathematical anomaly. In other words, when MTTR is small (around 30 s) it increases considerably the accumulation ratio, but it does not mean that the buffer capacity is as high as the parameter suggests.

In conclusion, an accumulation ratio grater than 6.0 is a good indicator that the buffer has a satisfactory dynamics, but it does not guarantee that the buffer is well sized. Especially, for conveyors with accumulation ratio above 15.

The second buffer parameter compared is the nominal recovery ratio. Table 6.14 shows Lines A, B and C results.

[5]A MTTR higher than 3 minutes can already be considered high, even though only values above 5 minutes are technically a macrodowntime.

Table 6.14: Nominal recovery ratio results for Lines A, B and C.

	Nominal recovery ratio		
Conveyor	**Line A**	**Line B**	**Line C**
DPL-DCR	0.15	0.05	0.08
DCR-BW	0.03	0.05	0.04
BW-IU	0.01	0.05	0.04
IU-FL	0.03	0.04	0.14
FL-PU	0.42	0.07	0.48
PU-LBs	0.13	0.11	0.10
LBs-RCR	0.02	0.02	0.04
RCR-PL	0.21	0.15	0.03

Combining Table 6.14 results and all line conclusion, we observed that a buffer with nominal ratio lower than 0.05 requires some attention. In addition, conveyors that present values higher than 0.05 and an accumulation ratio lower than 6.0 require further investigation.

A small value for nominal recovery ratio is associated with three different phenomena: low MTBF, small difference between nominal speeds and/or small buffer size. Thus, lower values of nominal recovery ratio can be improved by increasing buffer size, improving machine maintenance and/or upgrading an equipment maximum speed.

The third buffer parameter evaluated was mean recovery ratio. Table 6.15 shows all returnable bottle lines results.

Table 6.15: Mean recovery ratio results for Lines A, B and C.

	Mean recovery ratio		
Conveyor	**Line A**	**Line B**	**Line C**
DPL-DCR	0.41	0.56	0.30
DCR-BW	0.27	0.63	0.62
BW-IU	0.37	0.67	0.54
IU-FL	0.48	1.50	2.53
FL-PU	0.20	1.04	1.18
PU-LBs	0.67	1.00	0.95
LBs-RCR	0.35	0.33	0.91
RCR-PL	0.53	0.79	0.47

Integrating line and Table 6.15 results, we verified that a buffer with acceptable dynamics has a mean recovery ratio near the unit. The only exception for this rule is when a equipment presents an high MTBF (above 10 minutes). When these two conditions are combined, they generate a false positive indication. In other words, a mathematical anomaly occurs.

Lastly, we compared all three lines buffer efficiency (time-based). Table 6.16 presents the results. We did not compare buffer efficiency events-based, because of its low applicability for the studied lines.

Table 6.16: Buffer efficiency results for Lines A, C and D.

	Buffer efficiency		
Conveyor	**Line A**	**Line B**	**Line C**
DPL-DCR	70%	70%	87%
DCR-BW	85%	-21%	25%
BW-IU	92%	61%	27%
IU-FL	32%	75%	65%
FL-PU	71%	21%	-32%
PU-LBs	45%	92%	100%
LBs-RCR	69%	85%	12%
RCR-PL	42%	3%	76%

Lines A, B and C results suggest that a buffer efficiency lower than 40% should be carefully evaluated. When a negative value for this parameter is found, it is necessary to investigate the existence of macrodowntimes or another anomaly on line behavior, such as excessive blocked events due to interference between crate and bottle circuit.

In conclusion, buffer parameters should be analyzed together, because analyzing one parameter alone can lead to wrong or incomplete conclusions. Although it is necessary to evaluate buffer parameters combined, we developed some "rules of thumb" to help process and production engineers to accelerate their studies on determining their line actual bottleneck. These "rules of thumb" are:

- Accumulation ratio should be higher than 6.0 and lower than 15;
- Nominal recovery ratio should be higher than 0.05;
- Mean recovery ratio should be around 1.0;
- Buffer efficiency should be above 40%.

It is necessary to point out that these rules must be evaluated together. Furthermore, the parameter that has to be analyzed first is buffer efficiency. The others are also important, but they have the purpose to help understanding the reasons of low buffer efficiency, instead of point out an isolated problem.

6.3 Rules of thumb: testing

Aiming to develop rules of thumb robust enough for filling lines with different layouts and products, we applied them to a can filling line (Line D). We chose it because this line layout is considerably different of a returnable bottle line, that was used for the rules of thumbs development.

We divided the rules of thumb test into four parts:

1. Calculation and analysis of critical parameters;
2. Rules of thumb application;
3. Graphs examination (M.E.R, the chart of the percentage of time that each equipment spent on each status);
4. Combination of the previous analysis through the examination of a chart that shows the combination between buffer and line parameters.

For the first part, we considered buffer strategy performance indicators (lower and upper buffer limits and line efficiency) and buffer parameters (nominal recovery, and mean recovery ratios and buffer efficiency) as critical.

Even for a simplified analysis, it is necessary to calculate MTBF, MTTR and availability. Thus, Table 6.17 shows Line D results for these parameters.

Table 6.17: Line D MTBF, MTTR and availability data.

Machine	MTBF (s)	MTTR (s)	Availability
DPL	288	18	0.94%
FL	1109	133	0.89%
PU	2013	146	0.93%
IU2	6235	77	0.99%
IU3	3101	72	0.98%
PCK	470	78	0.86%
PL1	408	29	0.93%
PL2	348	33	0.91%

Line D MTBF results are considerably higher when compared to all returnable bottle lines. For instance, the highest MTBF value for Line A, B and C is around 1200 s and the highest value for Line D is almost three times this value (6235 s). It suggests that Line D machine reliability is higher when compared to returnable bottle lines.

Firstly, we evaluated buffer strategy performance. Table 6.18 shows the results.

Table 6.18: Line D results for line efficiency, upper and lower buffer limits and buffer strategy performance.

Parameter	Value (%)
Line efficiency (η_{line})	81.8
Lower Limit (η^{0}_{line})	69.5
Upper Limit ($\eta^{\inf}_{line}$)	89.3
Buffer strategy performance (β)	62.2

Line D presents the highest lower buffer limit (69%), among all filling lines evaluated (Lines A, B, C and D). It indicates that the reliability of this line is better when compared to the returnable bottle lines analyzed.

Even though this can line presents higher upper and lower buffer limits, it also has the lowest buffer strategy performance value (62%). It suggests that this line have some improvement opportunities on buffer design.

Secondly, we calculated Line D buffer parameters (accumulation, nominal recovery, mean recovery ratio and buffer efficiencies). Table 6.19 shows the results.

Table 6.19: Line D buffer parameters results.

Conveyor	Type of buffer	Accumulation ratio	Nominal recovery ratio	Mean recovery ratio	$\eta_{\textbf{buffer}}$
DPL - FL	Anti-starve	16.56	0.21	3.48	0.05
FL - PU	Anti-block	1.33	1.84	2.45	0.74
PU - IUs	Anti-block	6.06	1.37	8.30	0.77
IUs - PCK	Anti-block	3.92	0.03	0.10	0.74
PCK - PLs	Anti-block	10.26	0.08	0.81	-0.27

Thirdly, we applied the proposed "rules of thumb" to Line D. Table 6.20 shows the results and its color code correspondence is:

- RED: the conveyor does not satisfy the rule;
- GREEN: the conveyor does follow the rule;
- YELLOW: the conveyor result are on a transition point;

Table 6.20: Results of the "rules of thumb" applied on Line D buffer parameters.

Conveyor	Accumulation ratio	Nominal recovery ratio	Mean recovery ratio	η_{buffer}
DPL - FL	> 15			< 0.40
FL - PU	< 6			
PU - IUs				
IUs - PCK	< 6	< 0.05	< 1.0	
PCK - PLs		0.08	< 1.0	< 0.40

The only conveyor that follows all proposed rules are PU-IUs. It indicates that the pasteurization unit does not present many blocked events due to any inspector unit failure.

On the opposite hand, all the other conveyors do not follow at least one rule. FL-PU and IUs-PCKs are conveyors that present a positive result for the buffer efficiency rule, but do not follow at least one other rule. It indicates that even though these conveyors tend to present some buffer dynamic problem, it does not have a considerable impact on buffer efficiency. This conclusion is mostly based on the fact that buffer efficiency parameter shows the effective impact of each buffer on the adjacent equipment. Hence, this parameter can be considered more important than the others.

Contrarily to FL-PU and IUs-PCK conveyors, DPL-FL and PCK-PLs present a negative result for buffer efficiency rule. In addition, these conveyors also show negative results for at least one more rule. Each of these conveyors were evaluated separately.

DPL-FL

This conveyor has a high accumulation ratio, which suggests that the depalletiser MTTR can be considered small, causing a mathematical anomaly. In addition, this conveyor presents a low value for buffer efficiency (5%). It indicates that almost every DPL stop lead the filler to stop by starvation. In other words, this buffer is not capable to keep the filler running while the depalletiser fails or starves. Thus, increasing this buffer can reduce the total time that the filler spend on starvation status.

PCK-PLs

The conveyor PCK-PLs is the only one that presents a yellow cell. We chose this color for two main reasons: it has the second lower value for nominal recovery rate and negative results when we applied the mean recovery ratio and buffer efficiency rules. This outcome suggests that the limit for nominal recovery ratio for can lines are higher when compared to returnable bottle lines.

Differently of DPL-FL conveyor, PCK-PLs presents not only a low value for buffer efficiency, but a negative one. The two reasons that explains this result are: line layout and the location of the sensors that discharges the blocked status.

Line D has a particular layout. It consists of a conveyor mechanism that chooses to which palletiser the packages will be sent (see Figure 6.57). There are two options: palletisers 1 and 2 or palletiser 3. This mechanism is positioned considerably close to the packer (around 4 meters) and it takes 40 to 60 s to change its position. The positions are: elevation (palletizer 3) or without elevation (the same level of the output conveyor). This last position send the packages to palletizers 1 and 2. Hence, while the conveyor mechanism changes its position, the packer remains blocked. Even though the palletizer 3 operated only 3.5% of the time, this phenomenon probably contributed negatively to buffer efficiency.

Since PL3 is seldom used (only 3.5% of the time that Line D produced), we suggest that the brewery relocate palletizer 3 to another existing can filling line with lack of capacity on its palletizers. Another possibility is use this spare palletizer when building a new can filling line, instead of buying a new machine.

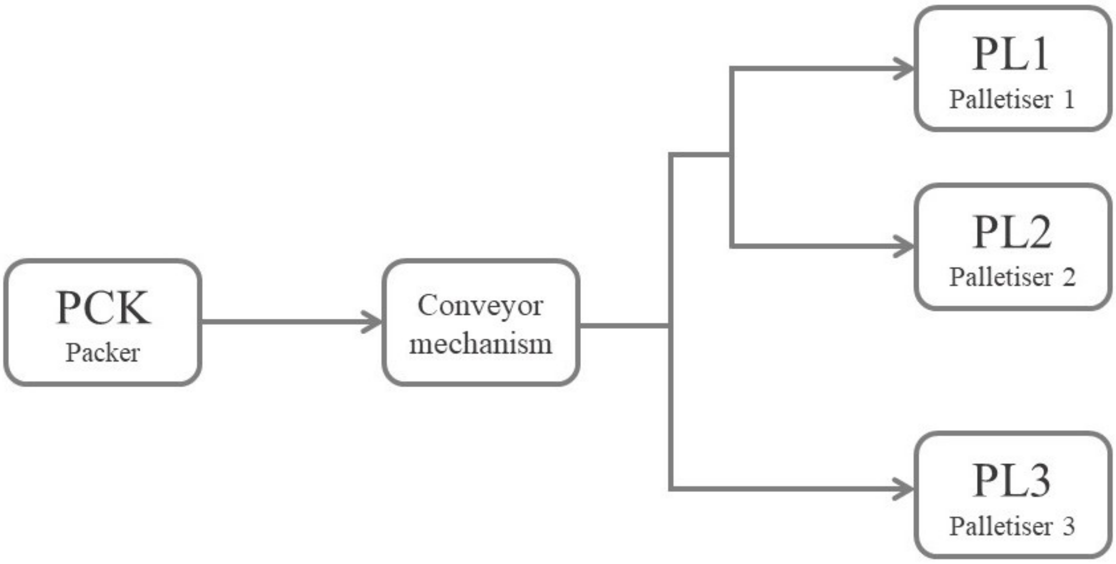


Figure 6.57: Illustration of the conveyor mechanism used to select the palletisers.

The position of the sensor that discharges the packer blocked status can also be considered a particularity of Line D. Figure 6.58 illustrates the described phenomenon.

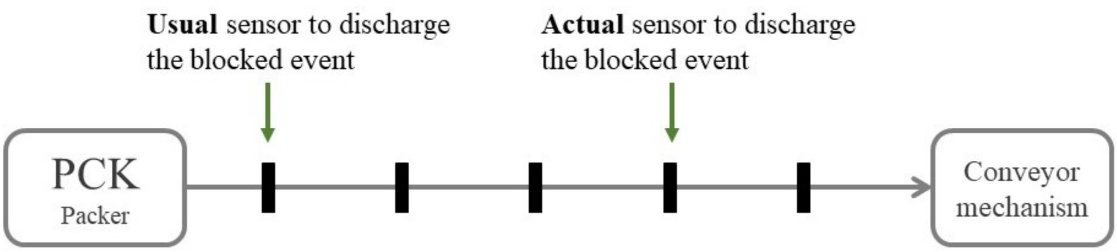


Figure 6.58: Schema of the location of the usual sensor to discharge blocked status and the actual sensor used for the packer.

The main problem associated with using the farthest sensors from the packer is because this machine will sense lately that the conveyor is clear to restart its production. The dead time created increases the time that the packer stays blocked, even though the palletisers have already recovered their production.

To better understand Line D behavior, we interviewed some operators and supervisors. When the operation team was questioned about why the sensor that discharged the blocked status are considerably far from the packer, they argued that the packages would experience frequent crash if the sensor is too close to the machine. In other words, a package crash happens when the conveyor stops and the packer are still sending the remaining packages that were inside of it. Thus, the packages that are leaving the packer crash with the ones that are on the conveyor. This phenomenon compromise the quality of the cans (they can crumple them) and prevent the line to restore its production without an operator intervention.

This operational discomfort corroborates with the conclusion that although PCK-PLs conveyor has some layout particularities, its small size is mainly responsible for its negative buffer efficiency. Hence, increasing this buffer would not only help to avoid packer blocked events, but would also decrease their duration. In other words, it would be possible to use a sensor closer to the packer to discharge its blocked event.

To validate the results achieved with line and buffer parameters analysis, we analyzed and compared the previous results with M.E.R. graph (Figure 6.59) and Line D chart with the percentage of each equipment on each status (Figure 6.60).

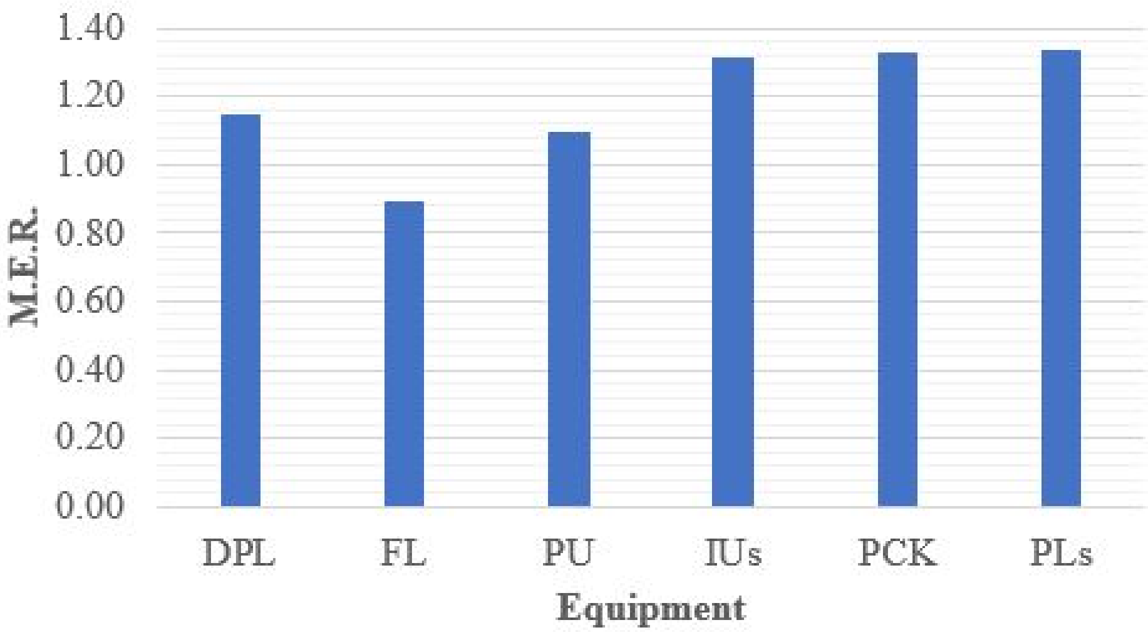


Figure 6.59: M.E.R of all Line D equipment.

The filler presents the lowest value of M.E.R. for Line E, as expected. Despite the adequate design for the nominal speeds, PCK and PLs do not present a M.E.R. following the V-graph. This result is due to the fact that their availability are low, when compared to IUs (see Table 6.17). It indicates that the reliability and/or of the packer and palletisers 1 and 2 should be improved.

The conveyor IUs-PCK did not follow some rules of thumb proposed, probably because IUs and PCK have a similar M.E.R. In addition, this M.E.R. similarity could also explain the negative value of PCK-PLs buffer efficiency.

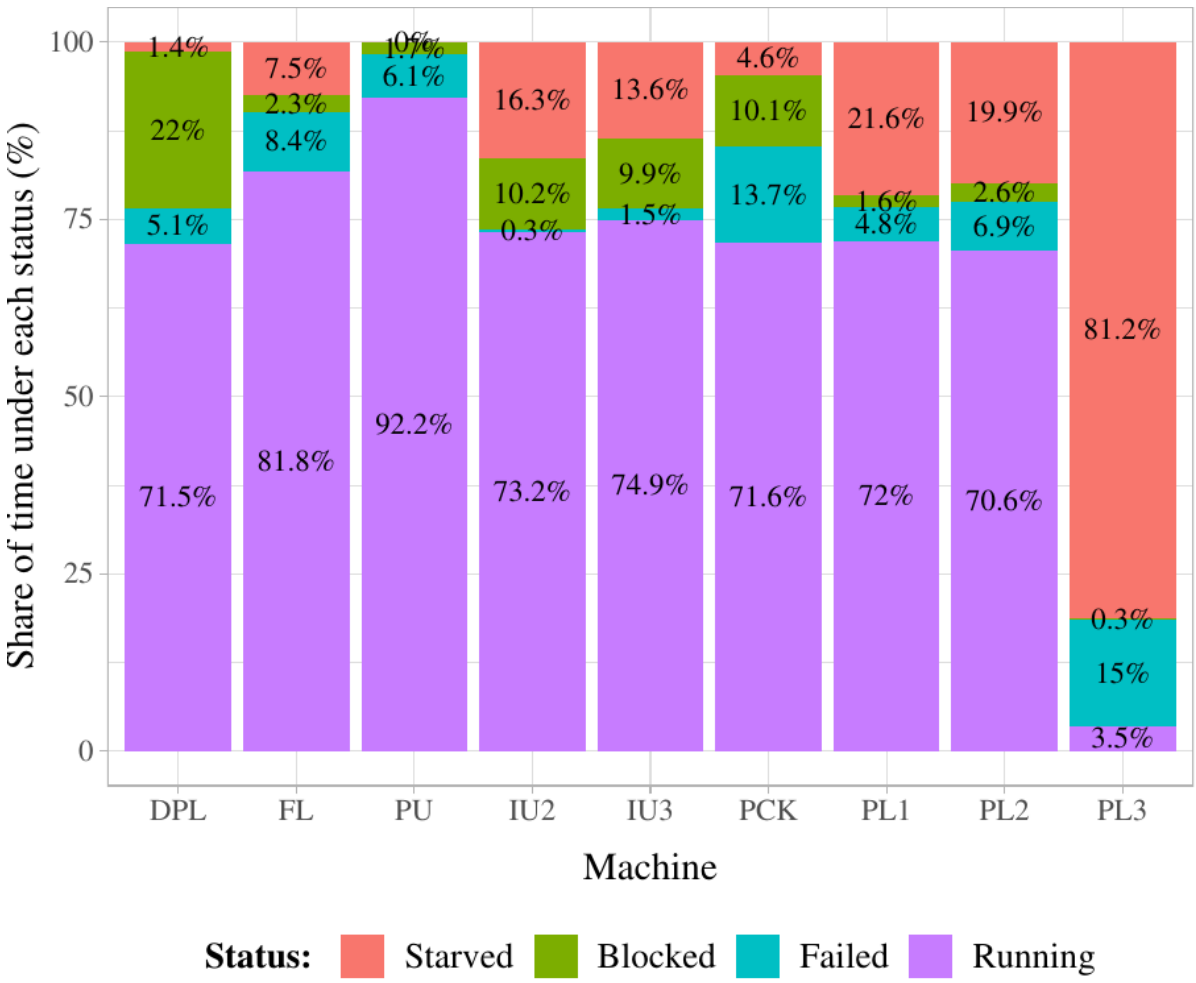


Figure 6.60: Column chart of Line D equipment divided by each status (running, failed, starved and blocked).

Evaluating Figure 6.60 results, we verified that the filler highest not-running status is failed, the second is starved and the last is blocked.

Excluding PL3, which ran only 3.5% of the time, PCK presents the highest time on failed status. Some failures are caused by how this equipment operates, for instance: loading new shrink film and can blockage at the machine entrance.

To clearly illustrate the relationship between buffer efficiencies and the time that each machine stays under each not-running status we built a column chart (Figure 6.61). It is similar to what we did for Lines A, B and C.

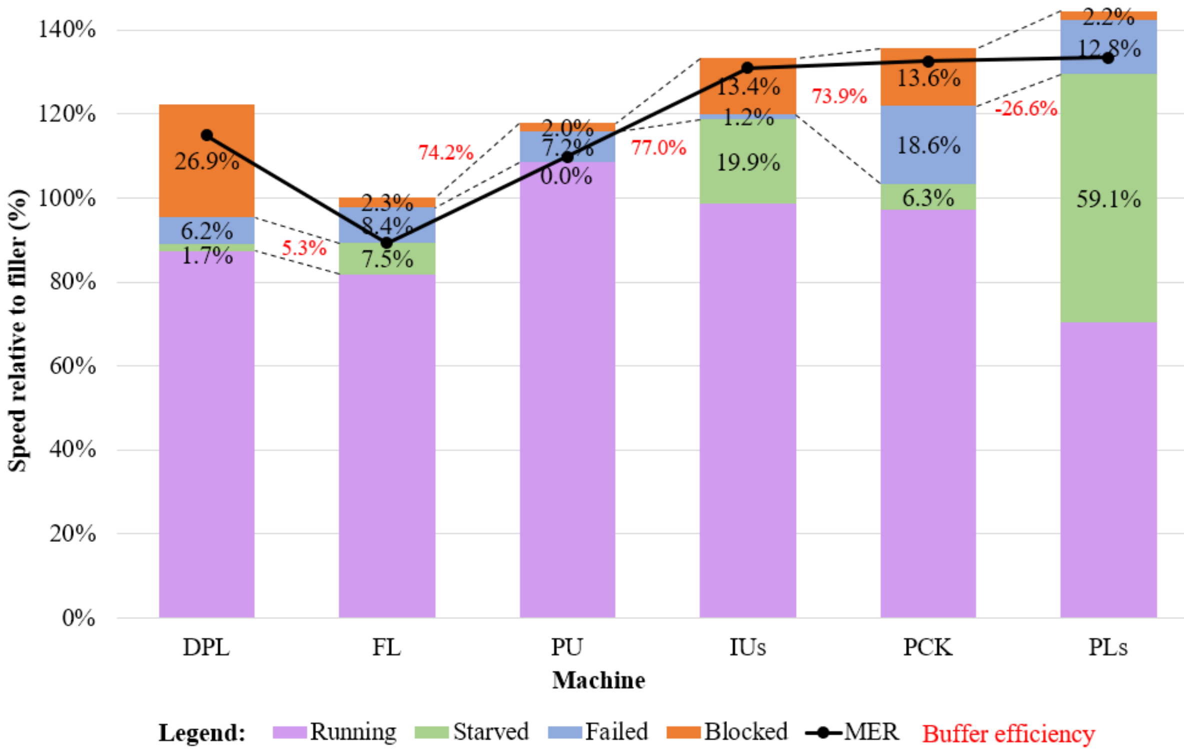


Figure 6.61: Column graph of Line E equipment divided by each status (running, failed, starved and blocked), M.E.R. and buffer efficiencies.

Figure 6.61 shows that the filler starvation events have more impact on line efficiency then blocked occurrences. Event though starvation scenarios are more relevant, we analyzed both of them.

Almost all depalletiser starvation and failure events cause a starvation event on the filler. It happens because of DPL-FL low buffer efficiency. Therefore, to decrease the time under starvation status there are two options: to increase DPL-FL buffer and/or to improve depalletiser reliability using the same method proposed for the filler.

Regarding filler blocked events, we identified three main causes: the pasteurization unit and packer failure events and PCK-PLs negative buffer efficiency. Thus, in order to reduce this kind of event there are three alternatives: to improve the reliability of the pasteurization unit or the packer or to increase PCK-PLs buffer size.

Moreover, to improve filler reliability, a detailed evaluation of the root cause of the most common failures must be carried out.

Any of these actions would reduce not-running events, but it is more advisable to focus on starvation and failure occurrences. In other words, the actions to improve filler and depalletiser reliability and DPL-FL buffer size would cause a more significant impact on line efficiency.

Combining all the previous analysis, we concluded that they complement each other. The line and buffer parameters reveals some buffers that could be increased and line status and M.E.R. charts give some insights regarding to machine reliability and how the equipment failures propagate through the other machines.

For Line D, for instance, the actions that could have the best return of investment are: upgrade filler and depalletiser reliability and increase DPL-FL buffer size. Each of these actions must be carefully evaluated, because it is not clear which of them is easier and/or less expensive to be implemented.

6.4 Rules of thumb: summary

Comparing the results achieved for returnable bottle and can lines, some conclusions can be drawn:

- Buffer strategy performance (β) higher than 70% suggests that the filling line analyzed probably has machine reliability problems, and values lower than 30% indicates buffer size problems;
- Accumulation ratio should be between 6.0 and 15;
- Nominal recovery ratio should be higher than 0.08;
- Mean recovery ratio should be around 1.0;
- Buffer efficiency should be higher than 40%.

M.E.R. and the column charts, that show the percentage of time that each equipment spent on each status, help to identify which machine requires a more detailed evaluation on its preventive maintenance routine.

It is important to emphasize that all parameters should be analyzed combined, due to the fact that a simpler analysis might indicate a wrong conclusion about the effective improvement opportunities.

Regarding to buffer parameters, buffer efficiency tends to be more relevant, but the others help to understand the reason of the low efficiency and to identify possible solutions.

The rules of thumb developed have some restrictions:

- They only can be applied to flow shop process without assembling steps;
- They can only be applied to filling lines with a layout similar to a returnable bottle or a can line. If the line layout is considerably different, we recommend to apply the whole methodology described to identify the best ranges for the specific line and buffer parameters;
- For lines that process different sizes of containers each one has to be evaluated separately, as if it were a different filling line;
- If the filling line processes different types of filling fluids that influences line dynamics, they should be considered a different filling line. For example, if the product has a different viscosity requiring lower or higher machine speeds.

Filling lines with a considerable different layout (one-way bottle lines, for instance) may present slight distinct reference values for nominal and average recovery ratio. It happened with Line D when we evaluated the nominal recovery ratio for the conveyor PCK-PLs. Although some buffer parameters reference values might differ for different types of filling lines, buffer efficiency should be higher than 40% for any type.

For filling lines similar to Line A or D, but with more machines for each step: two fillers for example, we advise to have an extra care when combining buffers and using mean values for parallel equipment. More information about how to deal with parallel machines are in Section 5.5.

When a machine is identified as a improvement opportunity for line efficiency, we advise to apply the methodology described on section 5.4 to have a clear understanding of how preventive maintenance can be changed.

6.4.1 Recommendations for the evaluated filling lines

The specific conclusions of each line analyzed on this study was summed up, each line was evaluated separately.

Line A

Line A presented improvement opportunities related to machine maintenance. Combining reliability and buffer analysis, it was verified that this line preventive maintenance strategy should be reviewed to focus on bottle washer, inspector unit, filler and pasteurization unit.

Line B

Line B results suggested that this line has machine and buffer size improvement opportunities. The equipment selected to have their maintenance reviewed were: bottle washer, filler and pasteurization unit. The buffer size opportunities identified were: improve crate circuit dynamics and increase RCR-PL buffer.

Line C

Line C also presented machine and buffer opportunities. The equipment identified were: bottle washer, filler and pasteurization unit. In addition, the buffer size opportunities identified were increasing FL-PU and/or BW-IU size. But, it is important to point out that improving these three machines reliability will also have a positive impact on buffer parameters.

Line D

Line D also presented machine and buffer size opportunities. The machines identified were the depalletiser and the filler. In addition, it is suggested to increase the size of the buffer DPL-FL in order to decrease starvation events on the filler.

Chapter 7: Conclusions and Suggestions for future research

Considering all the results developed in this thesis, we highlight four technical innovations:

- It was the first to evaluate a whole returnable bottle filling line;
- We are the first to analyze real data to differentiate micro and macrodowntimes;
- This study proposed an unique methodology for rapidly evaluate line and buffer parameters;
- We developed all analysis using the open source platform R. It indicates that all the proposed methodology could be performed at lower cost than other available commercial tools.

Moreover, this thesis was divided in two parts: RAM analysis of a whole returnable bottle line and the development of rules of thumb for filling lines and each of them have their own main conclusions.

7.1 RAM Analysis

RAM analysis results suggested that four machines directly impair line efficiency: the filler, the inspector unit, the bottle washer and the pasteurization unit. This result corroborates with the hypothesis that the filler is not the only piece of equipment that influences line efficiency.

7.2 Rules of thumb: development and test

We developed some rules of thumb to identify the actual bottleneck of any filling line with simple line parameters. They were built based on the results of three returnable bottle lines and validated against a can line. From these rules, the most relevant indicator is buffer efficiency, but the others also help to understand the reasons of an eventual low efficiency and to identify possible solutions.

The proposed rules of thumb can only be applied to filling lines with a layout similar to a returnable bottle or a can line. If the line layout is considerably different, we recommend to apply the whole methodology described to identify the best ranges for the specific line and buffer parameters.

7.3 Sum up

Thus, the main conclusions of this study were:

- We identified that the buffer strategy performance (β) can identify if a filling line needs to improve machine maintenance, buffer size or a mixture of them;
- Reliability analysis is suggested when a filling line presents machine maintenance as the main improvement opportunity;
- Even for filling lines with high efficiency we could identify buffer size improvement opportunities;
- The rules of thumb established can be applied, with some restrictions (see Section 6.4) to other filling lines.

This thesis aimed to be a first step on extracting useful information from a plethora of data enabled by technologies from Industry 4.0. It intended to suggest a simple method of evaluating line and buffer parameters, aiming to identify machine maintenance and buffer size and/or dynamic improvement opportunities.

7.4 Suggestions for future research

For future research, we suggest the development of a study focusing on failure types, their frequencies and actions to mitigate them. In addition, we suggest evaluating these rules of thumb on different manufacture lines, such as can and bottle manufacturing.

Another possibility is to quantitatively evaluate how much a buffer should be increased when a buffer size opportunity is identified. In addition, with a considerable number of filling lines it would be possible to suggest a mathematical correlation to buffer size based on existing filling lines. This correlation would be useful for both line retrofit and new designs.

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Appendix A: Line A Histogram of failure

A.1 Depalletizer - DPL

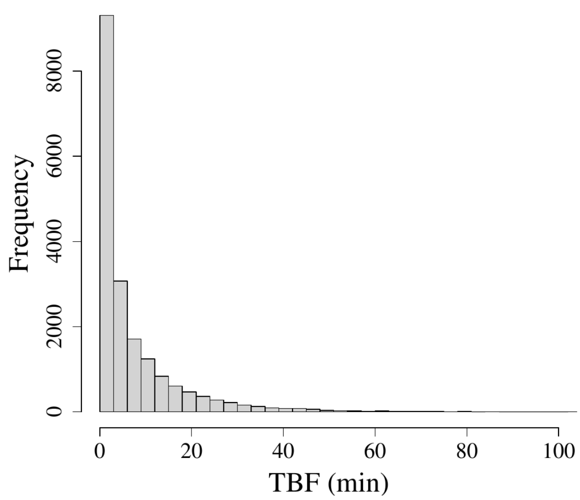

Figure A.1: Histogram of TBF data for Line A Depalletizer.

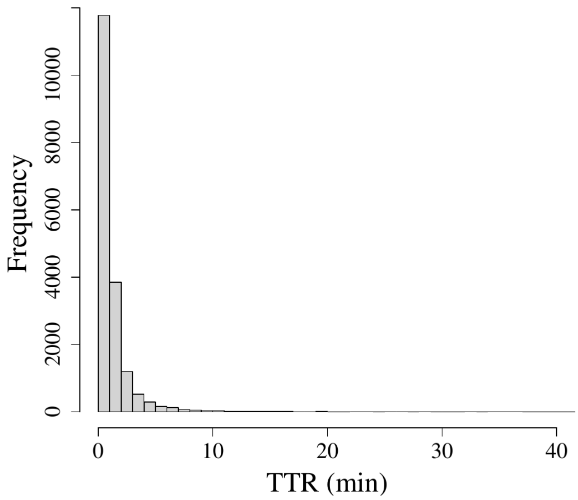

Figure A.2: Histogram of TTR data for Line A Depalletizer.

A.2 Decrater - DCR

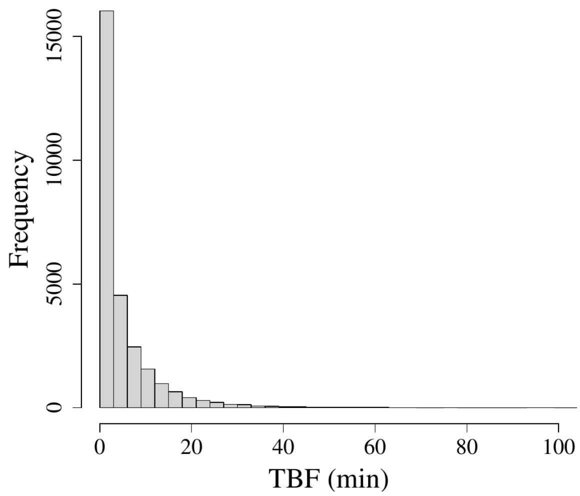

Figure A.3: Histogram of TBF data for Line A Decrater.

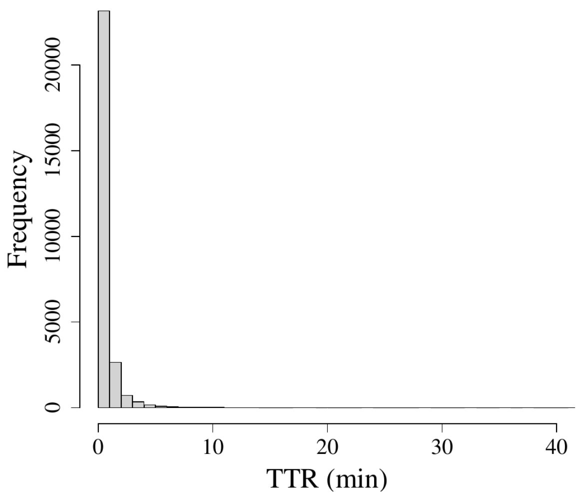

Figure A.4: Histogram of TTR data for Line A Decrater.

A.3 Bottle Washer - BW

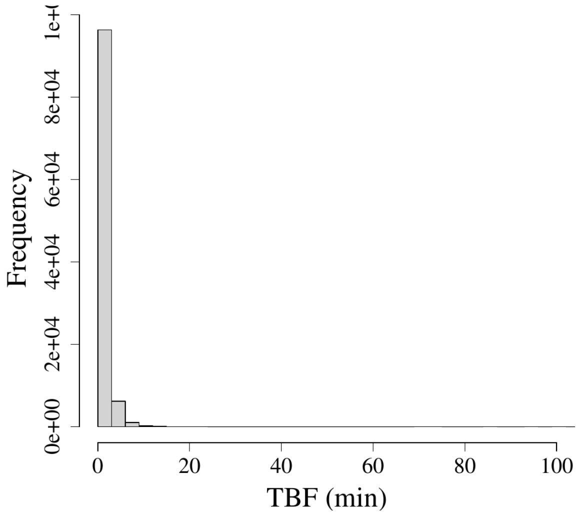

Figure A.5: Histogram of TBF data for Line A Bottle Washer.

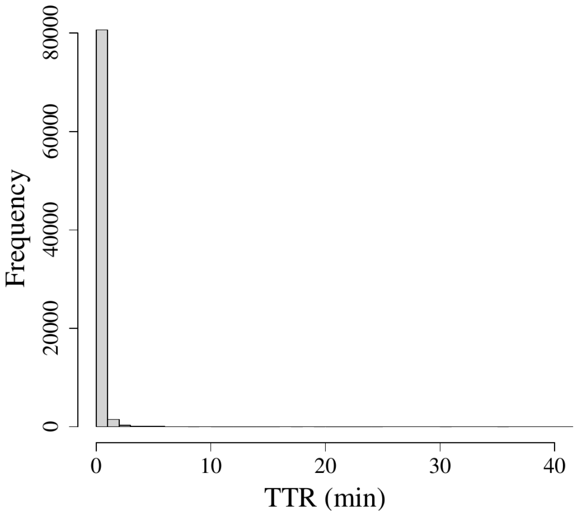

Figure A.6: Histogram of TTR data for Line A Bottle Washer.

A.4 Inspector Unit - IU

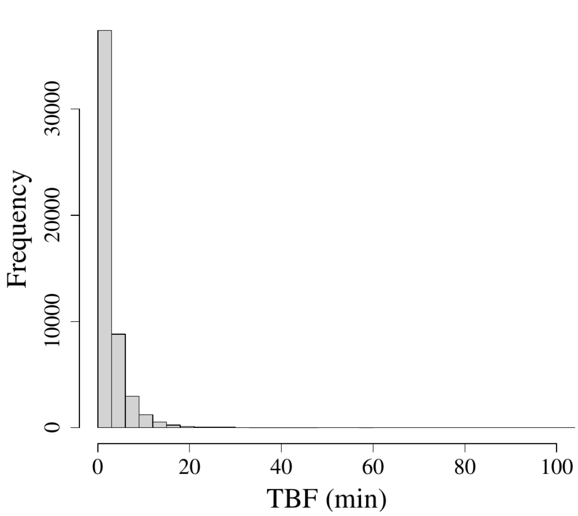

Figure A.7: Histogram of TBF data for Line A Inspector Unit.

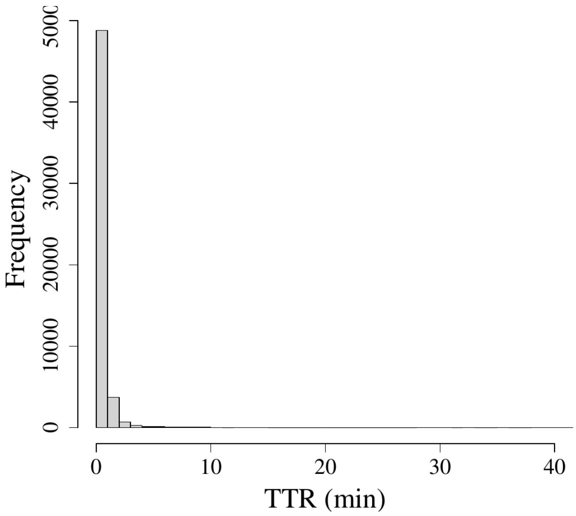

Figure A.8: Histogram of TTR data for Line A Inspector Unit.

A.5 Filler - FL

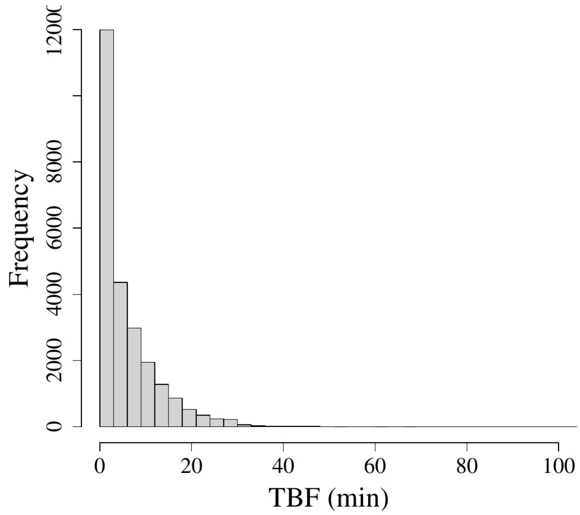

Figure A.9: Histogram of TBF data for Line A Filler.

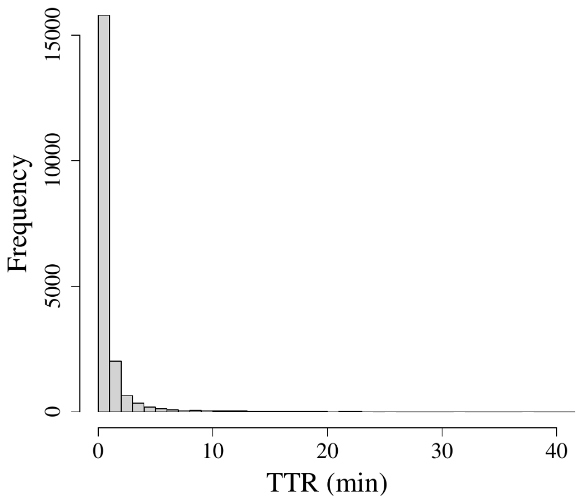

Figure A.10: Histogram of TTR data for Line A Filler.

A.6 Pasteurization Unit - PU

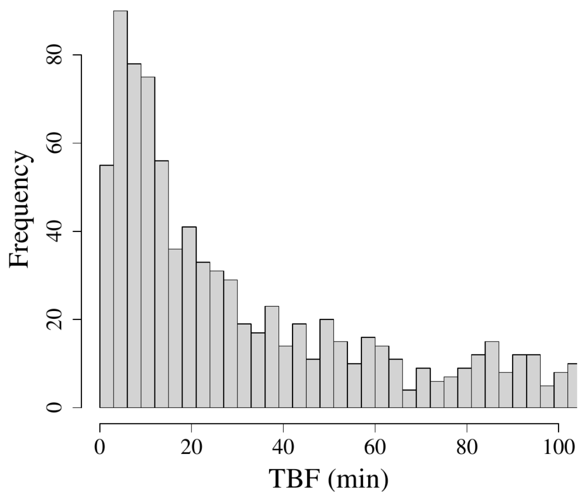

Figure A.11: Histogram of TBF data for Line A Pasteurization Unit.

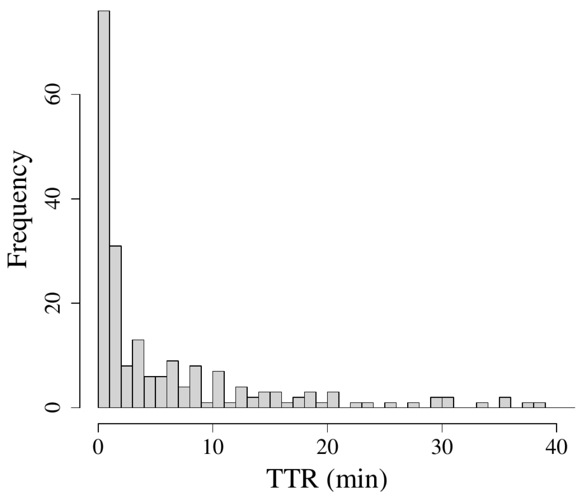

Figure A.12: Histogram of TTR data for Line A Pasteurization Unit.

A.7 Labeller 1 - LB1

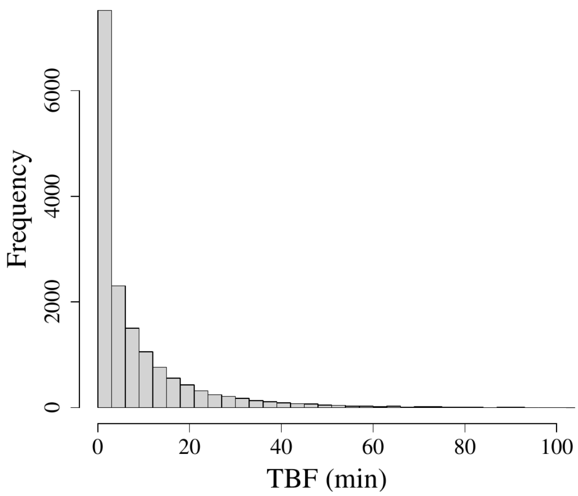

Figure A.13: Histogram of TBF data for Line A Labeller 1.

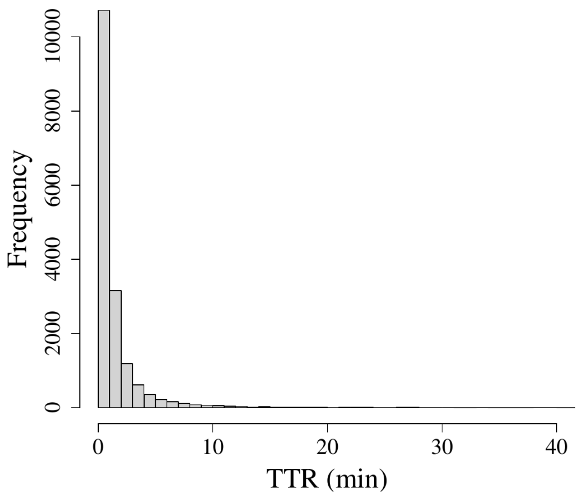

Figure A.14: Histogram of TTR data for Line A Labeller 1.

A.8 Labeller 2 - LB2

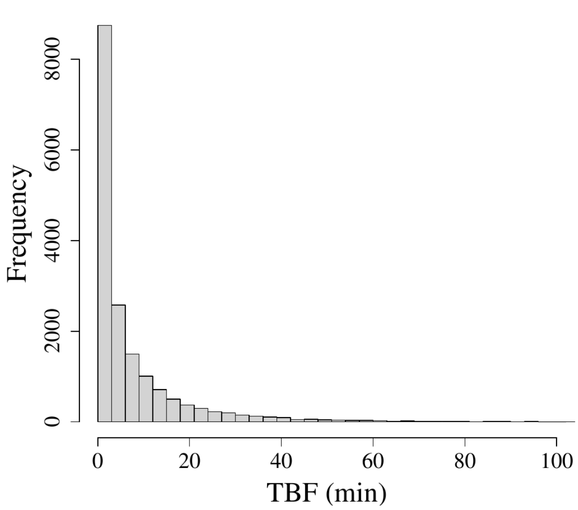

Figure A.15: Histogram of TBF data for Line A Labeller 2.

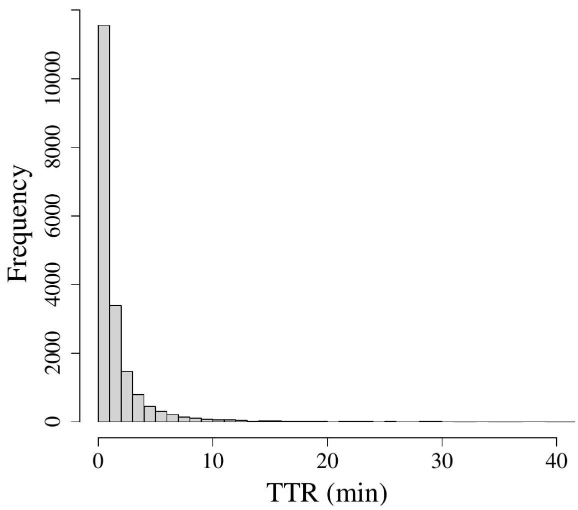

Figure A.16: Histogram of TTR data for Line A Labeller 2.

A.9 Recrater - RCR

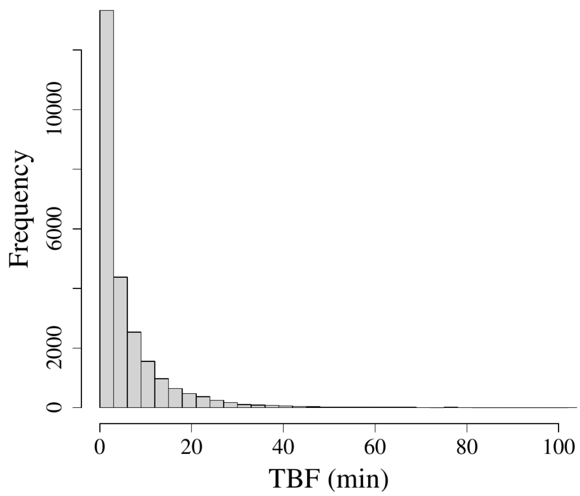

Figure A.17: Histogram of TBF data for Line A Recrater.

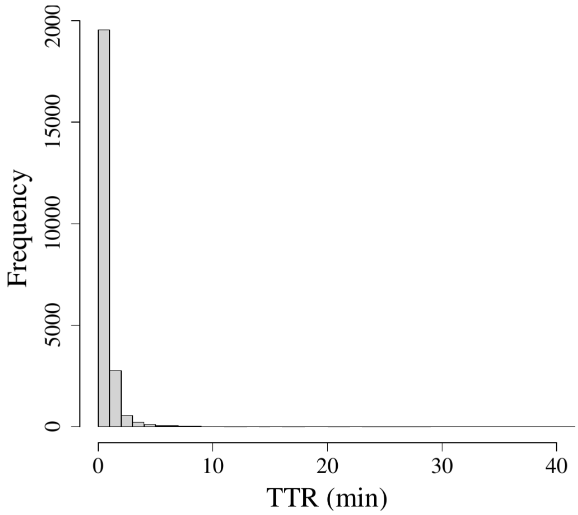

Figure A.18: Histogram of TTR data for Line A Recrater.

A.10 Palletizer - PL

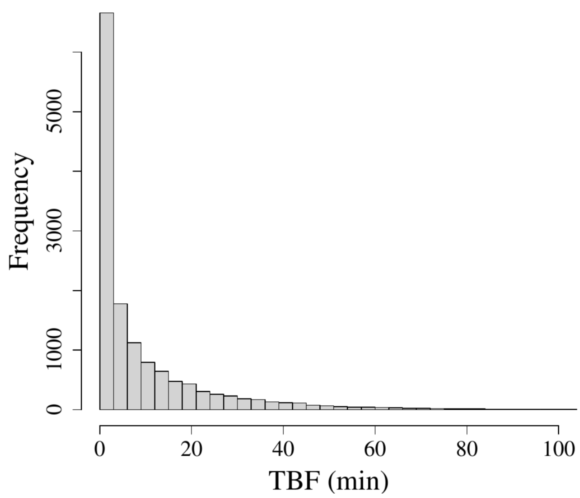

Figure A.19: Histogram of TBF data for Line A Palletizer.

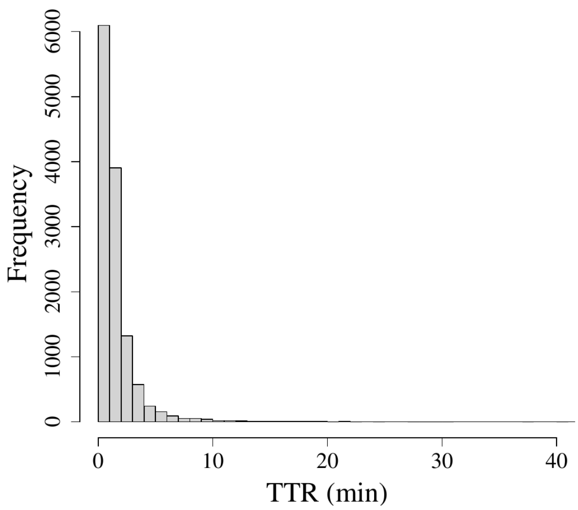

Figure A.20: Histogram of TTR data for Line A Palletizer.

Appendix B: Line A TBF and TTR trend graphs

B.1 Depalletizer - DPL

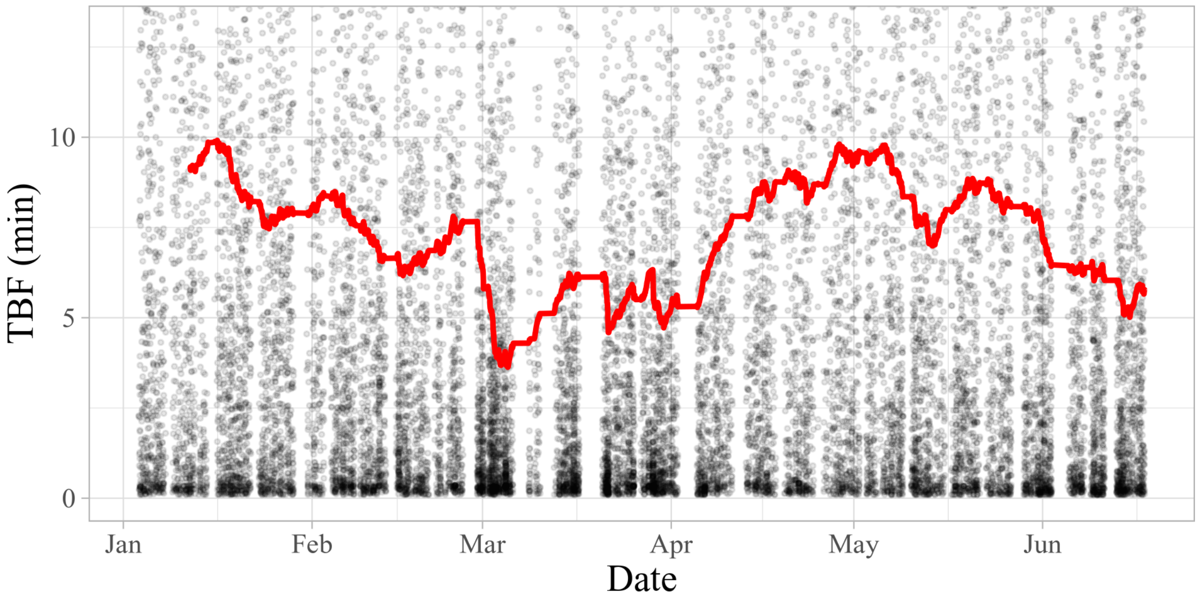

Figure B.1: Depalletizer TBF trend chart.

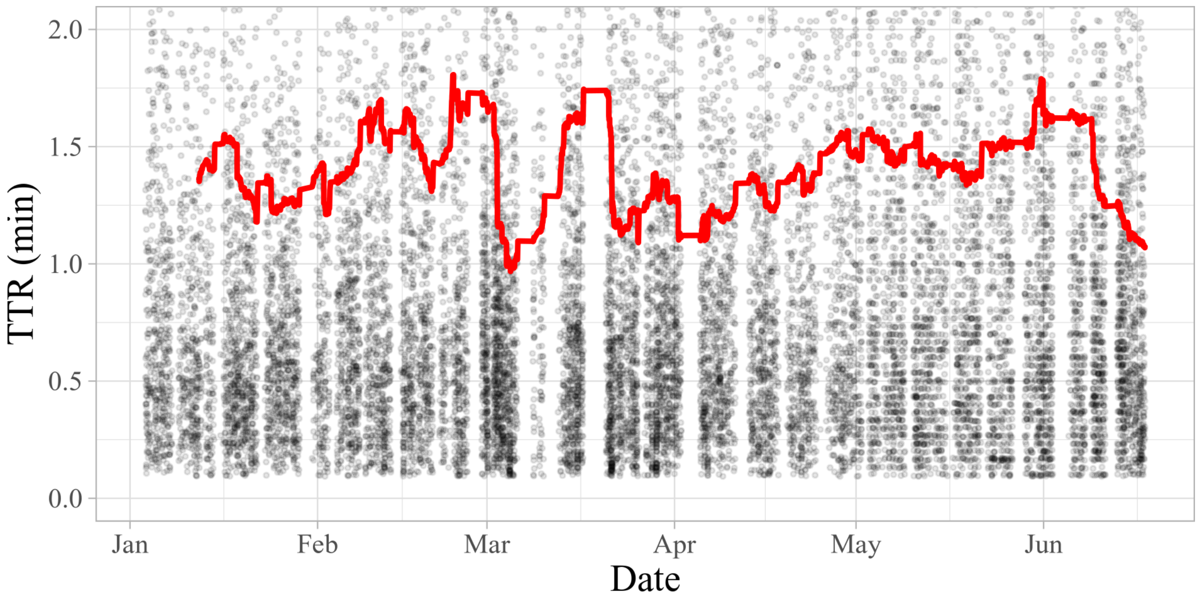

Figure B.2: Depalletizer TTR trend chart.

B.2 Decrater - DCR

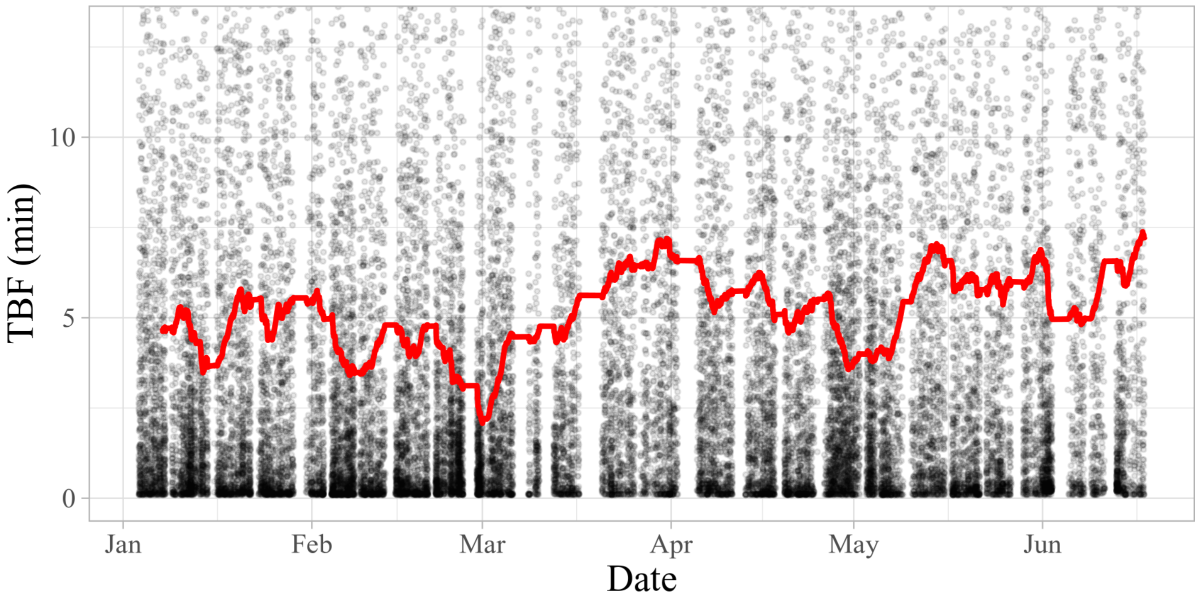

Figure B.3: Decrater TBF trend chart.

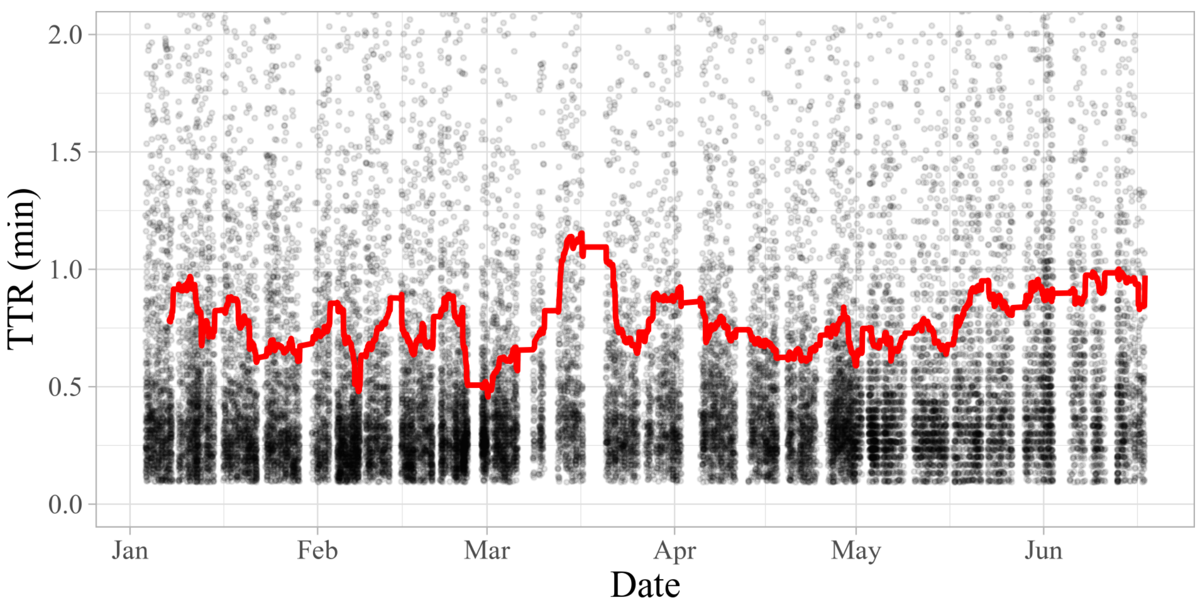

Figure B.4: Decrater TTR trend chart.

B.3 Bottle Washer - BW

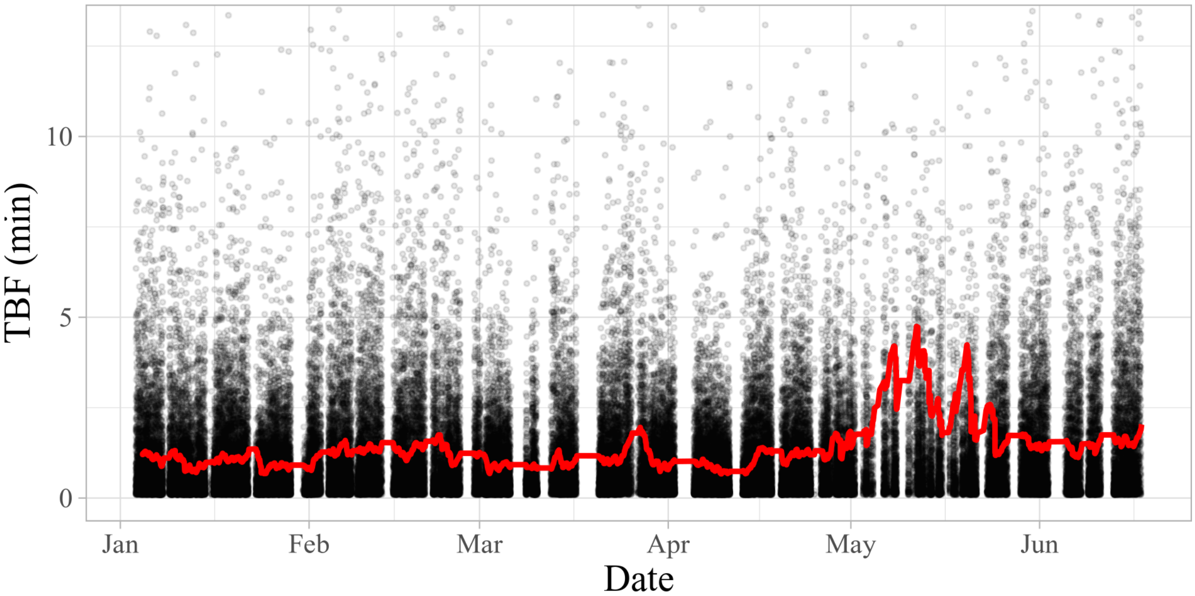

Figure B.5: Bottle Washer trend chart.

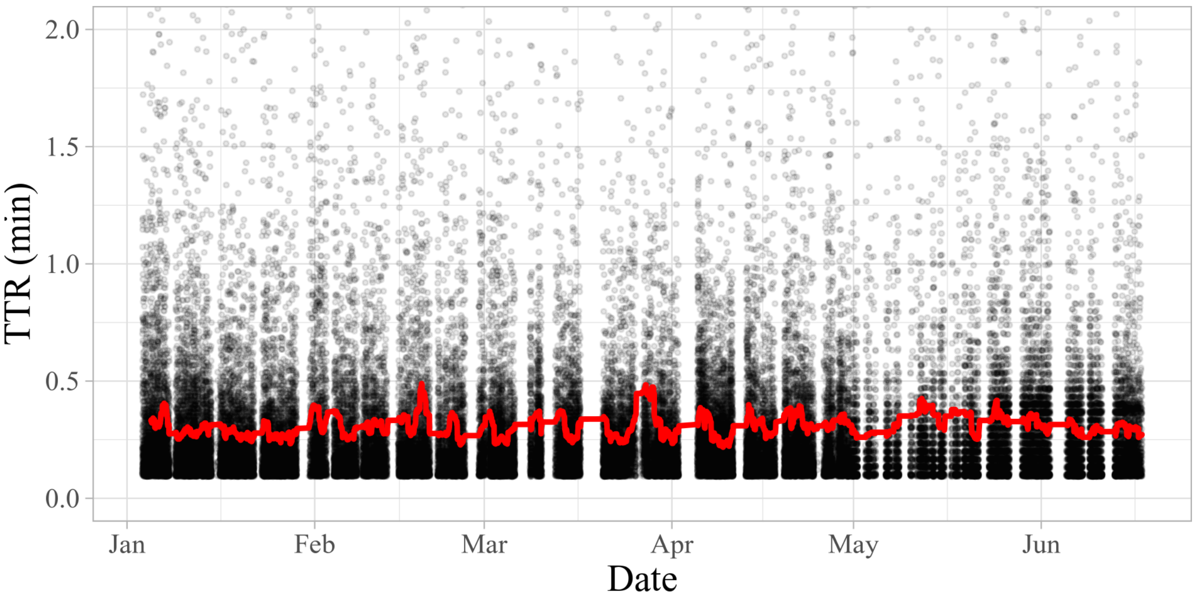

Figure B.6: Bottle Washer trend chart.

B.4 Inspector Unit - IU

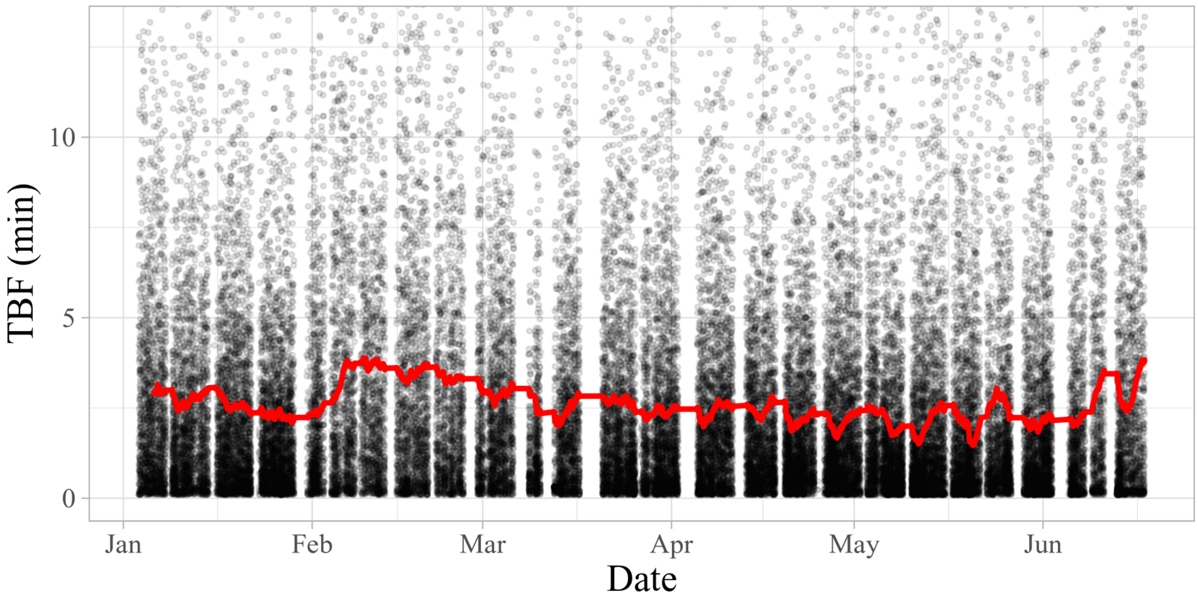

Figure B.7: Inspector Unit trend chart.

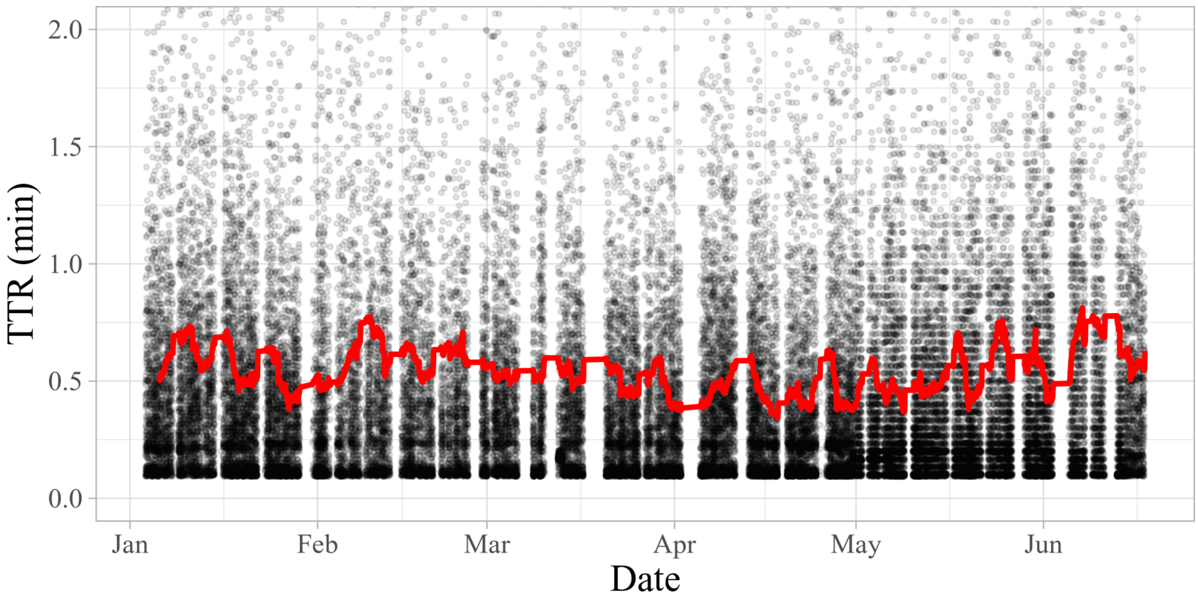

Figure B.8: Inspector Unit trend chart.

B.5 Filler - FL

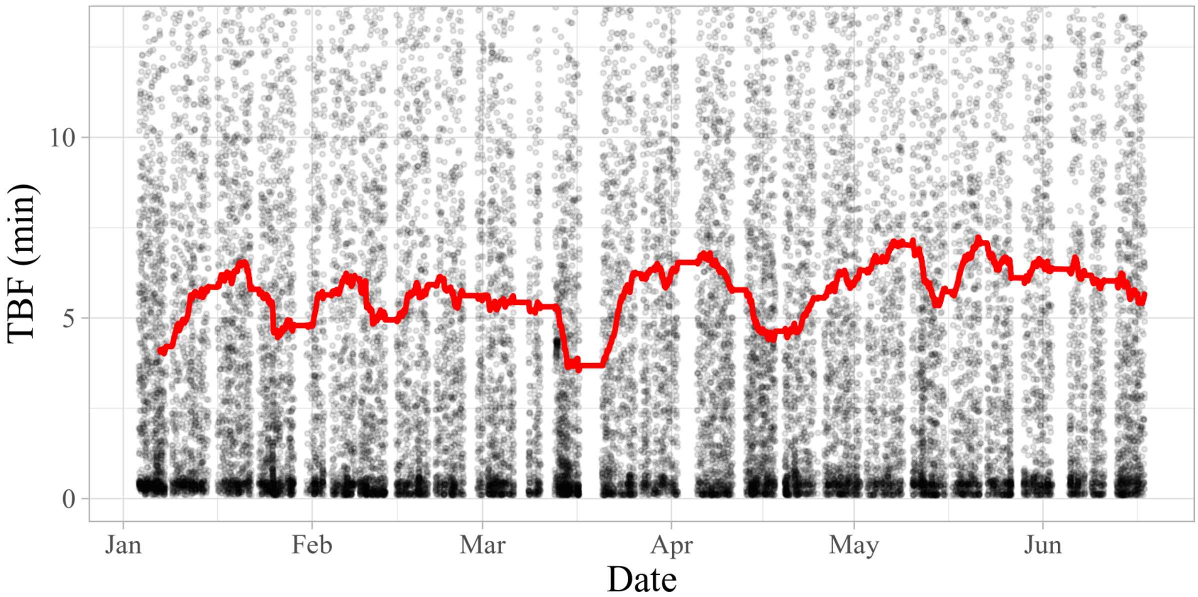

Figure B.9: Filler trend chart.

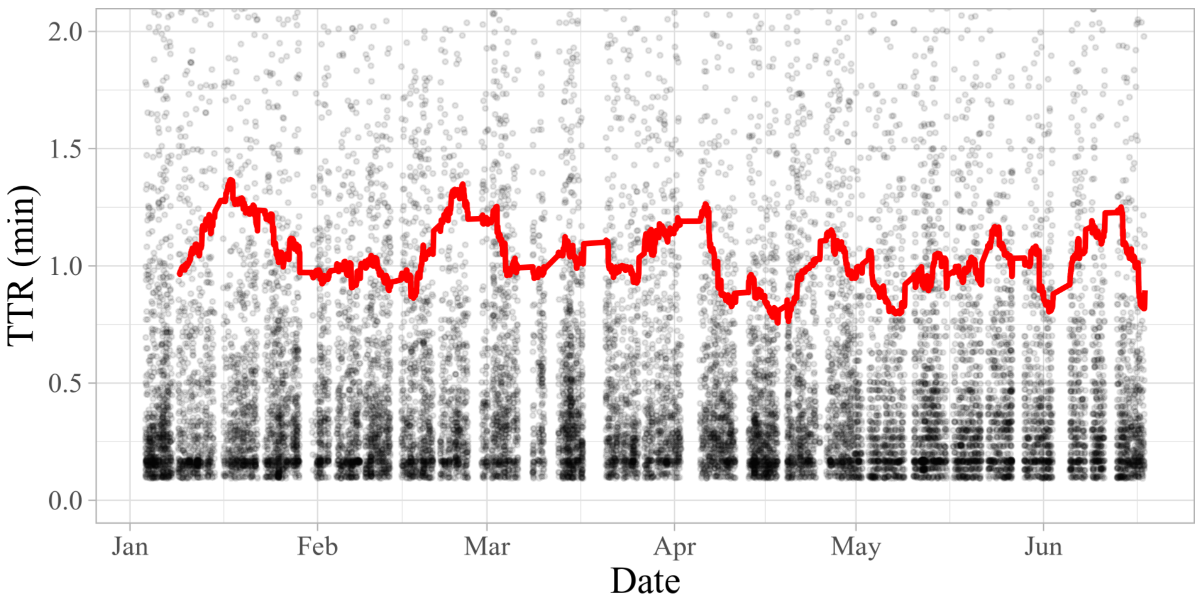

Figure B.10: Filler trend chart.

B.6 Pasteurization Unit - PU

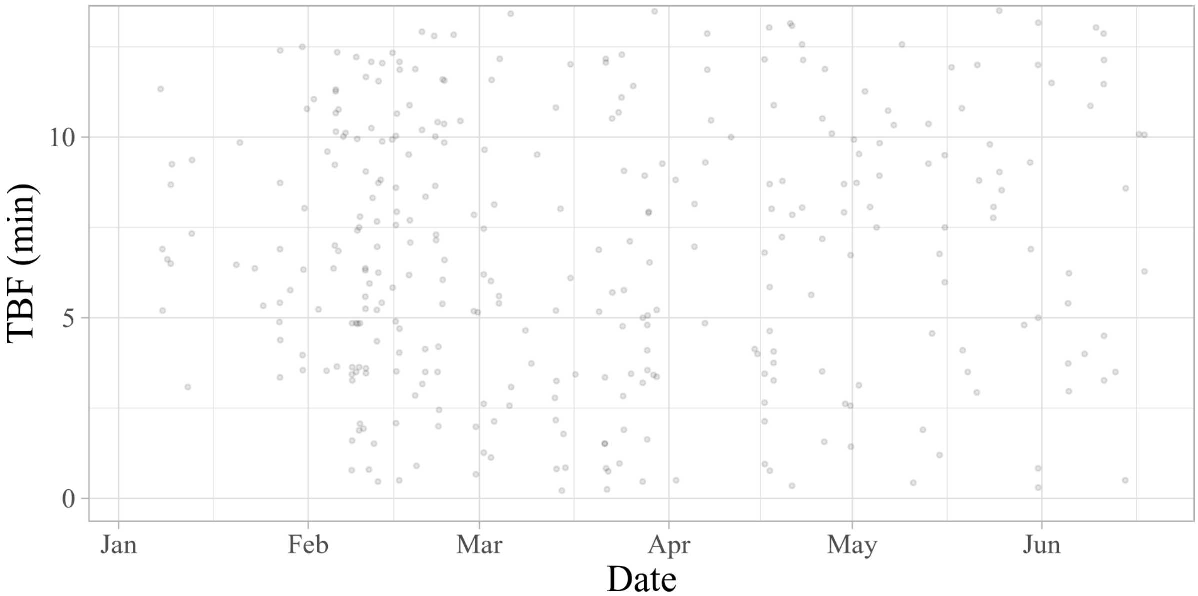

Figure B.11: Pasteurization Unit trend chart.

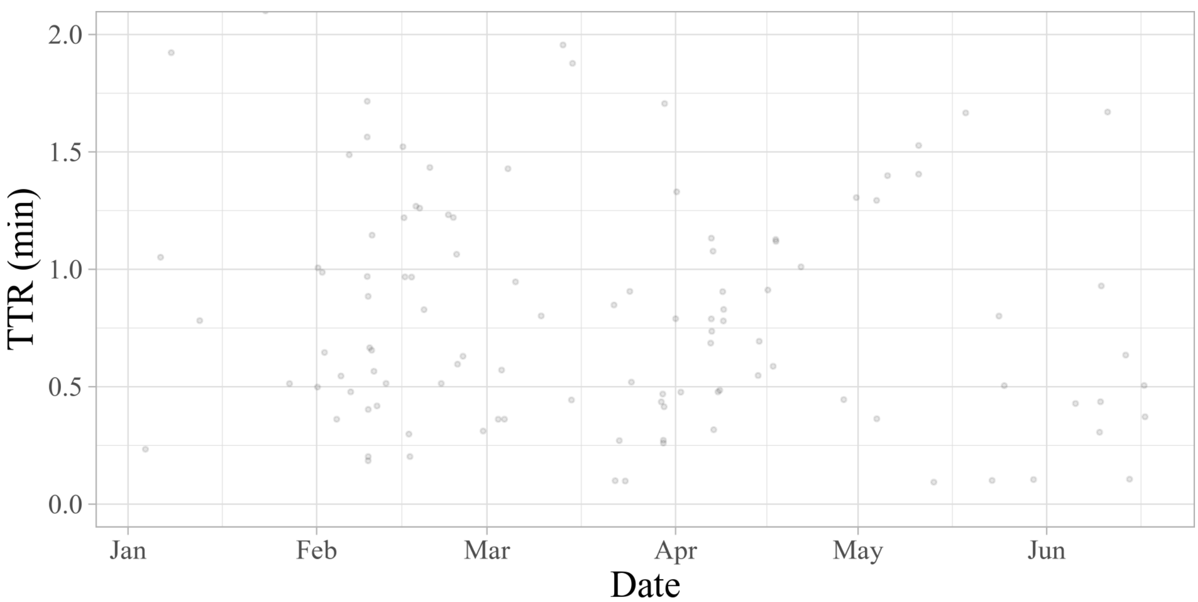

Figure B.12: Pasteurization Unit trend chart.

B.7 Labeller 1 - LB1

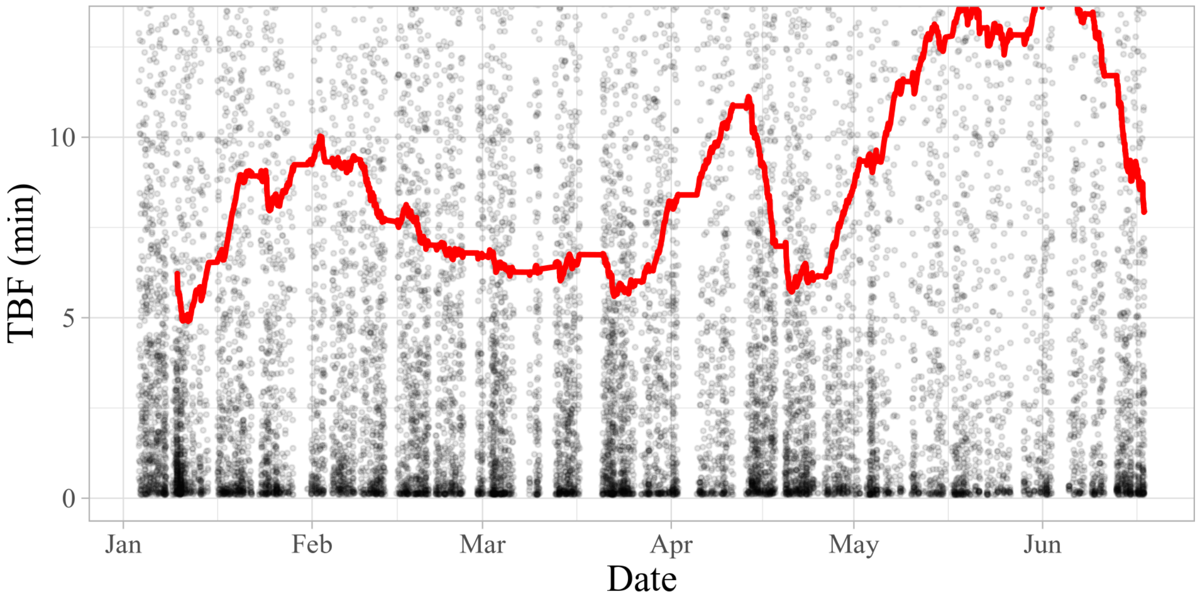

Figure B.13: Labeller 1 trend chart.

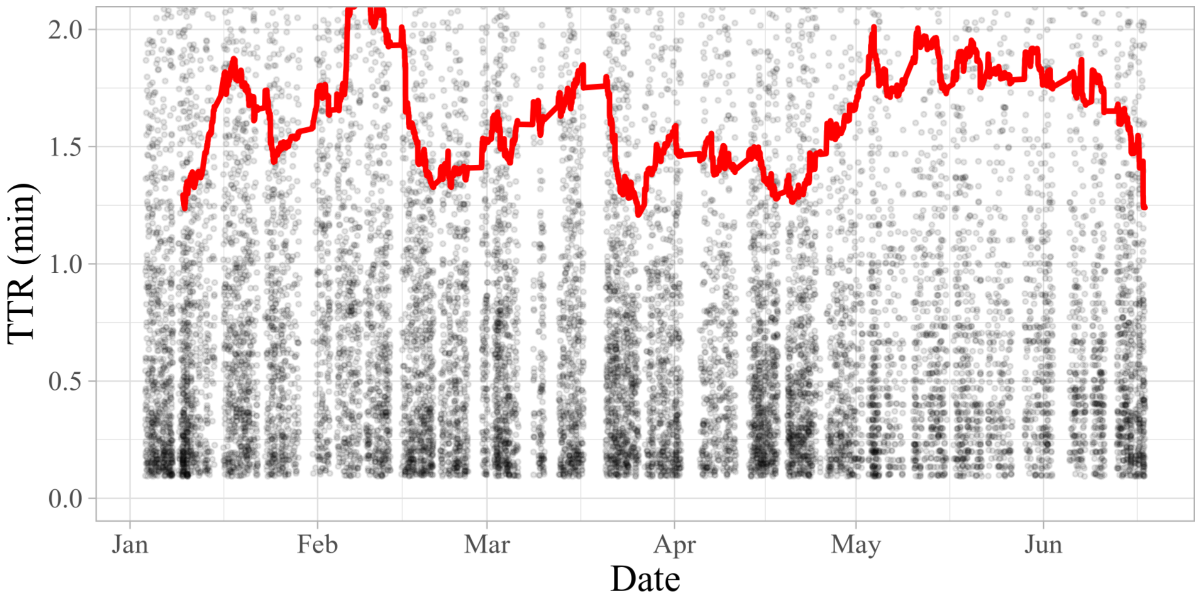

Figure B.14: Labeller 1 trend chart.

B.8 Labeller 2 - LB2

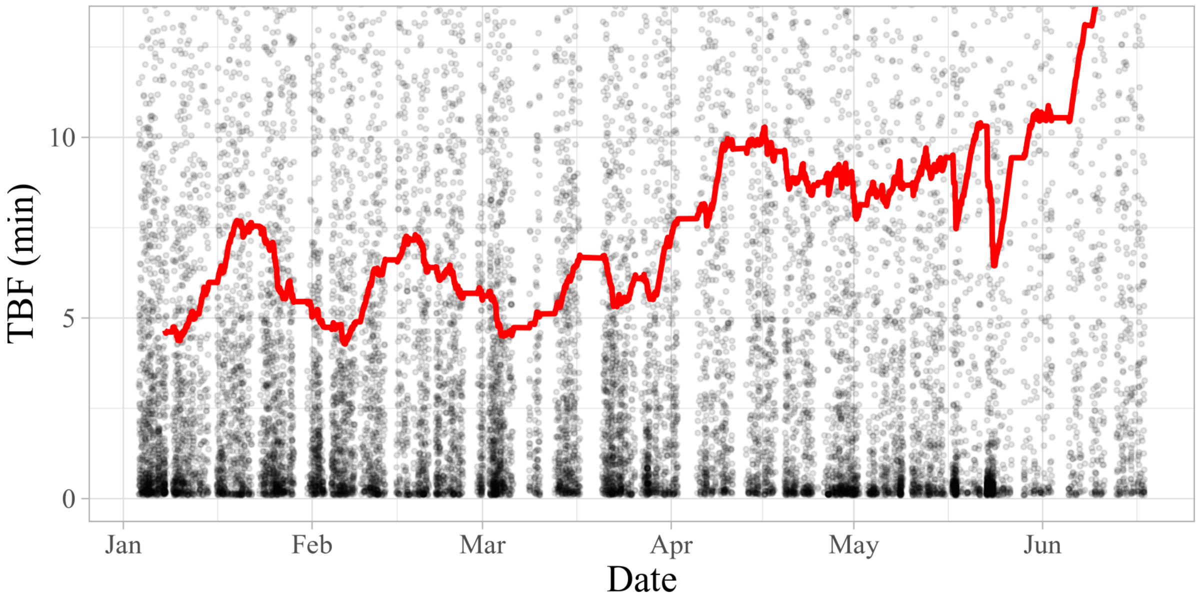

Figure B.15: Labeller 2 trend chart.

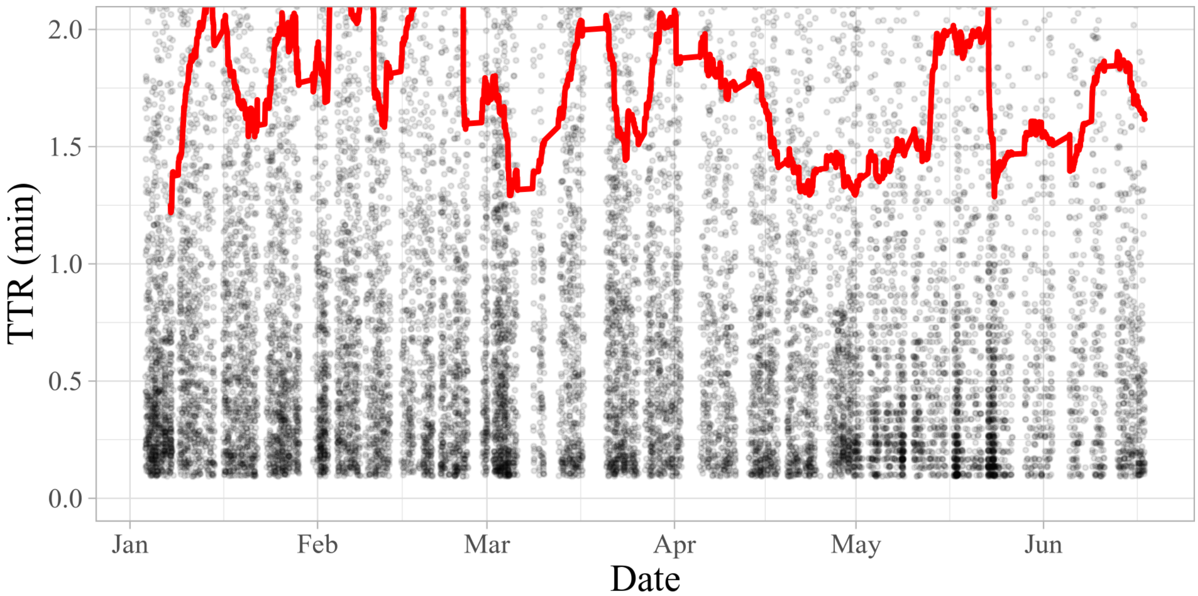

Figure B.16: Labeller 2 trend chart.

B.9 Recrater - RCR

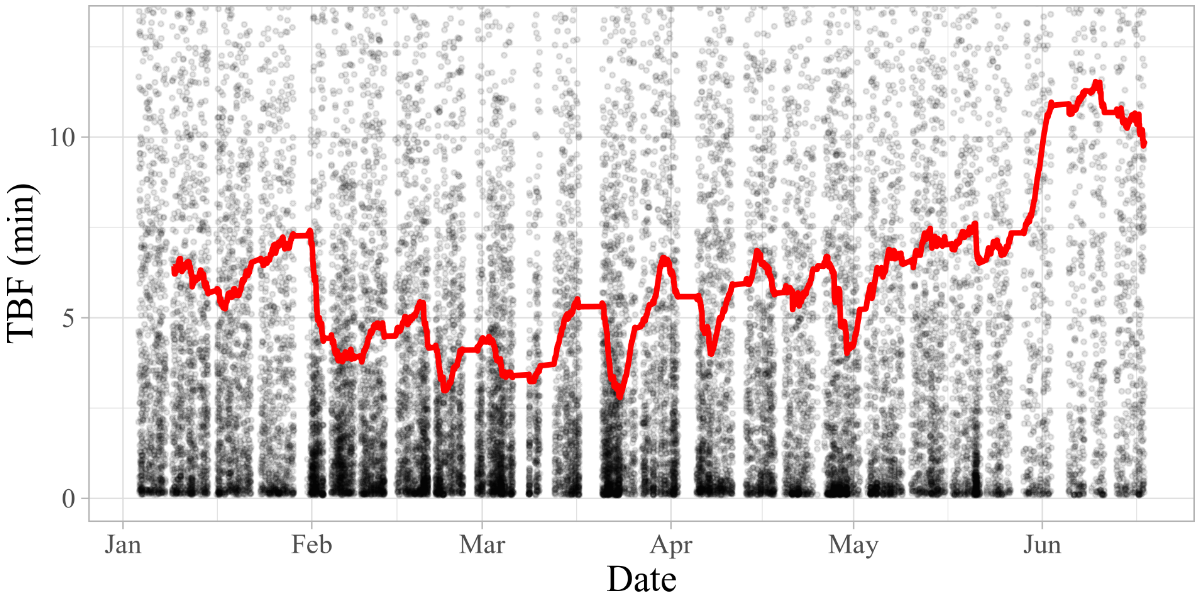

Figure B.17: Recrater trend chart.

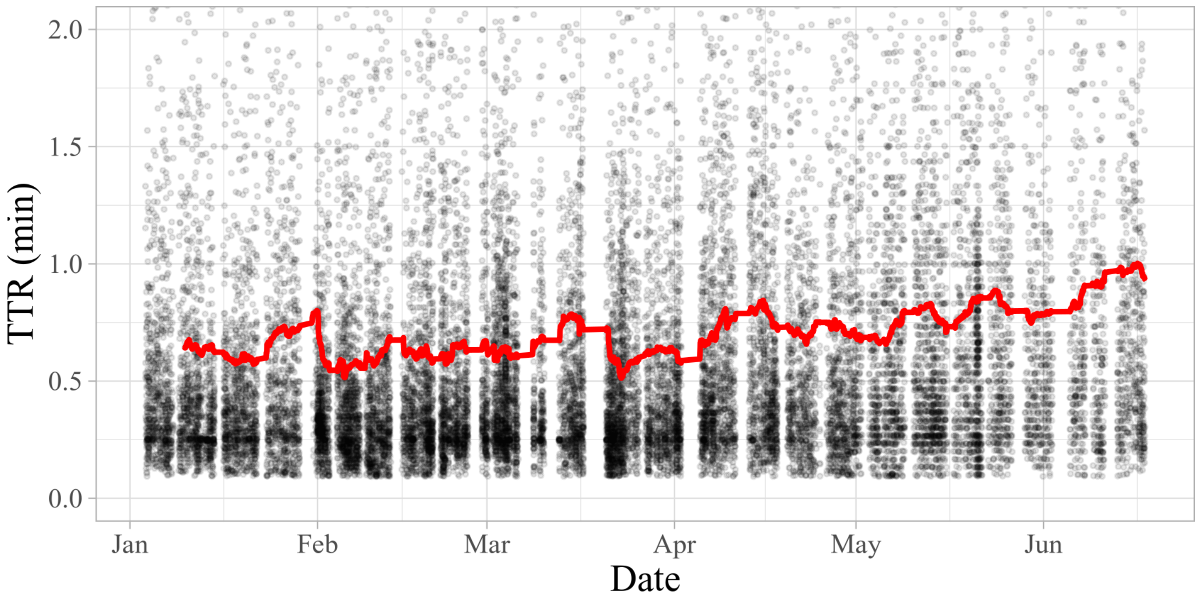

Figure B.18: Recrater trend chart.

B.10 Palletizer - PL

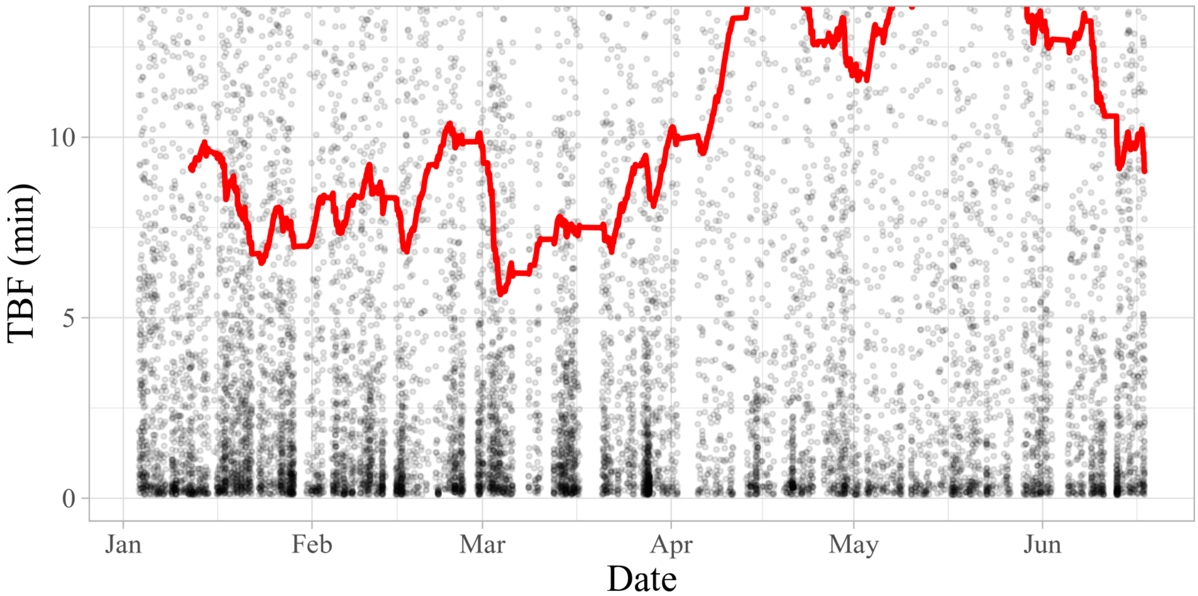

Figure B.19: Palletizer trend chart.

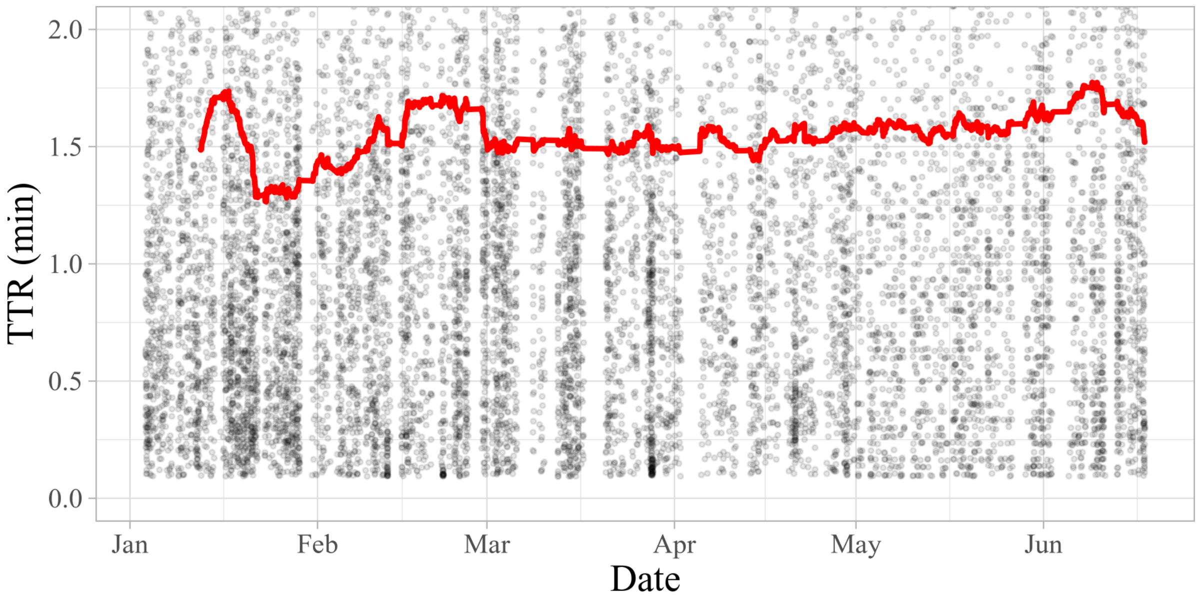

Figure B.20: Palletizer trend chart.

Appendix C: Line A IID test graphs

C.1 Depalletizer - DPL

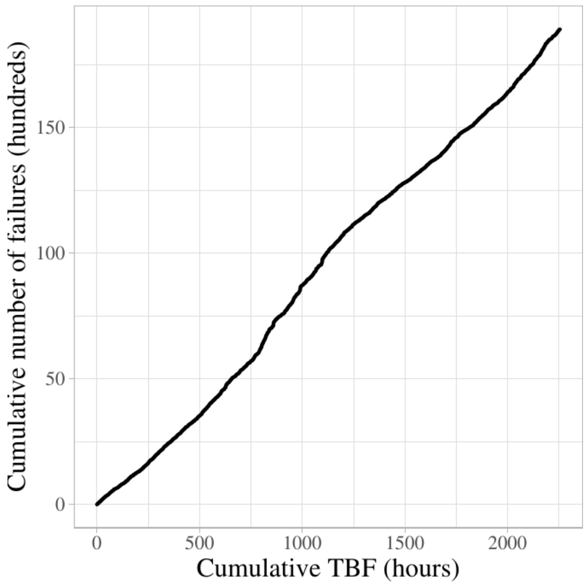

Figure C.1: Line A Depalletizer trend test for TBF data.

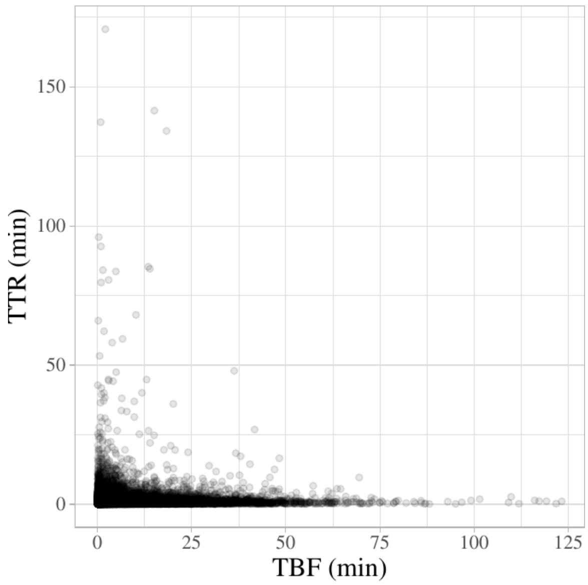

Figure C.2: Line A Depalletizer TBF vs TTR correlation test.

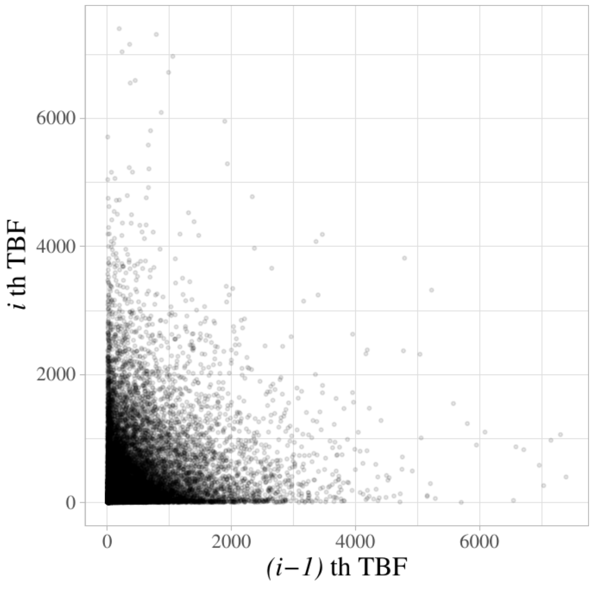

Figure C.3: Line A Depalletizer serial correlation for TBF data.

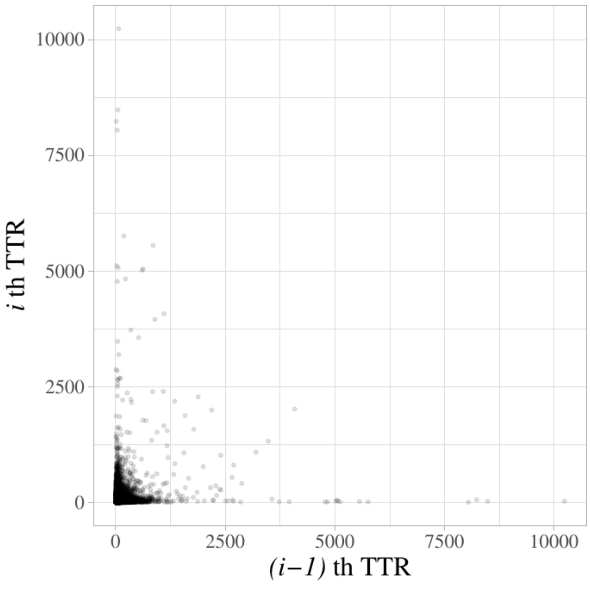

Figure C.4: Line A Depalletizer serial correlation for TTR data.

C.2 Decrater - DCR

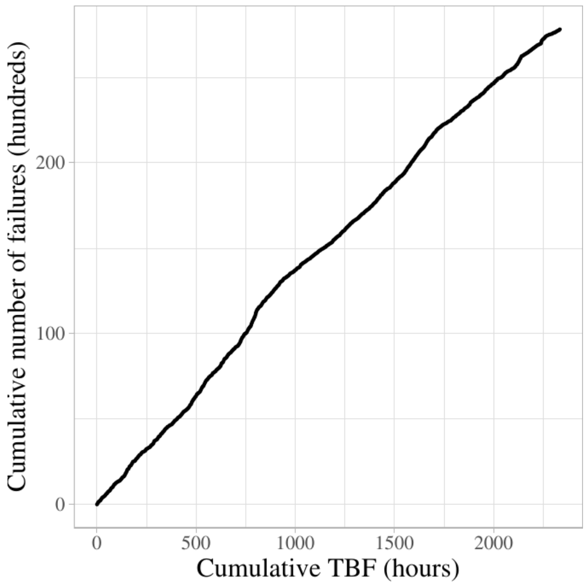

Figure C.5: Line A Decrater trend test for TBF data.

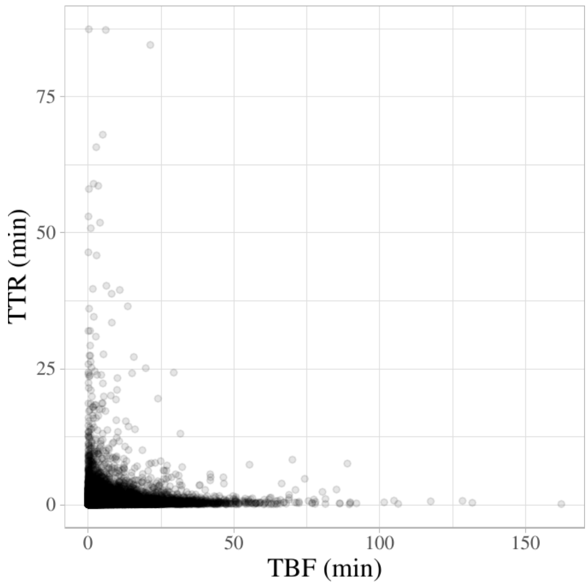

Figure C.6: Line A Decrater TBF vs TTR correlation test.

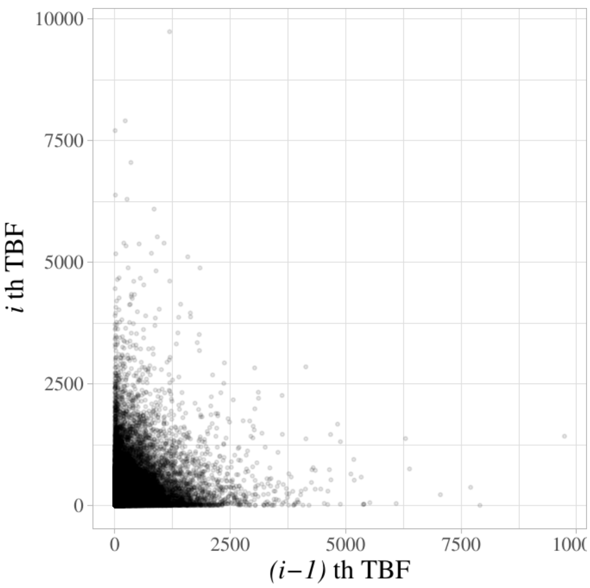

Figure C.7: Line A Decrater serial correlation for TBF data.

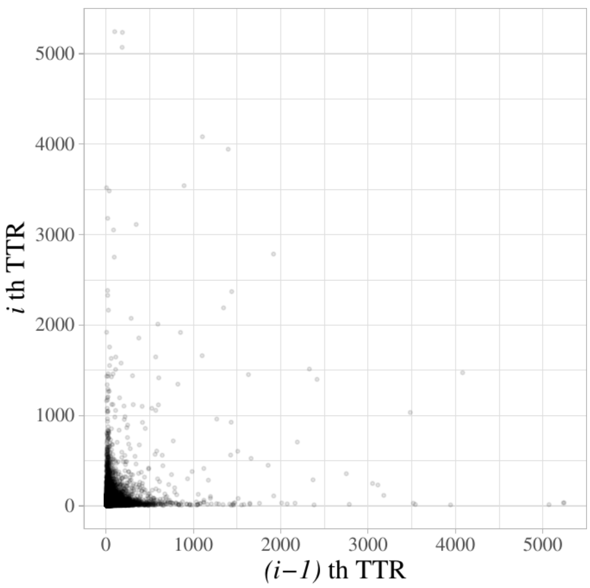

Figure C.8: Line A Decrater serial correlation for TTR data.

C.3 Bottle Washer - BW

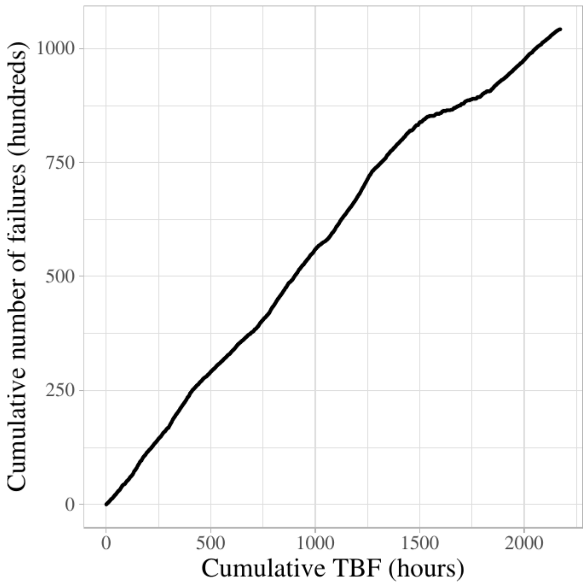

Figure C.9: Line A Bottle Washer trend test for TBF data.

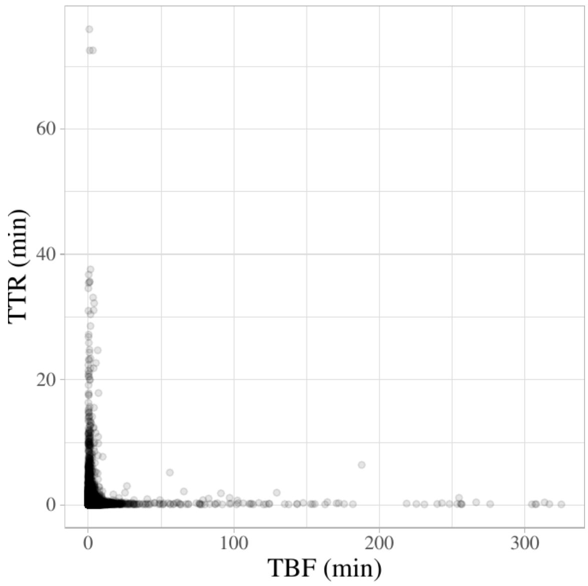

Figure C.10: Line A Bottle Washer TBF vs TTR correlation test.

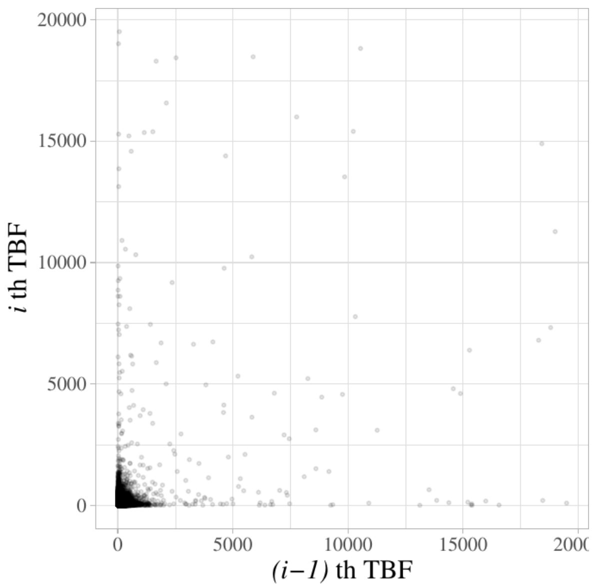

Figure C.11: Line A Bottle Washer serial correlation for TBF data.

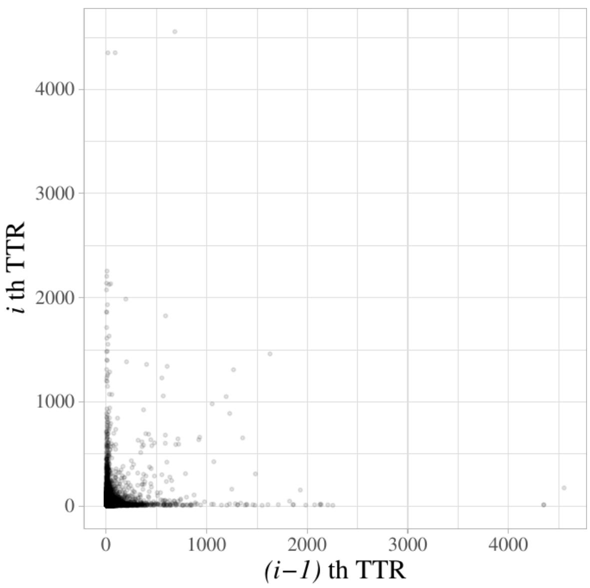

Figure C.12: Line A Bottle Washer serial correlation for TTR data.

C.4 Inspector Unit - IU

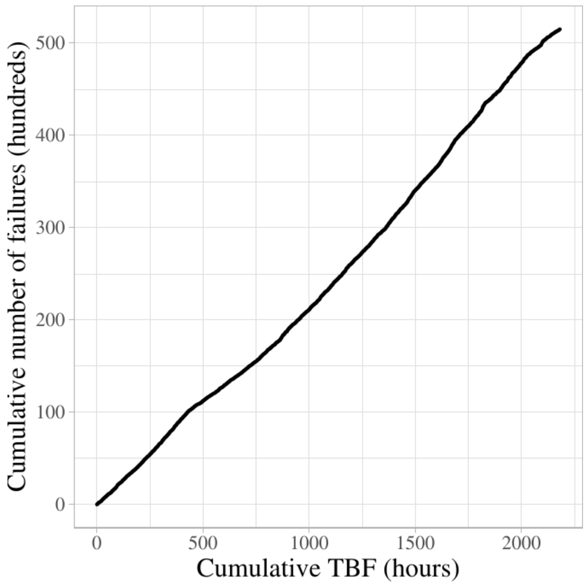

Figure C.13: Line A Inspector Unit trend test for TBF data.

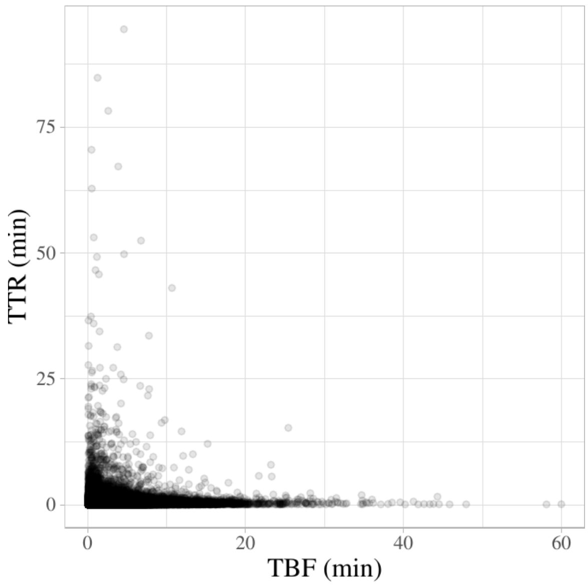

Figure C.14: Line A Inspector Unit TBF vs TTR correlation test.

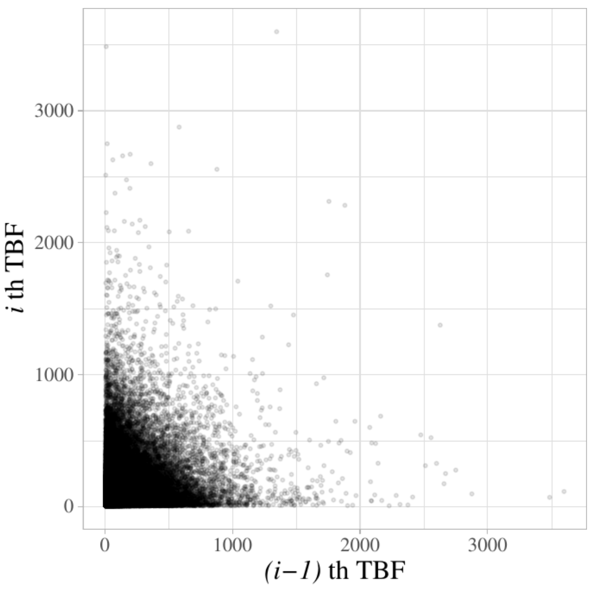

Figure C.15: Line A Inspector Unit serial correlation for TBF data.

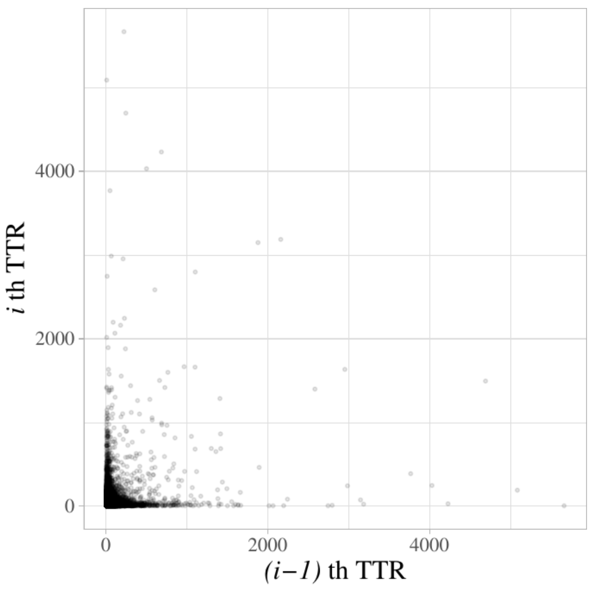

Figure C.16: Line A Inspector Unit serial correlation for TTR data.

C.5 Filler - FL

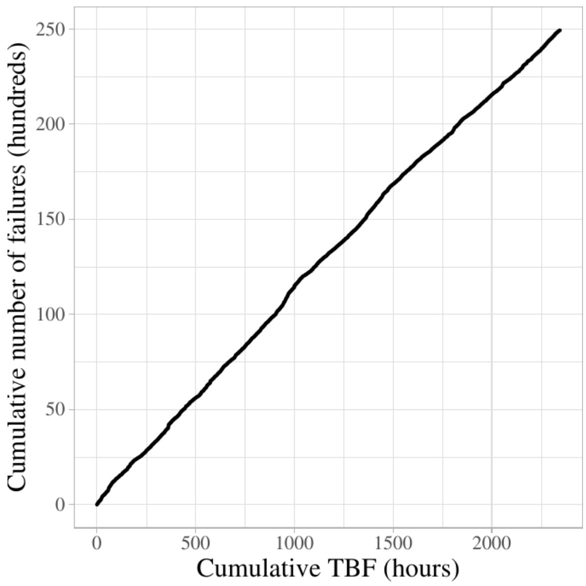

Figure C.17: Line A Filler trend test for TBF data.

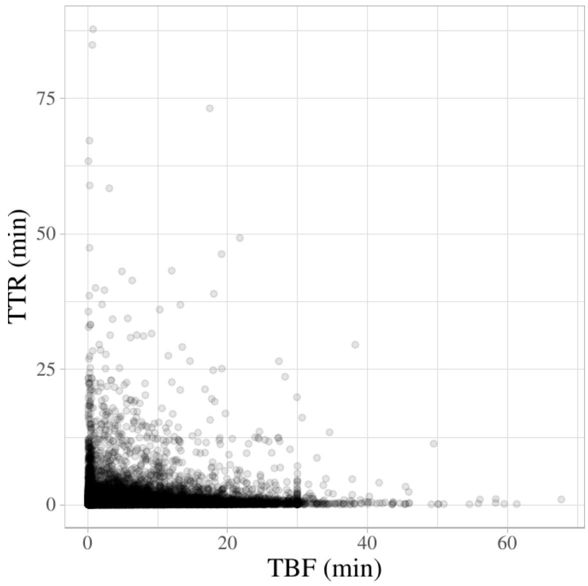

Figure C.18: Line A Filler TBF vs TTR correlation test.

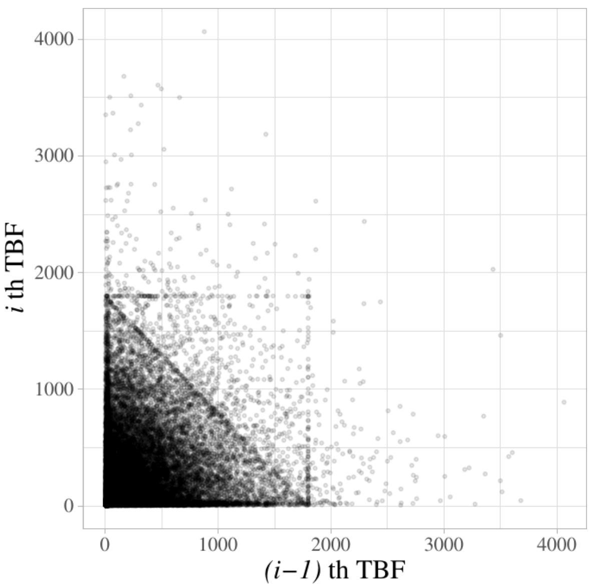

Figure C.19: Line A Filler serial correlation for TBF data.

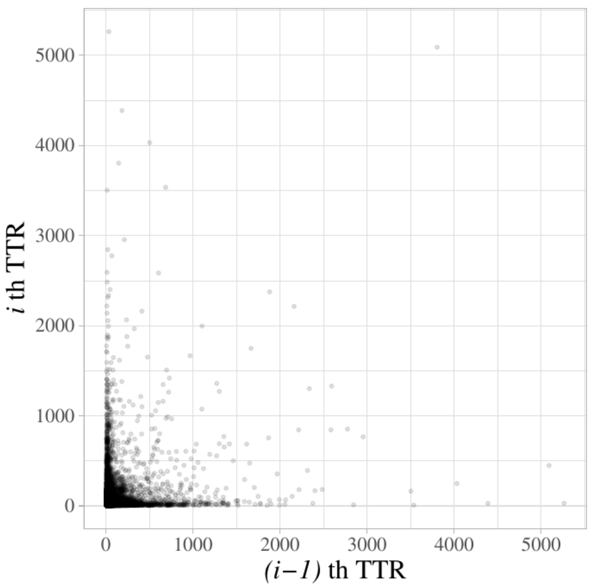

Figure C.20: Line A Filler serial correlation for TTR data.

C.6 Pasteurization Unit - PU

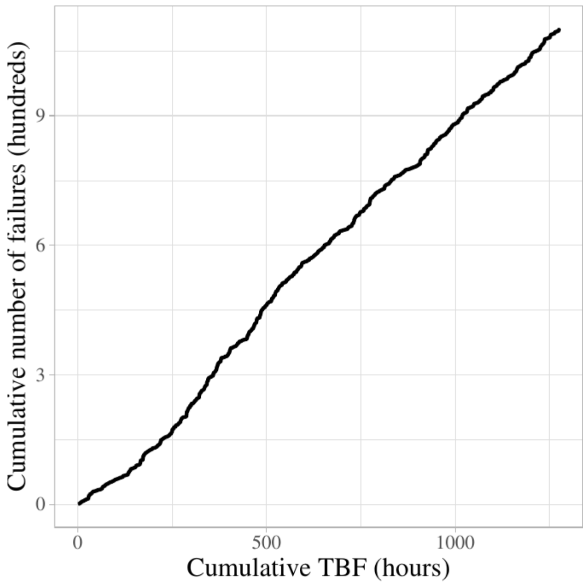

Figure C.21: Line A Pasteurization Unit trend test for TBF data.

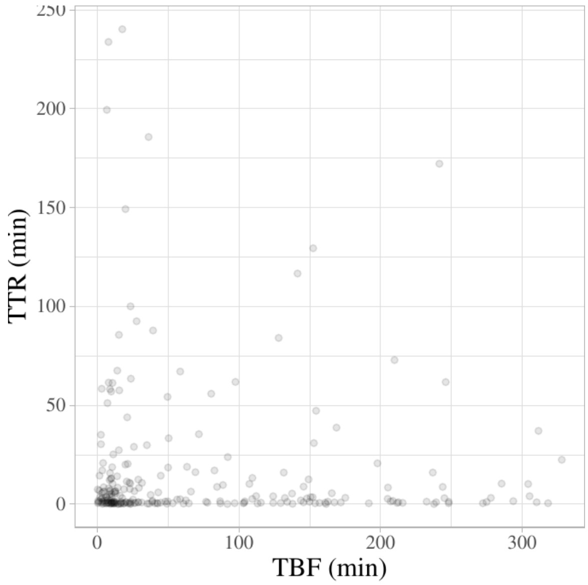

Figure C.22: Line A Pasteurization Unit TBF vs TTR correlation test.

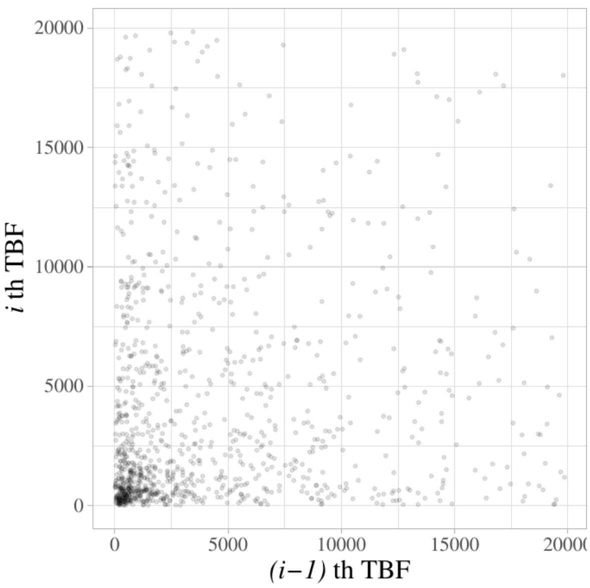

Figure C.23: Line A Pasteurization Unit serial correlation for TBF data.

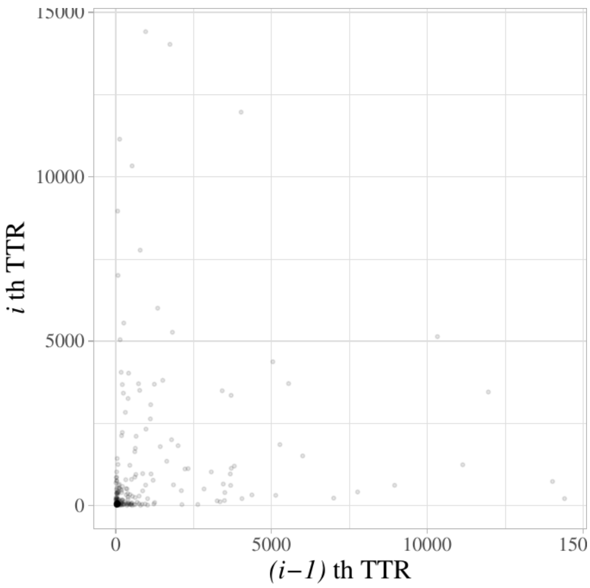

Figure C.24: Line A Pasteurization Unit serial correlation for TTR data.

C.7 Labeller 1 - LB1

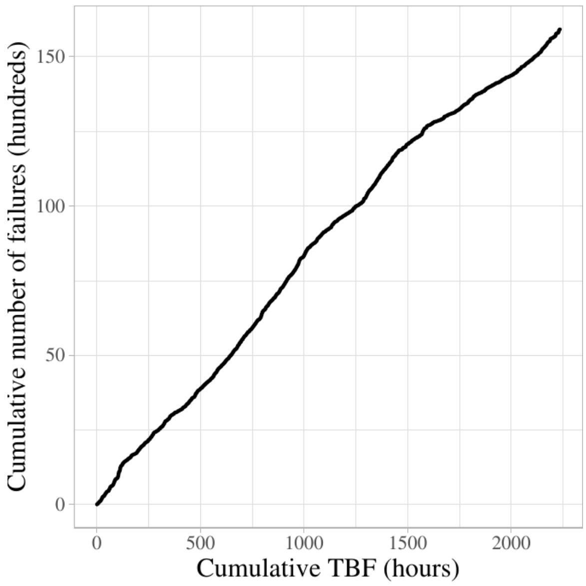

Figure C.25: Line A Labeller 1 trend test for TBF data.

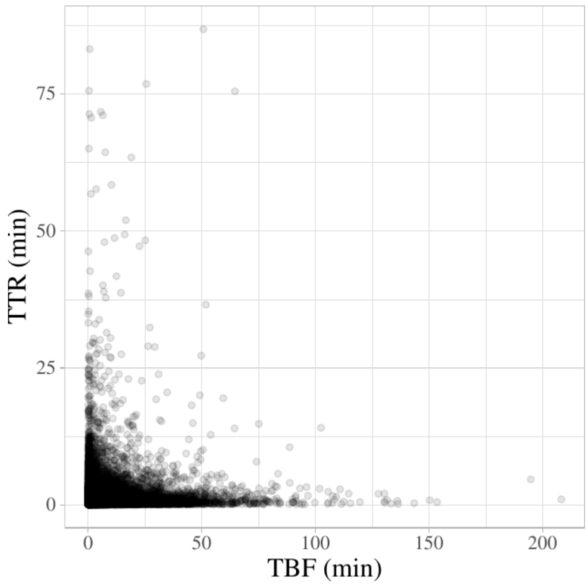

Figure C.26: Line A Labeller 1 TBF vs TTR correlation test.

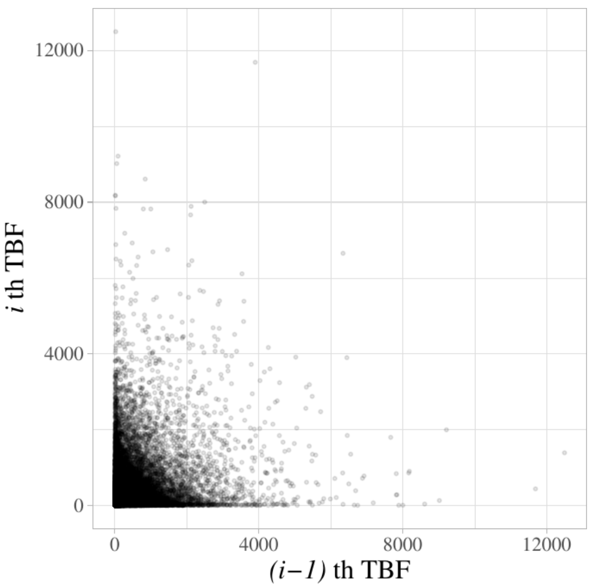

Figure C.27: Line A Labeller 1 serial correlation for TBF data.

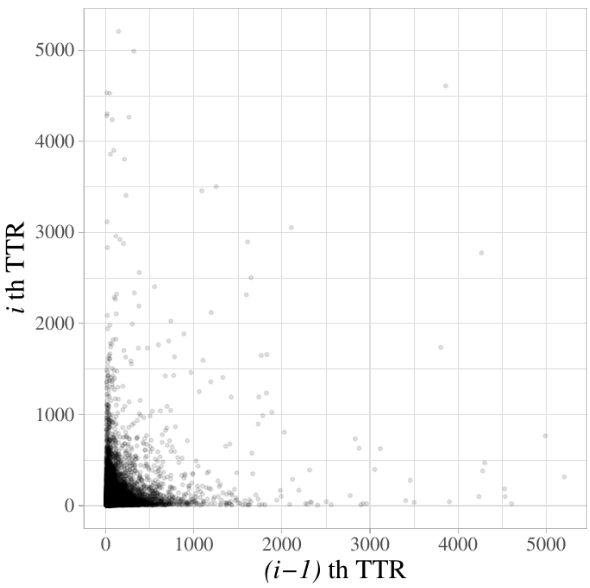

Figure C.28: Line A Labeller 1 serial correlation for TTR data.

C.8 Labeller 2 - LB2

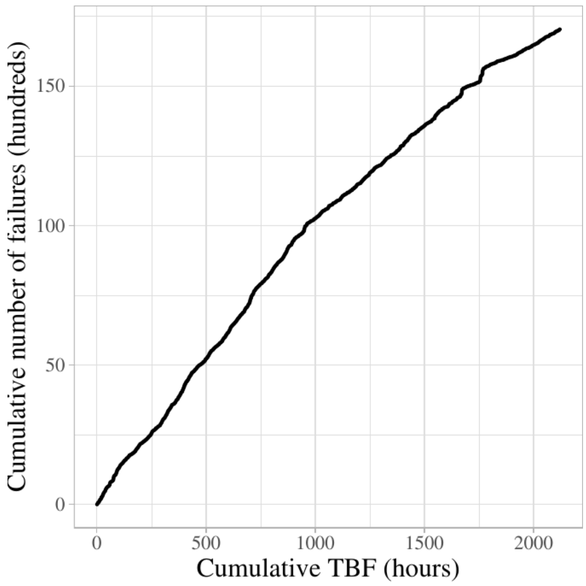

Figure C.29: Line A Labeller 2 trend test for TBF data.

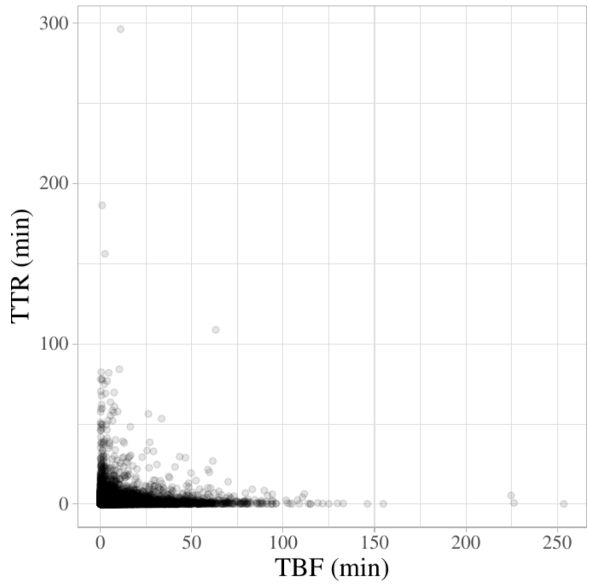

Figure C.30: Line A Labeller 2 TBF vs TTR correlation test.

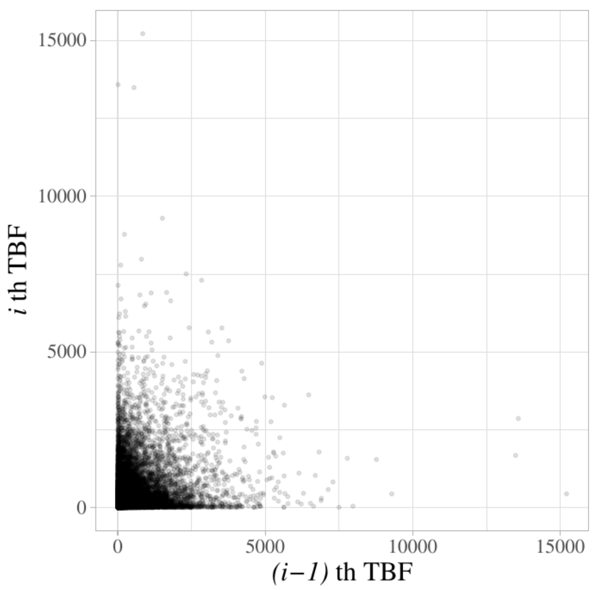

Figure C.31: Line A Labeller 2 serial correlation for TBF data.

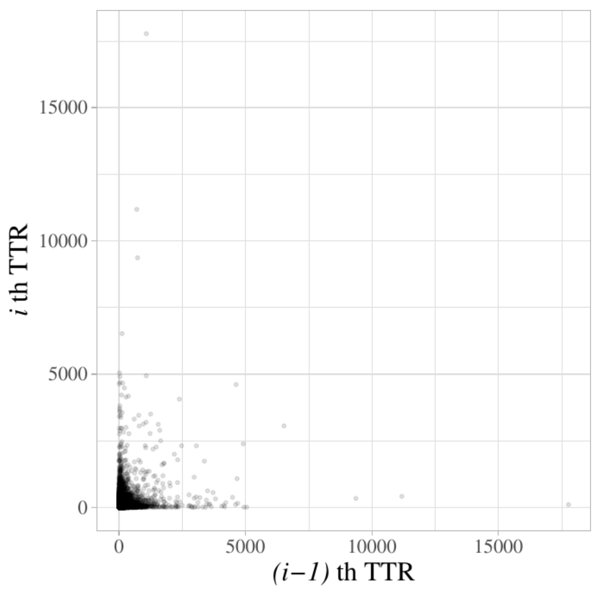

Figure C.32: Line A Labeller 2 serial correlation for TTR data.

C.9 Recrater - RCR

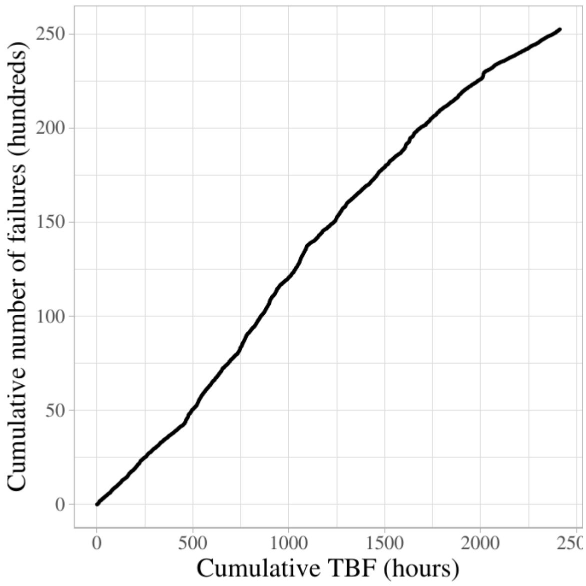

Figure C.33: Line A Recrater trend test for TBF data.

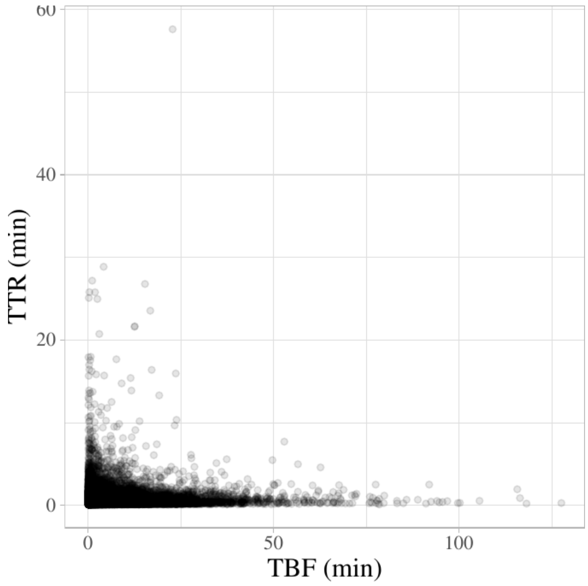

Figure C.34: Line A Recrater TBF vs TTR correlation test.

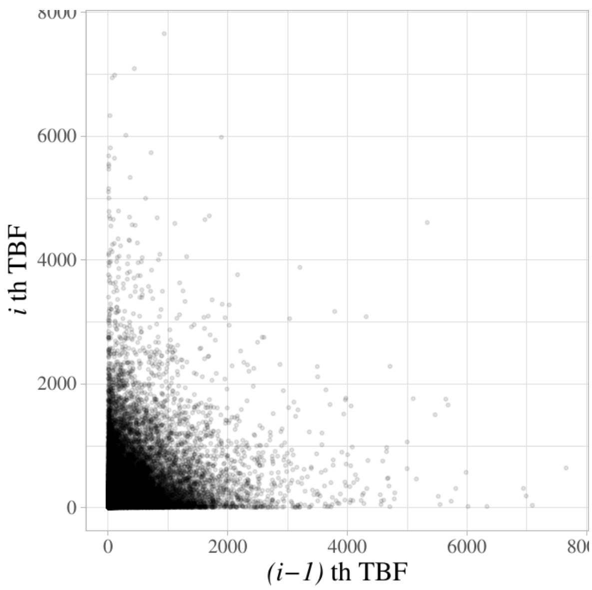

Figure C.35: Line A Recrater serial correlation for TBF data.

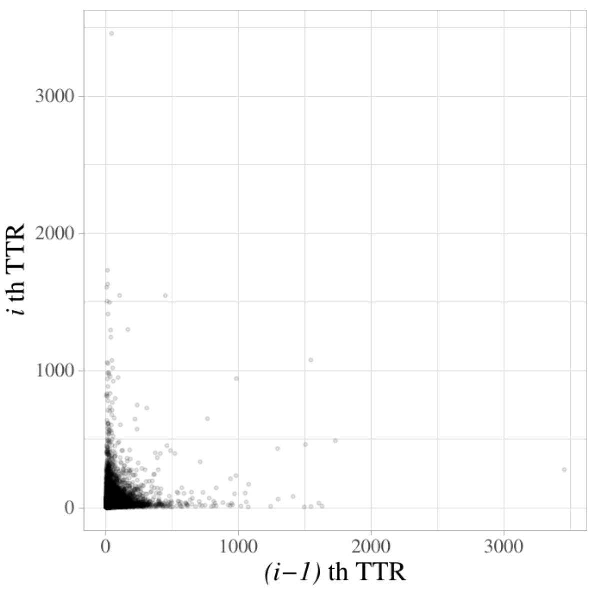

Figure C.36: Line A Recrater serial correlation for TTR data.

C.10 Palletizer - PL

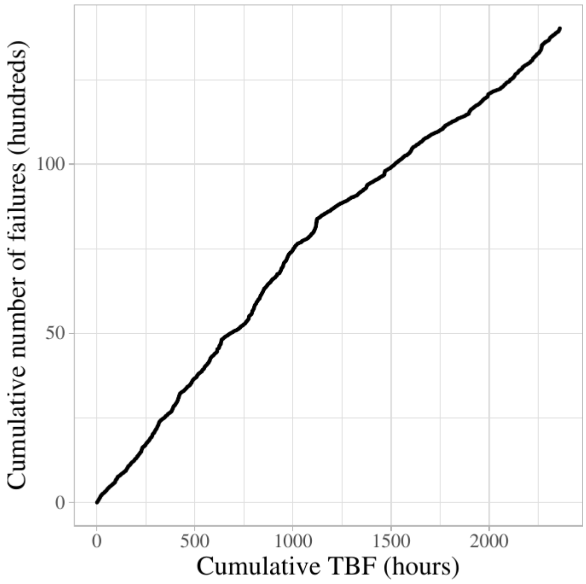

Figure C.37: Line A Palletizer trend test for TBF data.

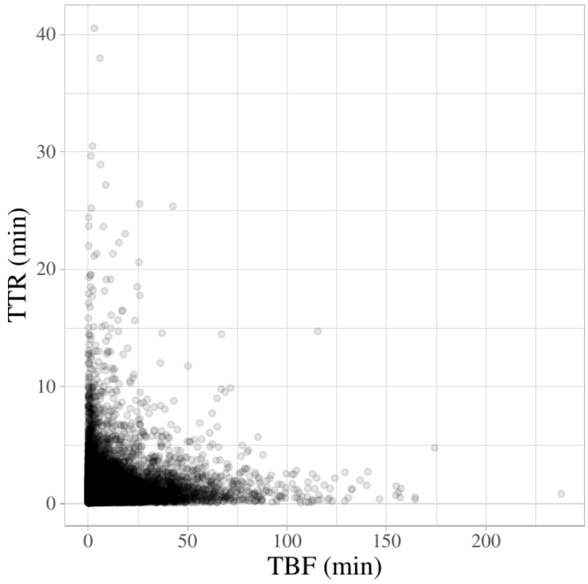

Figure C.38: Line A Palletizer TBF vs TTR correlation test.

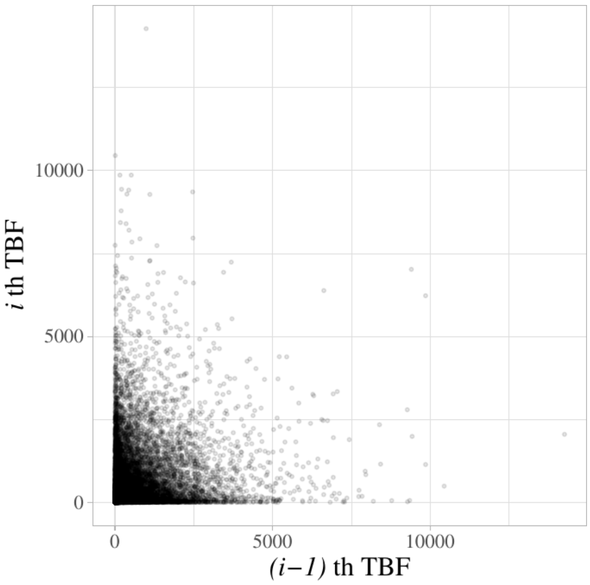

Figure C.39: Line A Palletizer serial correlation for TBF data.

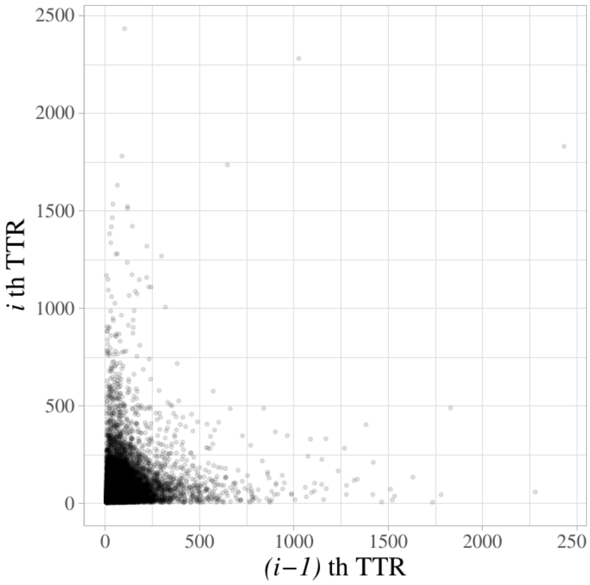

Figure C.40: Line A Palletizer serial correlation for TTR data.

Appendix D: Line A TBF and TTR Q-Q and P-P plots

D.1 Depalletizer - DPL

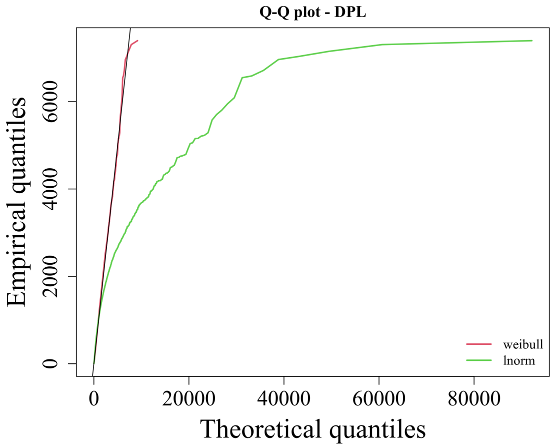

Figure D.1: Q-Q plot for the Depalletizer TBF data - comparison between Log-normal and Weibull.

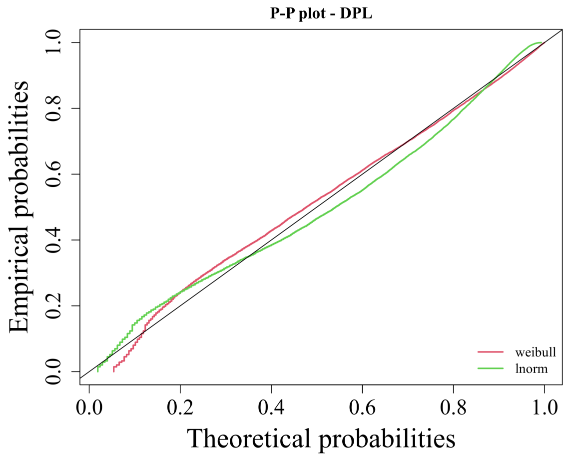

Figure D.2: P-P plot for the Depalletizer TBF data - comparison between Log-normal and Weibull.

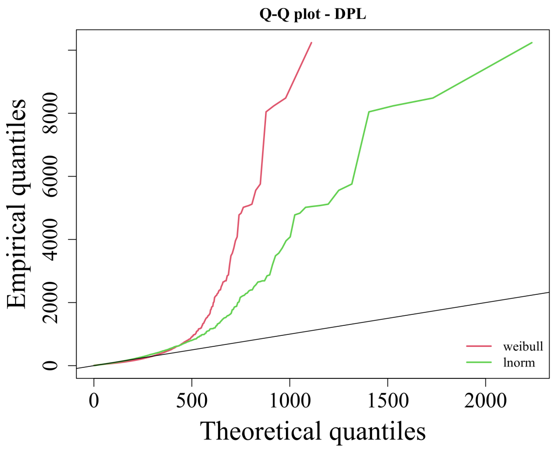

Figure D.3: Q-Q plot for the Depalletizer TTR data - comparison between Log-normal and Weibull.

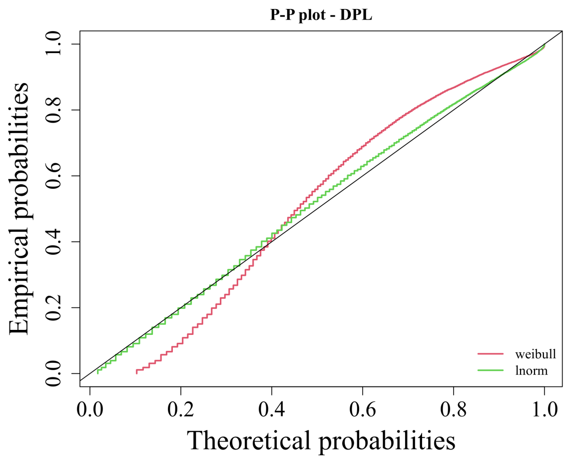

Figure D.4: P-P plot for the Depalletizer TTR data - comparison between Log-normal and Weibull.

D.2 Decrater - DCR

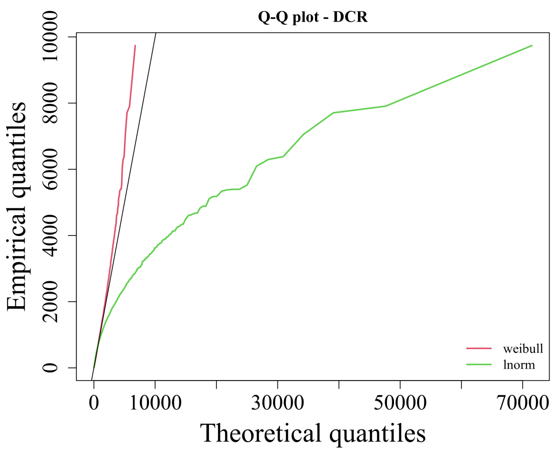

Figure D.5: Q-Q plot for the Decrater TBF data - comparison between Log-normal and Weibull.

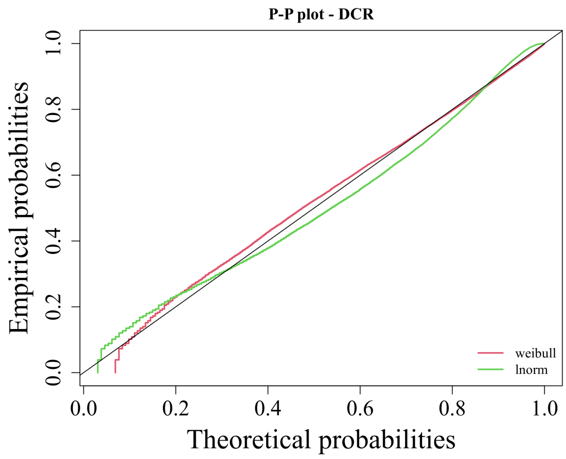

Figure D.6: P-P plot for the Decrater TBF data - comparison between Log-normal and Weibull.

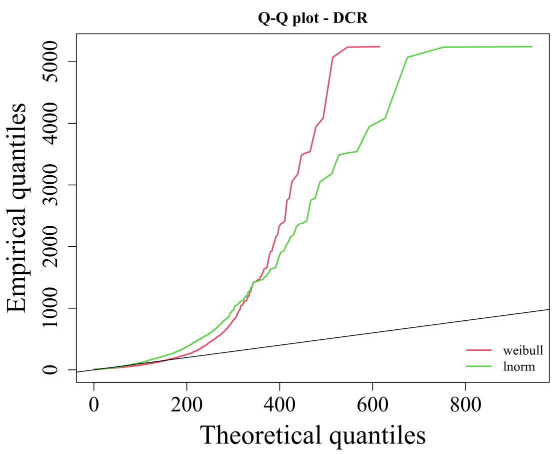

Figure D.7: Q-Q plot for the Decrater TTR data - comparison between Log-normal and Weibull.

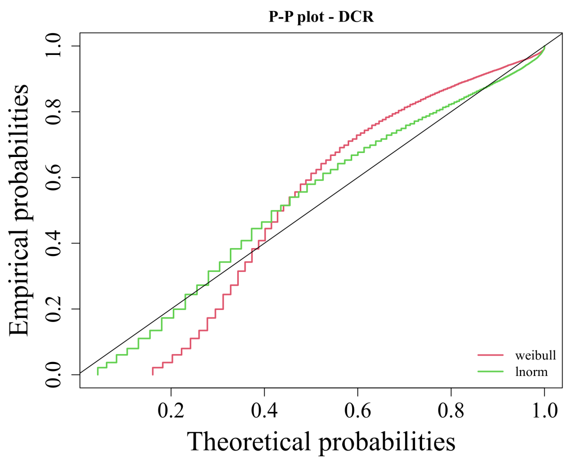

Figure D.8: P-P plot for the Decrater TTR data - comparison between Log-normal and Weibull.

D.3 Bottle Washer - BW

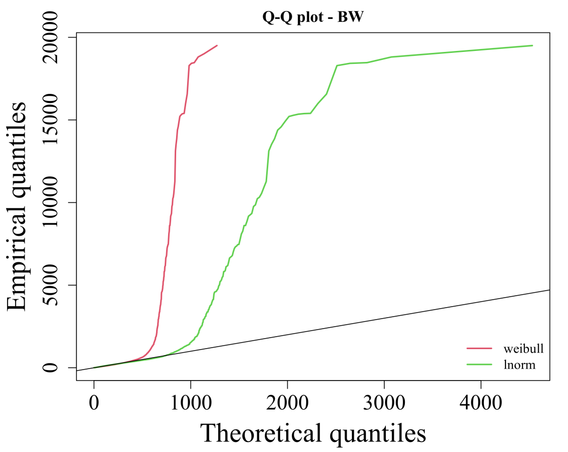

Figure D.9: Q-Q plot for the Bottle Washer TBF data - comparison between Log-normal and Weibull.

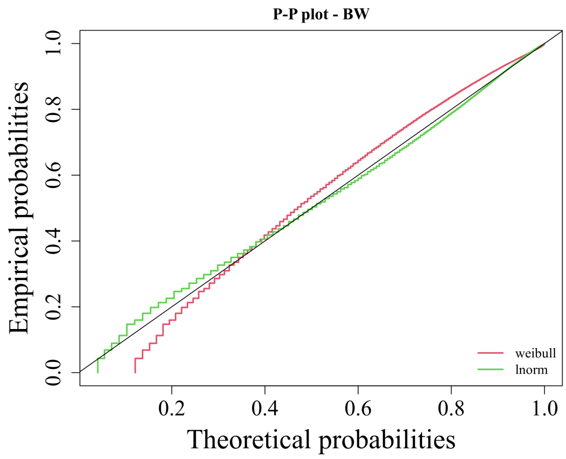

Figure D.10: P-P plot for the Bottle Washer TBF data - comparison between Log-normal and Weibull.

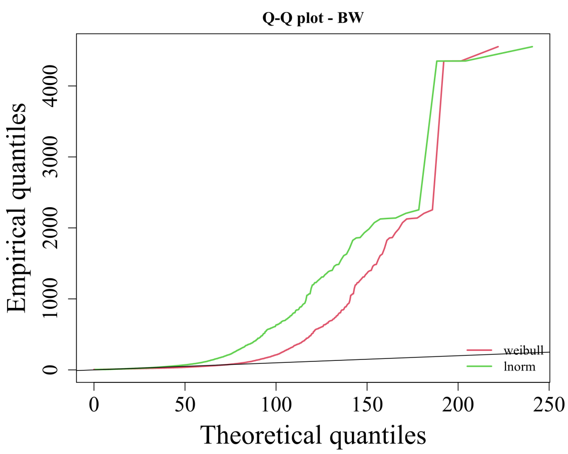

Figure D.11: Q-Q plot for the Bottle Washer TTR data - comparison between Log-normal and Weibull.

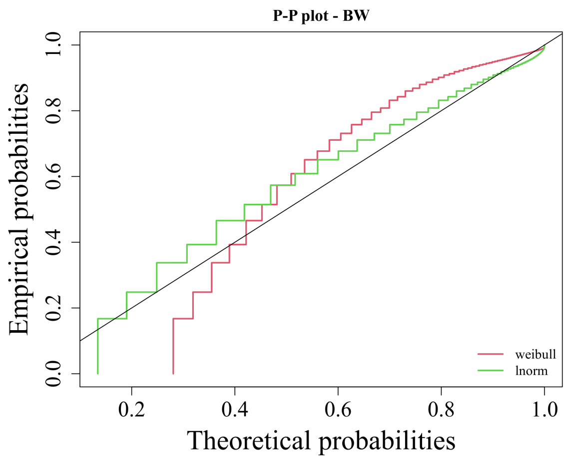

Figure D.12: P-P plot for the Bottle Washer TTR data - comparison between Log-normal and Weibull.

D.4 Inspector Unit - IU

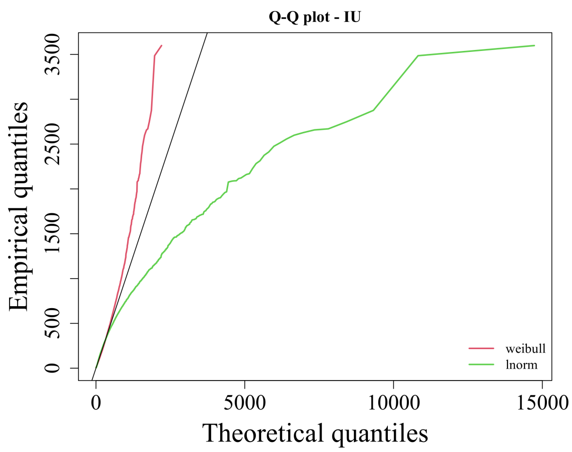

Figure D.13: Q-Q plot for the Inspector Unit TBF data - comparison between Log-normal and Weibull.

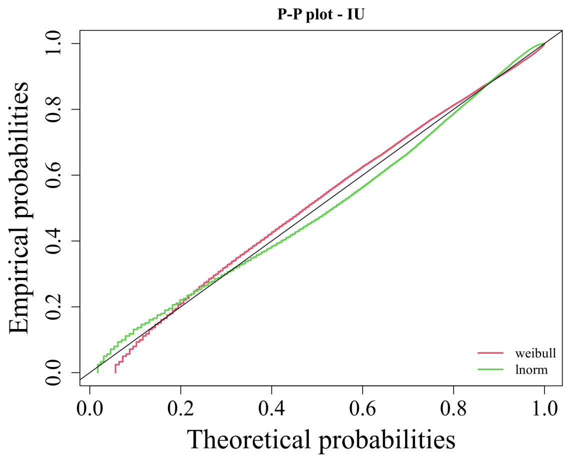

Figure D.14: P-P plot for the Inspector Unit TBF data - comparison between Log-normal and Weibull.

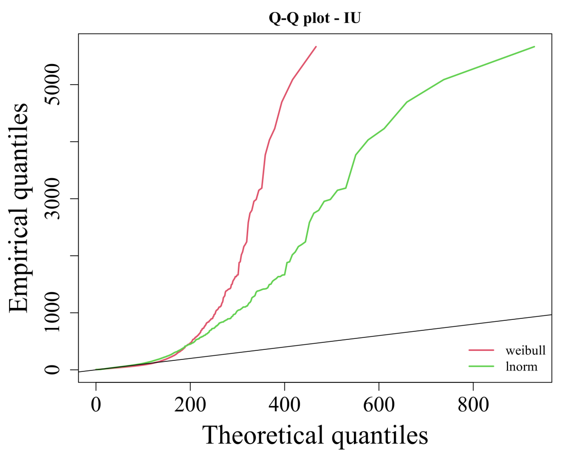

Figure D.15: Q-Q plot for the Inspector Unit TTR data - comparison between Log-normal and Weibull.

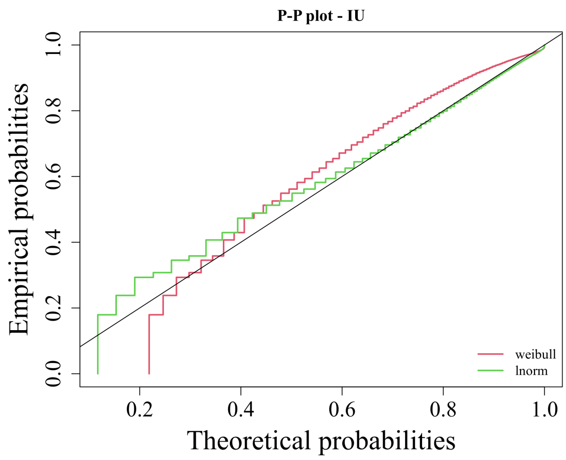

Figure D.16: P-P plot for the Inspector Unit TTR data - comparison between Log-normal and Weibull.

D.5 Filler - FL

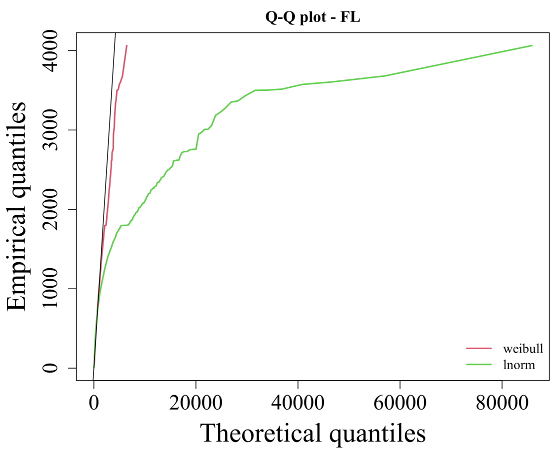

Figure D.17: Q-Q plot for the Filler TBF data - comparison between Log-normal and Weibull.

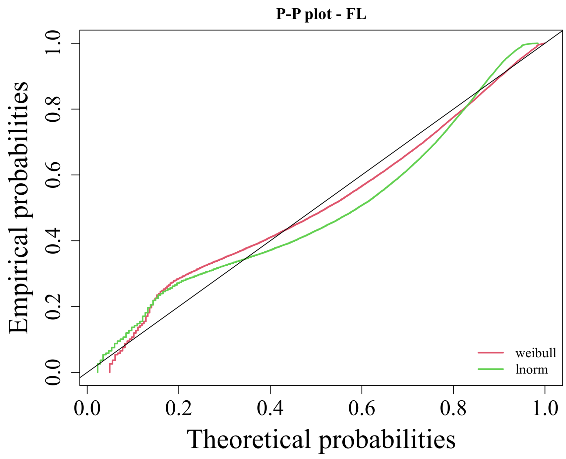

Figure D.18: P-P plot for the Filler TBF data - comparison between Log-normal and Weibull.

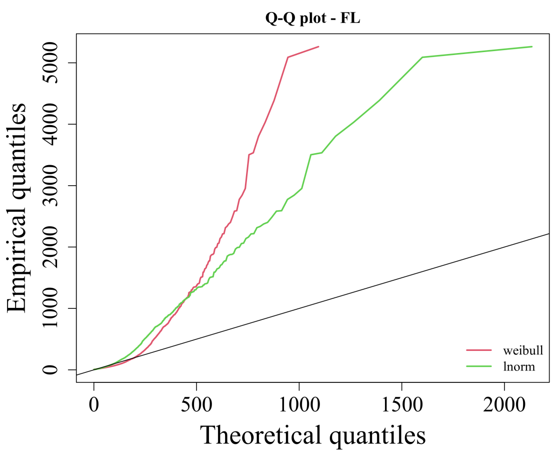

Figure D.19: Q-Q plot for the Filler TTR data - comparison between Log-normal and Weibull.

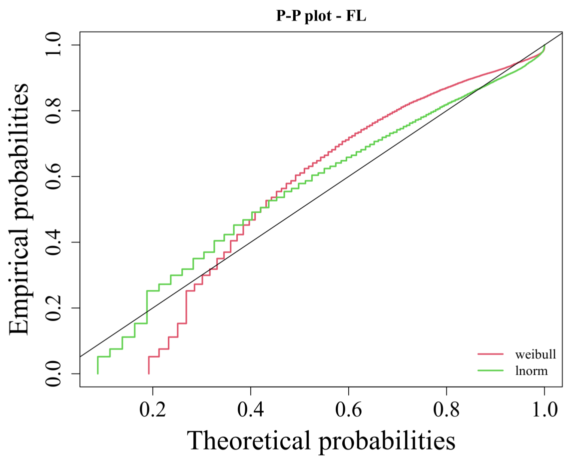

Figure D.20: P-P plot for the Filler TTR data - comparison between Log-normal and Weibull.

D.6 Pasteurization Unit - PU

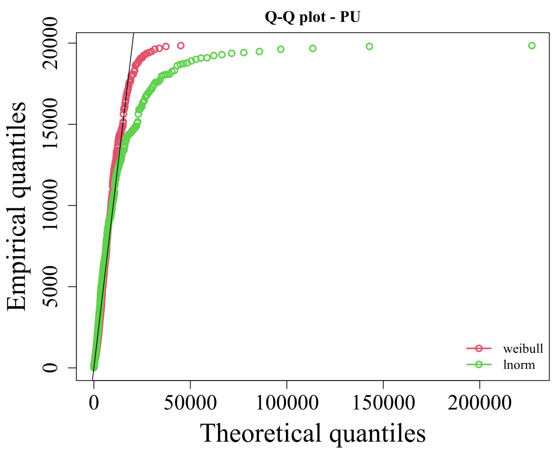

Figure D.21: Q-Q plot for the Pasteurization Unit TBF data - comparison between Log-normal and Weibull.

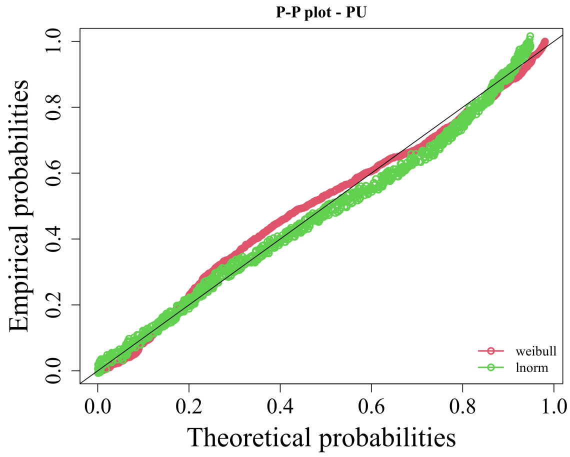

Figure D.22: P-P plot for the Pasteurization Unit TBF data - comparison between Log-normal and Weibull.

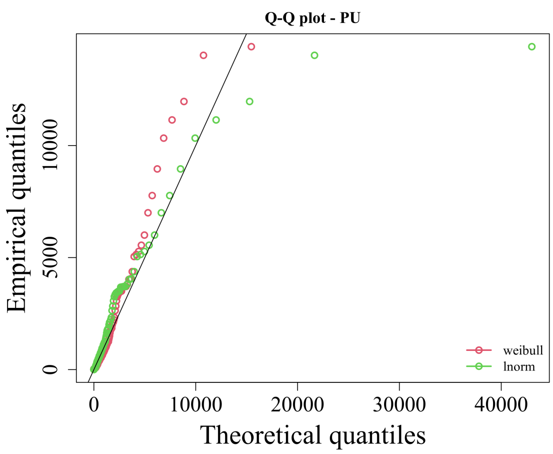

Figure D.23: Q-Q plot for the Pasteurization Unit TTR data - comparison between Log-normal and Weibull.

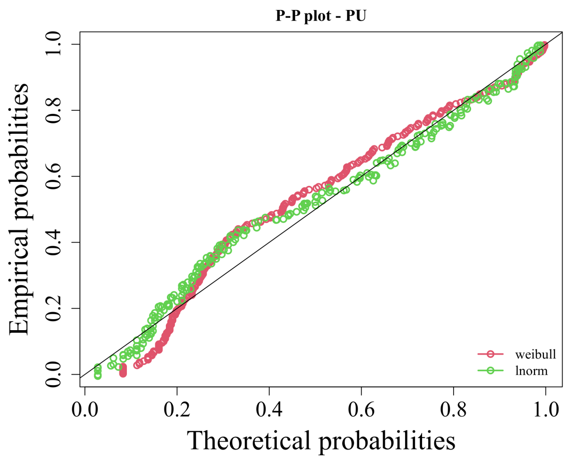

Figure D.24: P-P plot for the Pasteurization Unit TTR data - comparison between Log-normal and Weibull.

D.7 Labeller 1 - LB1

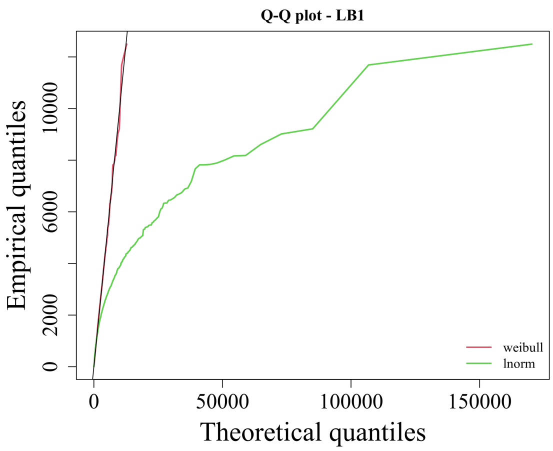

Figure D.25: Q-Q plot for the Labeller 1 TBF data - comparison between Log-normal and Weibull.

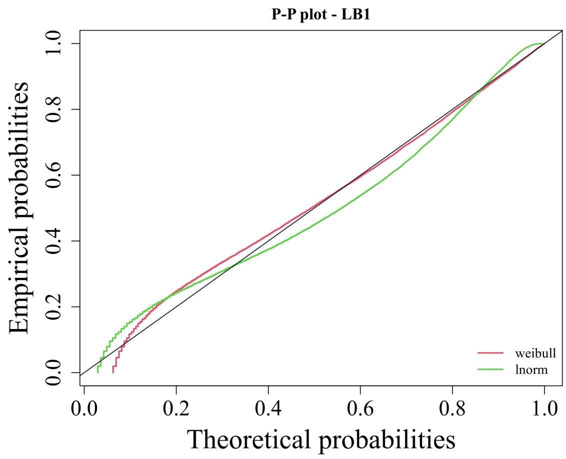

Figure D.26: P-P plot for the Labeller 1 TBF data - comparison between Log-normal and Weibull.

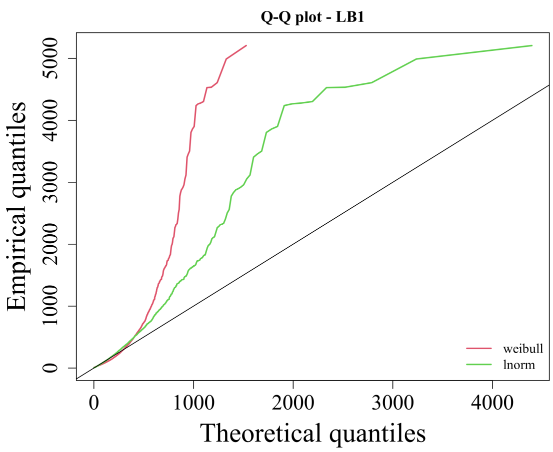

Figure D.27: Q-Q plot for the Labeller 1 TTR data - comparison between Log-normal and Weibull.

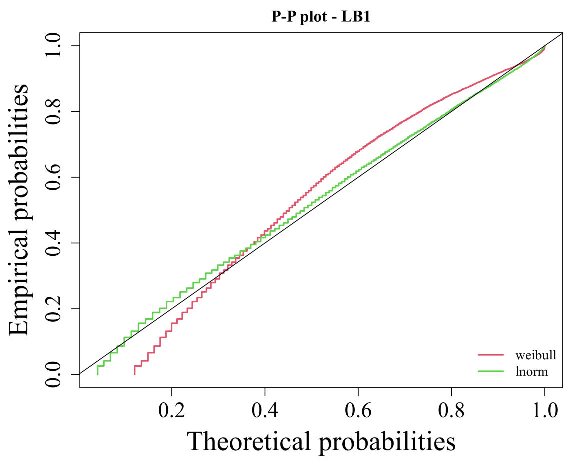

Figure D.28: P-P plot for the Labeller 1 TTR data - comparison between Log-normal and Weibull.

D.8 Labeller 2 - LB2

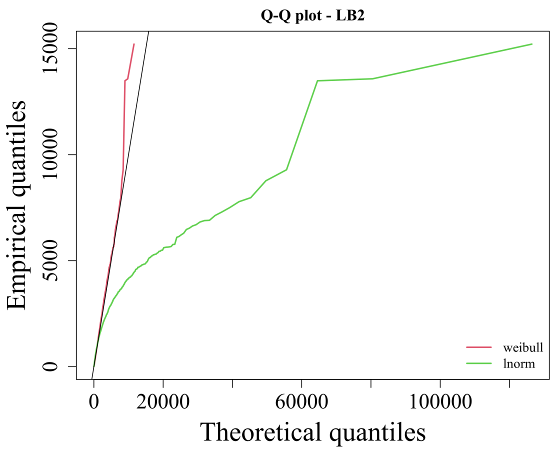

Figure D.29: Q-Q plot for the Labeller 2 TBF data - comparison between Log-normal and Weibull.

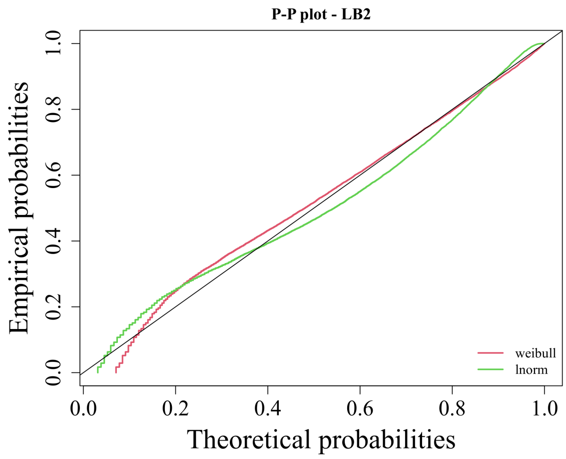

Figure D.30: P-P plot for the Labeller 2 TBF data - comparison between Log-normal and Weibull.

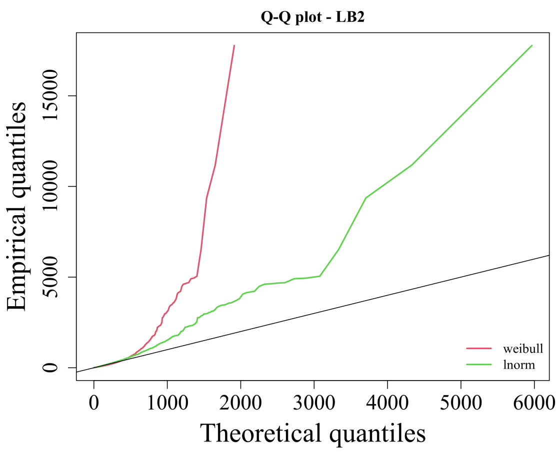

Figure D.31: Q-Q plot for the Labeller 2 TTR data - comparison between Log-normal and Weibull.

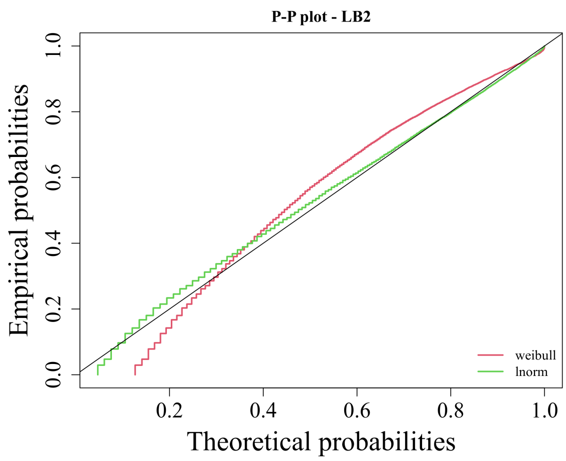

Figure D.32: P-P plot for the Labeller 2 TTR data - comparison between Log-normal and Weibull.

D.9 Recrater - RCR

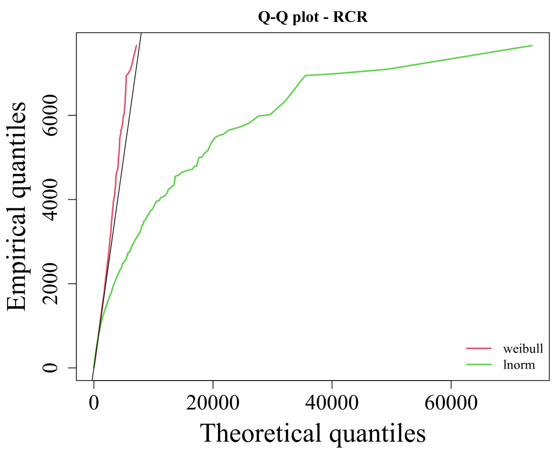

Figure D.33: Q-Q plot for the Recrater TBF data - comparison between Log-normal and Weibull.

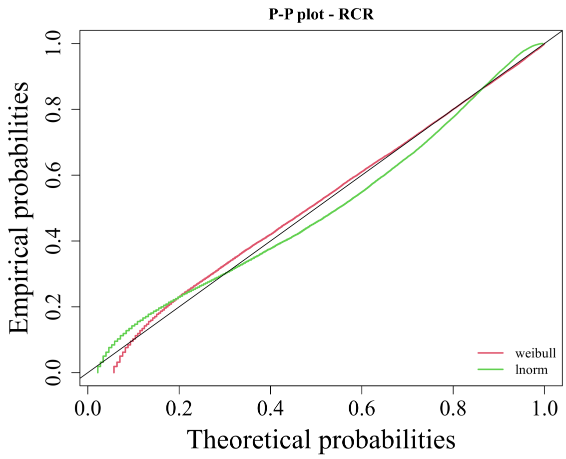

Figure D.34: P-P plot for the Recrater TBF data - comparison between Log-normal and Weibull.

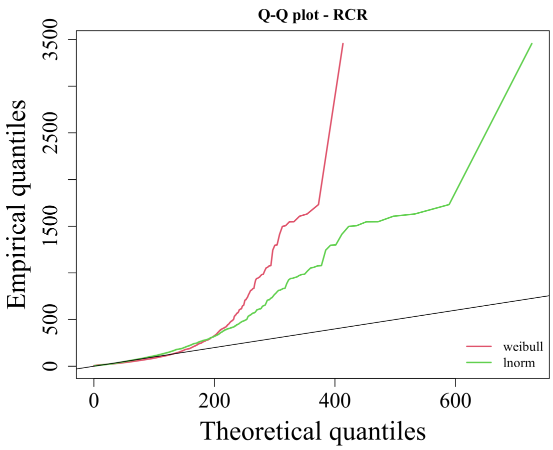

Figure D.35: Q-Q plot for the Recrater TTR data - comparison between Log-normal and Weibull.

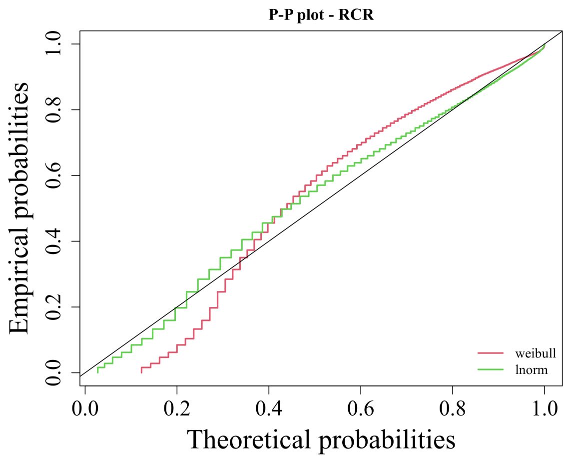

Figure D.36: P-P plot for the Recrater TTR data - comparison between Log-normal and Weibull.

D.10 Palletizer - PL

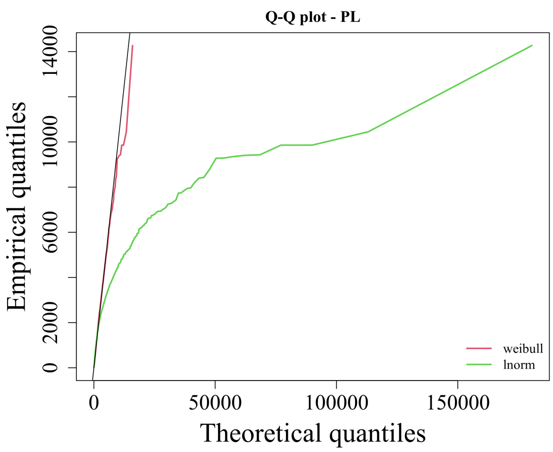

Figure D.37: Q-Q plot for the Palletizer TBF data - comparison between Log-normal and Weibull.

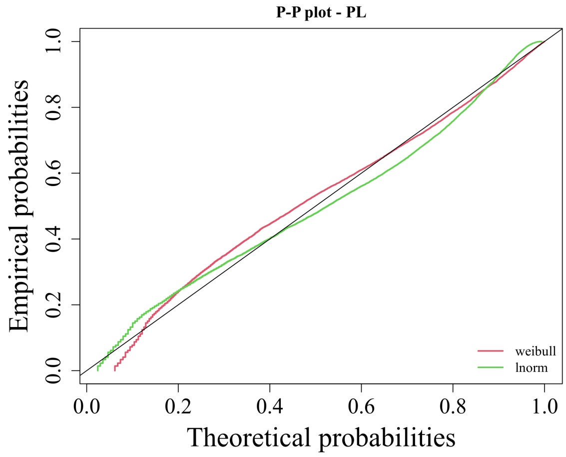

Figure D.38: P-P plot for the Palletizer TBF data - comparison between Log-normal and Weibull.

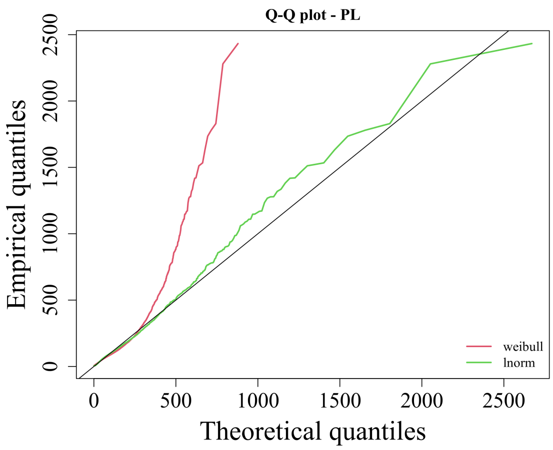

Figure D.39: Q-Q plot for the Palletizer TTR data - comparison between Log-normal and Weibull.

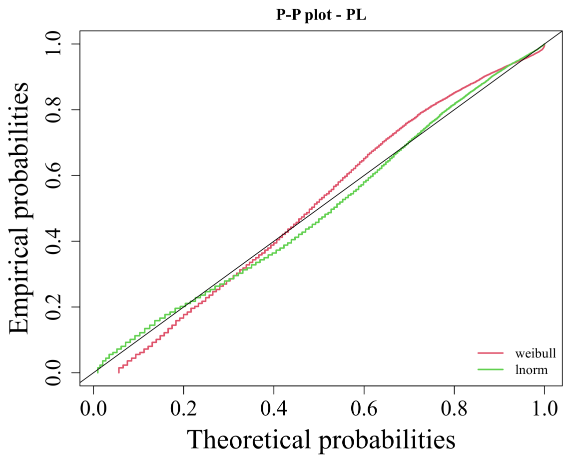

Figure D.40: P-P plot for the Palletizer TTR data - comparison between Log-normal and Weibull.

Appendix E: Line A Hazard plots

E.1 Depalletizer - DPL

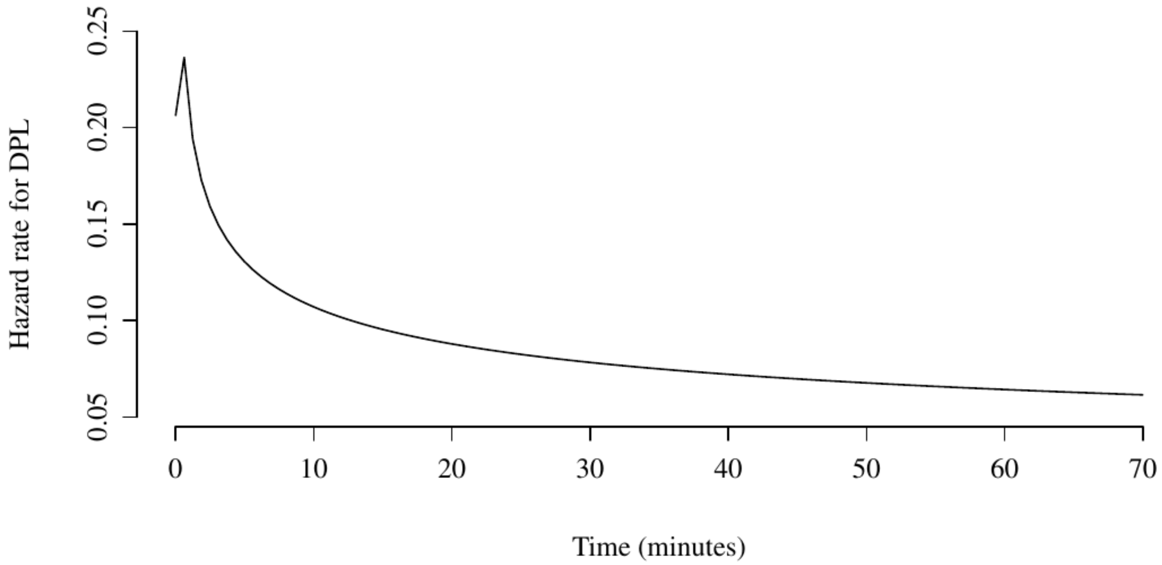

Figure E.1: Depalletizer hazard function.

E.2 Decrater - DCR

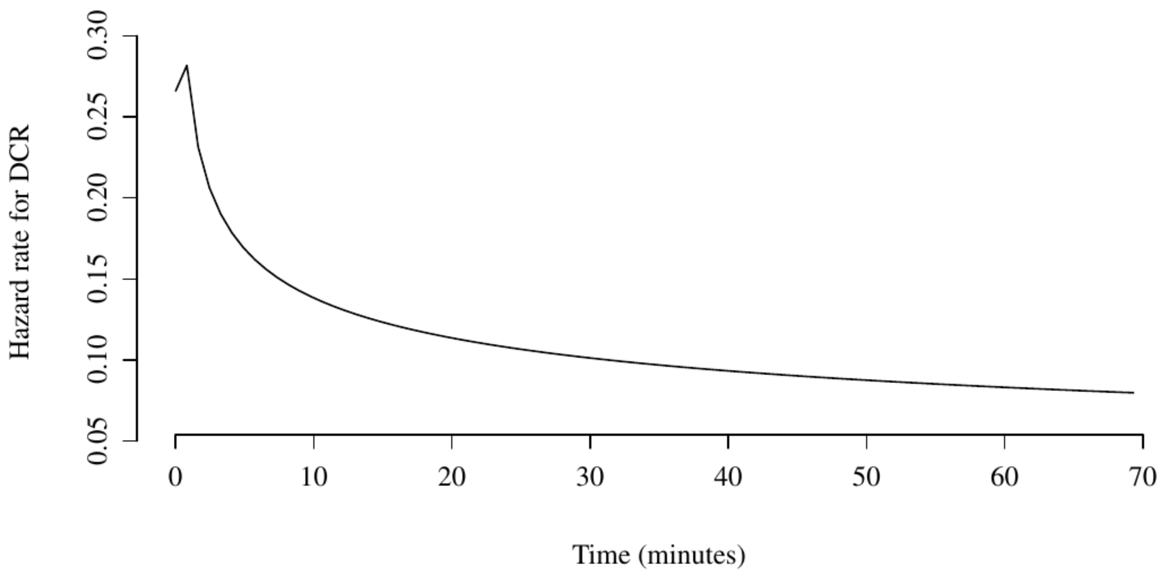

Figure E.2: Decrater hazard function.

E.3 Bottle Washer - BW

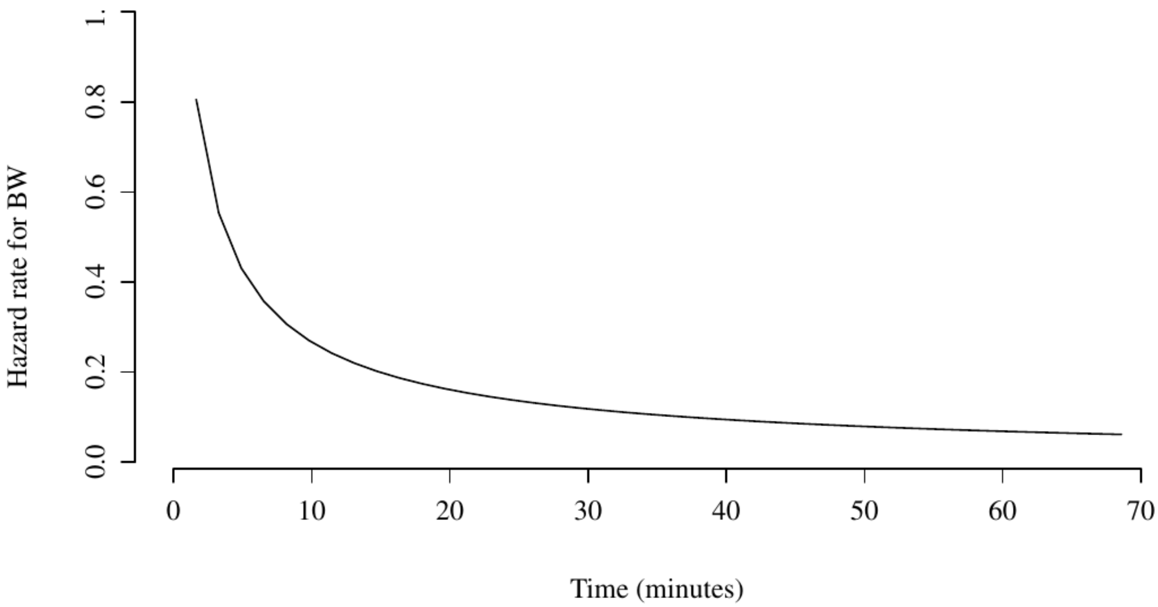

Figure E.3: Bottle Washer hazard function.

E.4 Inspector Unit - IU

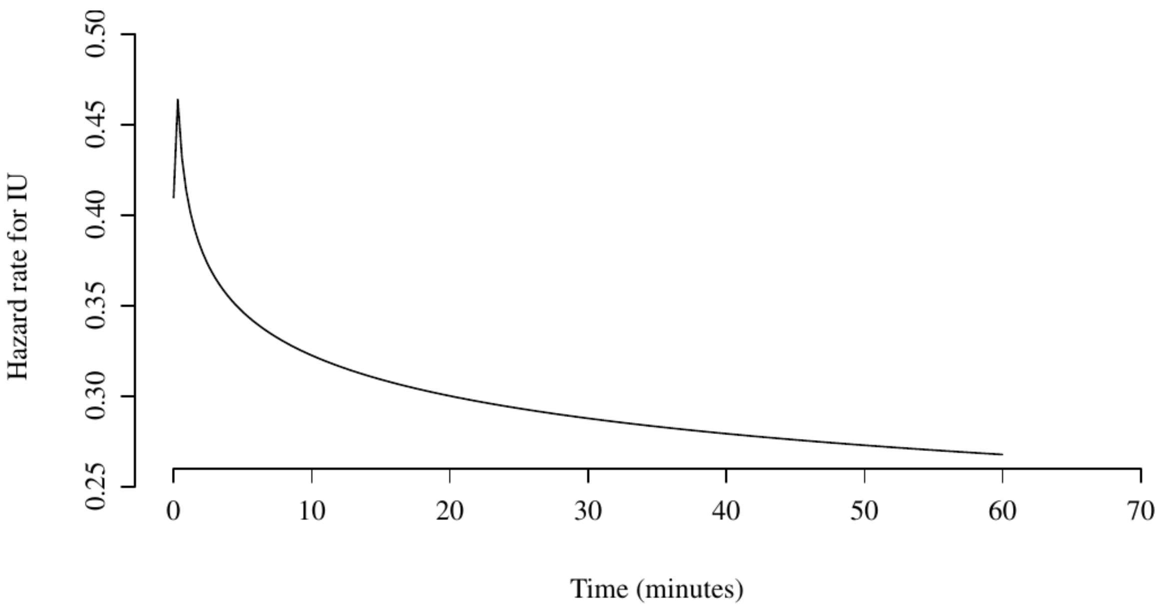

Figure E.4: Inspector Unit hazard function.

E.5 Filler - FL

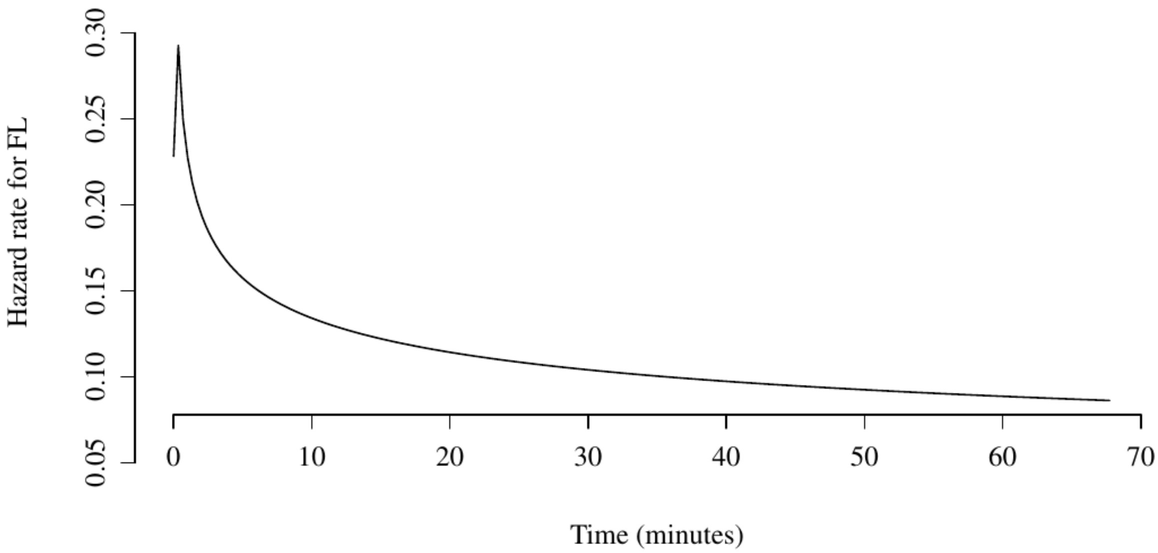

Figure E.5: Filler hazard function.

E.6 Pasteurization Unit - PU

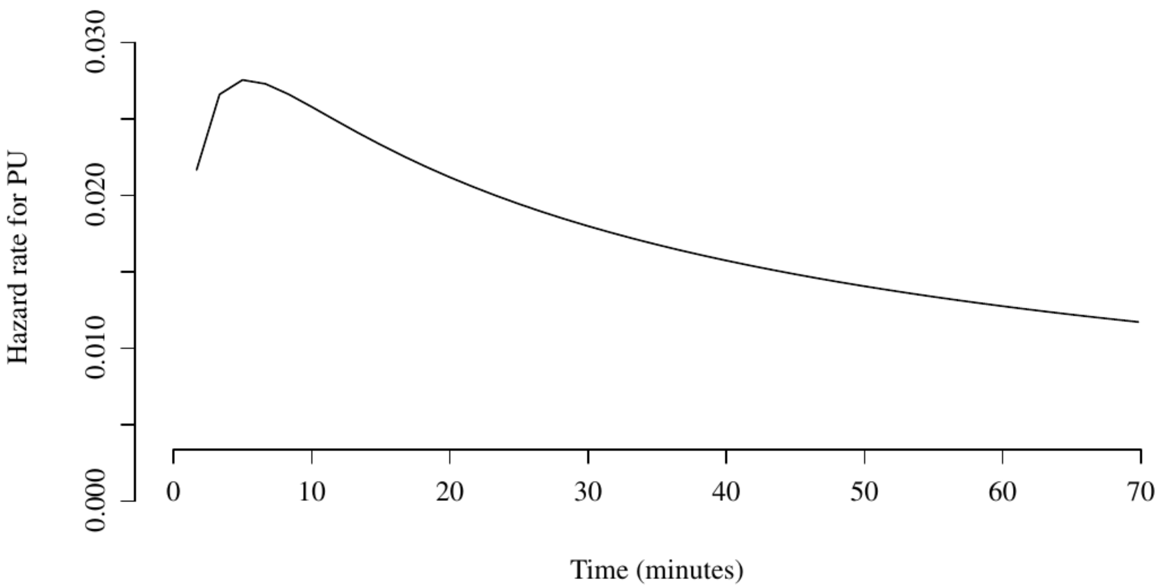

Figure E.6: Pasteurization Unit hazard function.

E.7 Labeller 1 - LB1

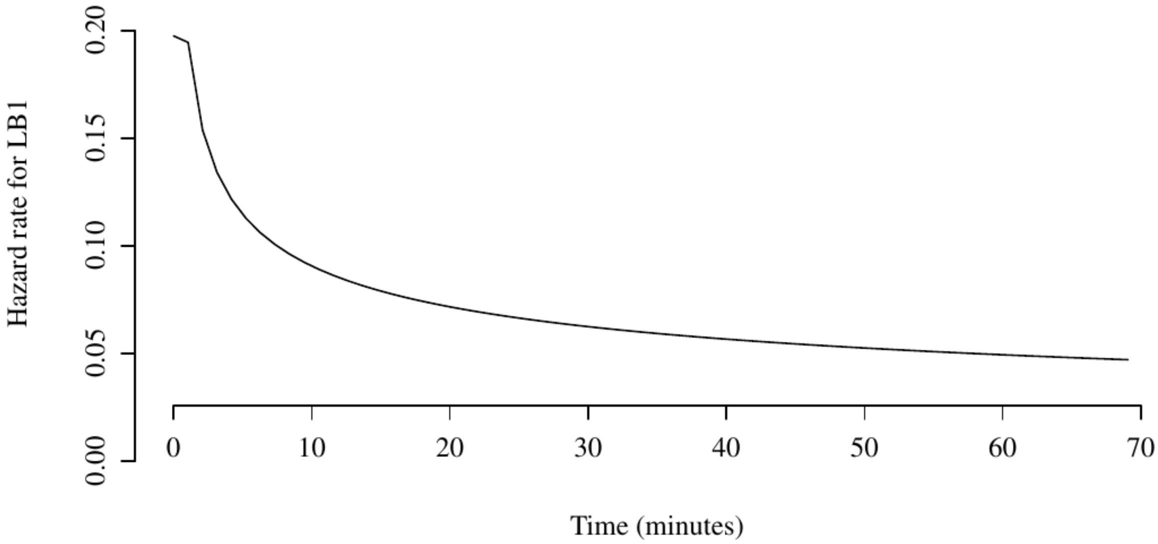

Figure E.7: Labeller 1 hazard function.

E.8 Labeller 2 - LB2

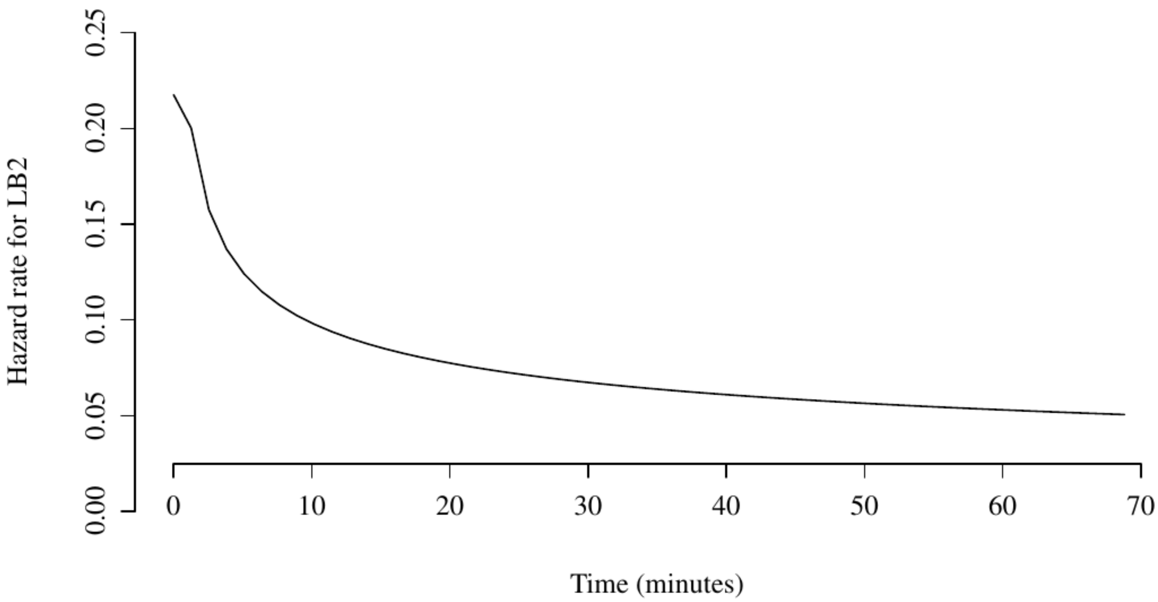

Figure E.8: Labeller 2 hazard function.

E.9 Recrater - RCR

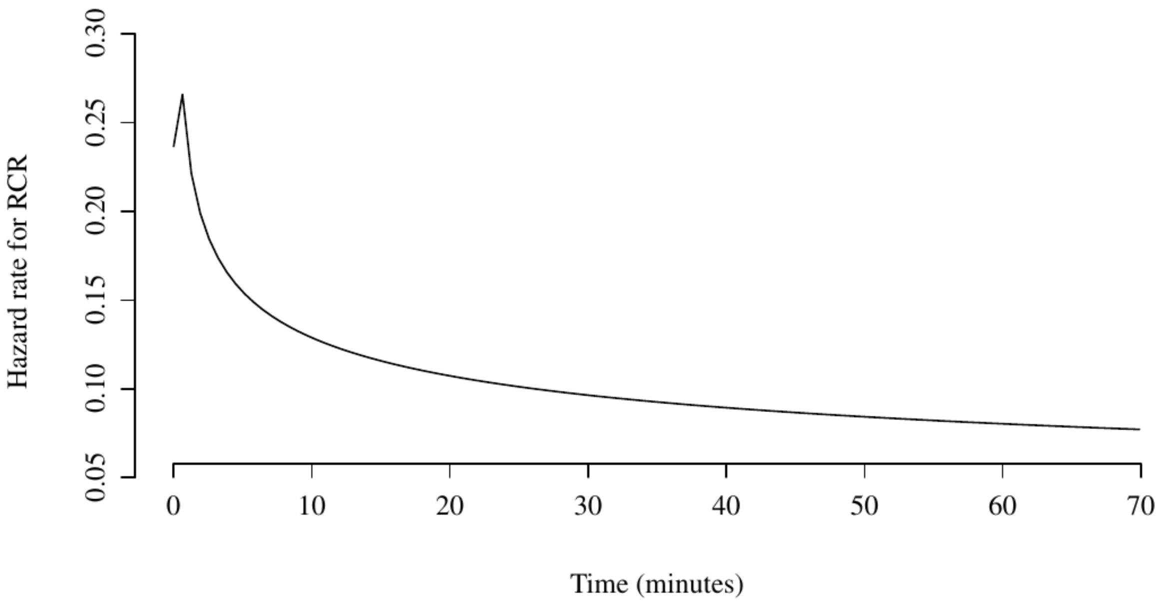

Figure E.9: Recrater hazard function.

E.10 Palletizer - PL

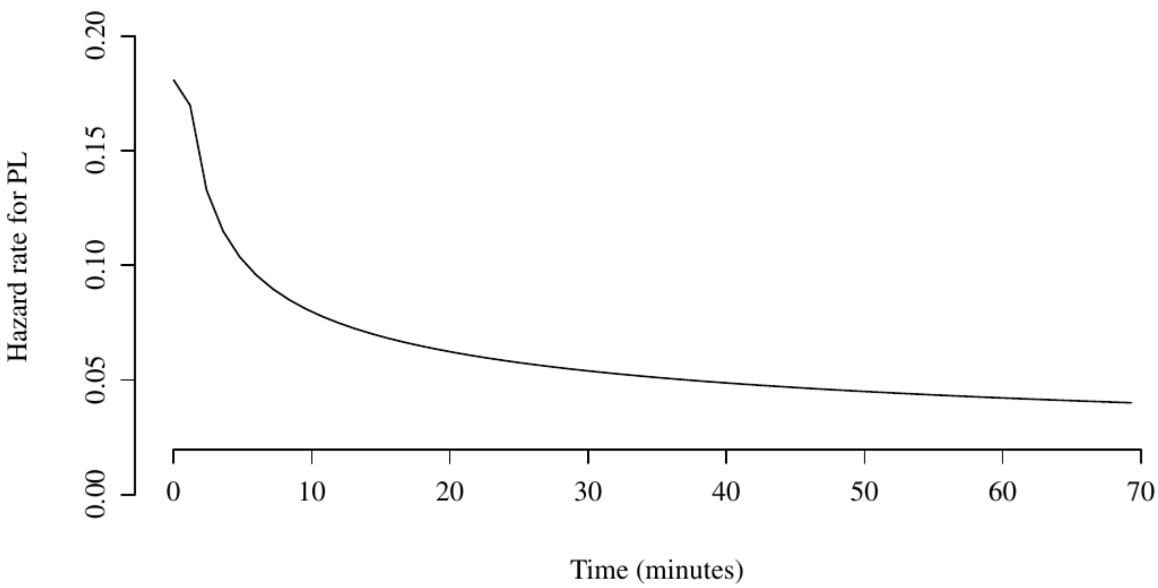

Figure E.10: Palletiser hazard function.

Appendix F: Line A Reliability probability graphs

F.1 Depalletizer - DPL

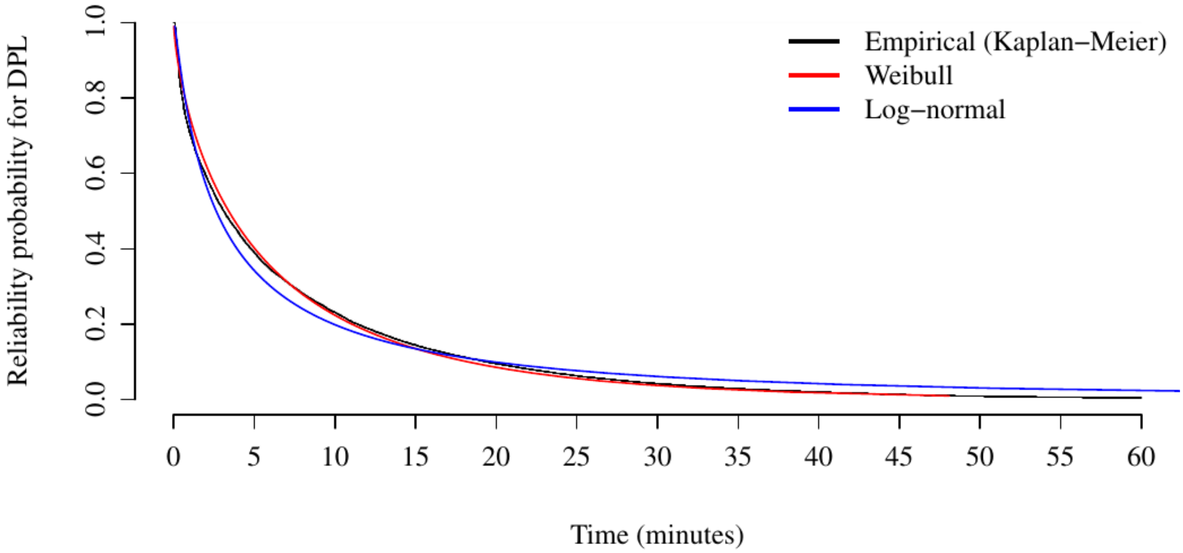

Figure F.1: Depalletizer reliability plot.

F.2 Decrater - DCR

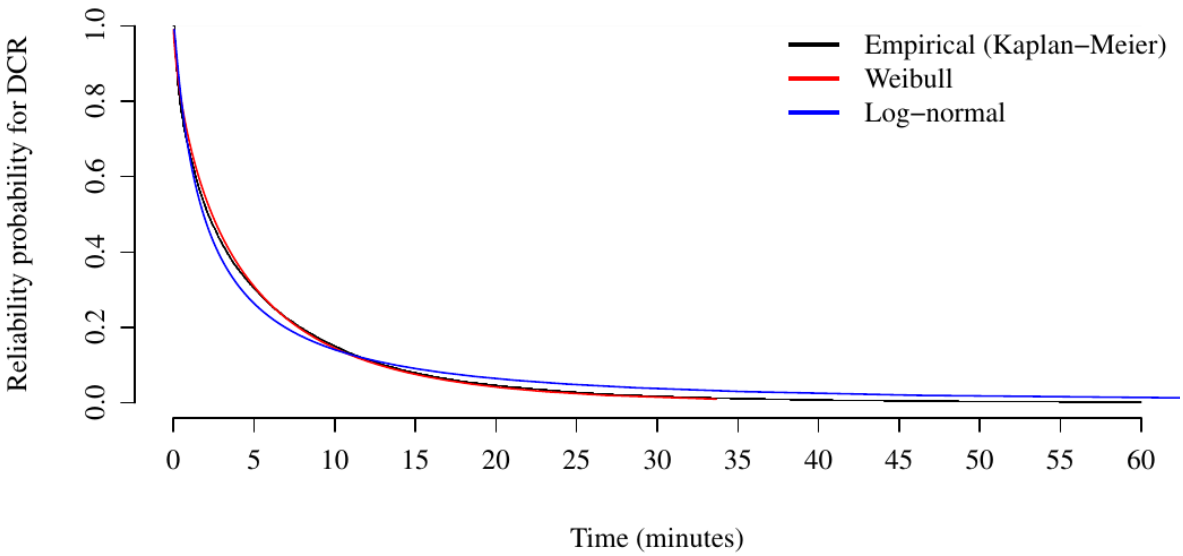

Figure F.2: Decrater reliability plot.

F.3 Bottle Washer - BW

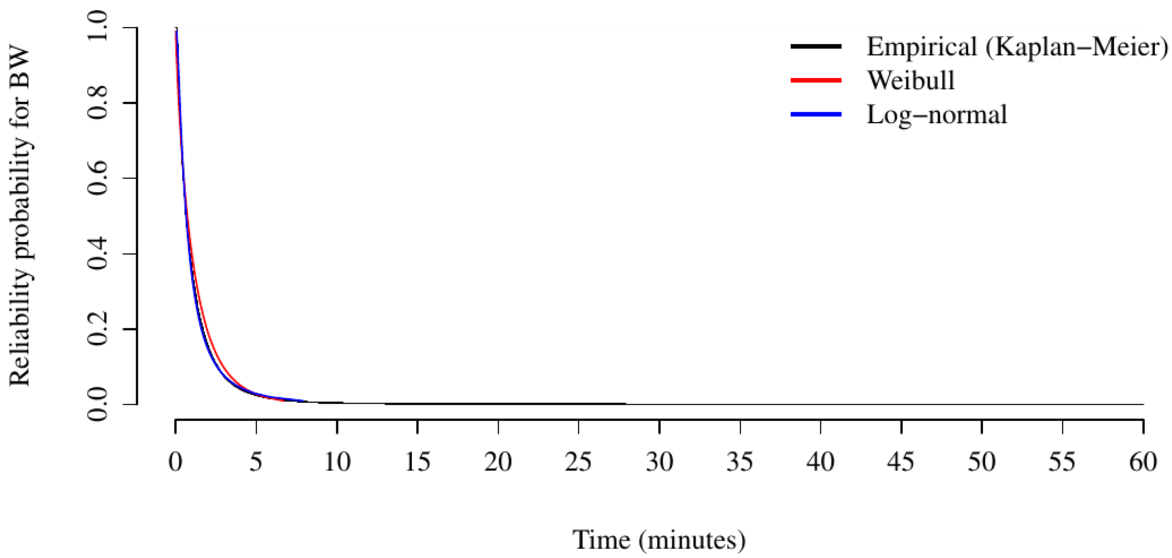

Figure F.3: Bottle Washer reliability plot.

F.4 Inspector Unit - IU

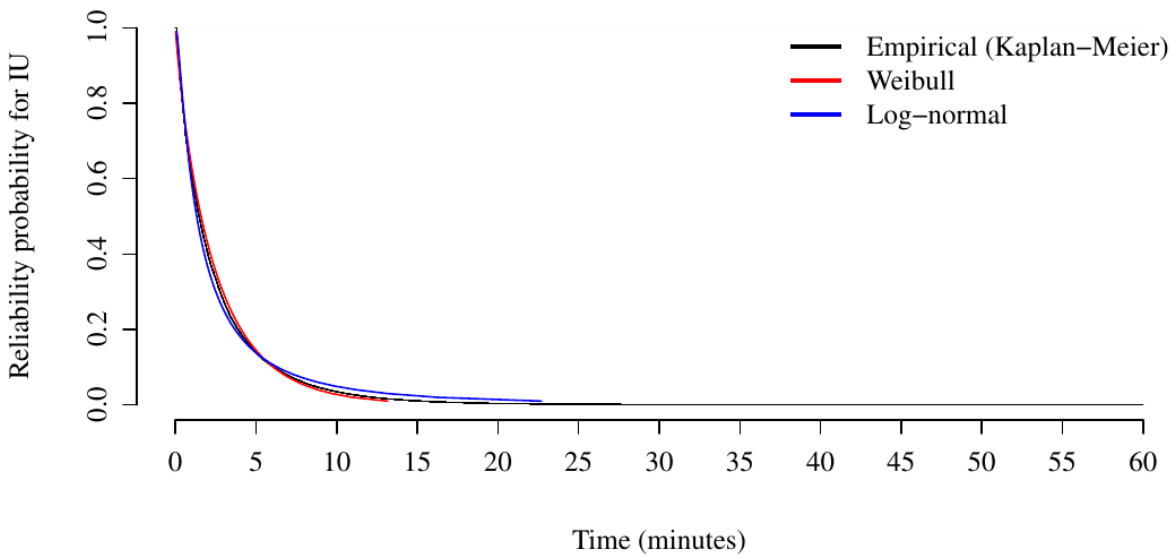

Figure F.4: Inspector Unit reliability plot.

F.5 Filler - FL

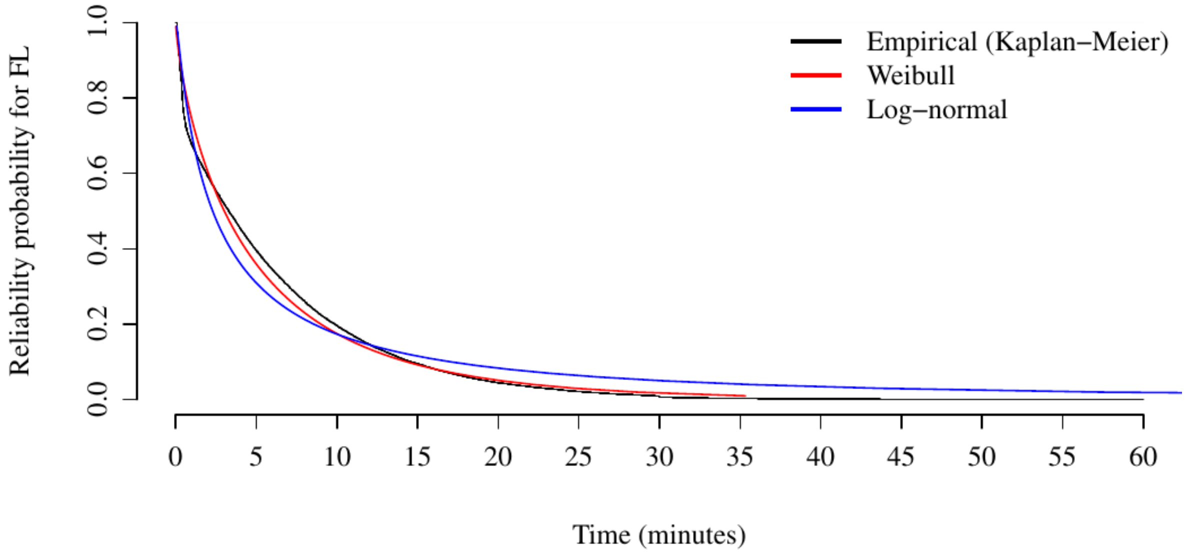

Figure F.5: Filler reliability plot.

F.6 Pasteurization Unit - PU

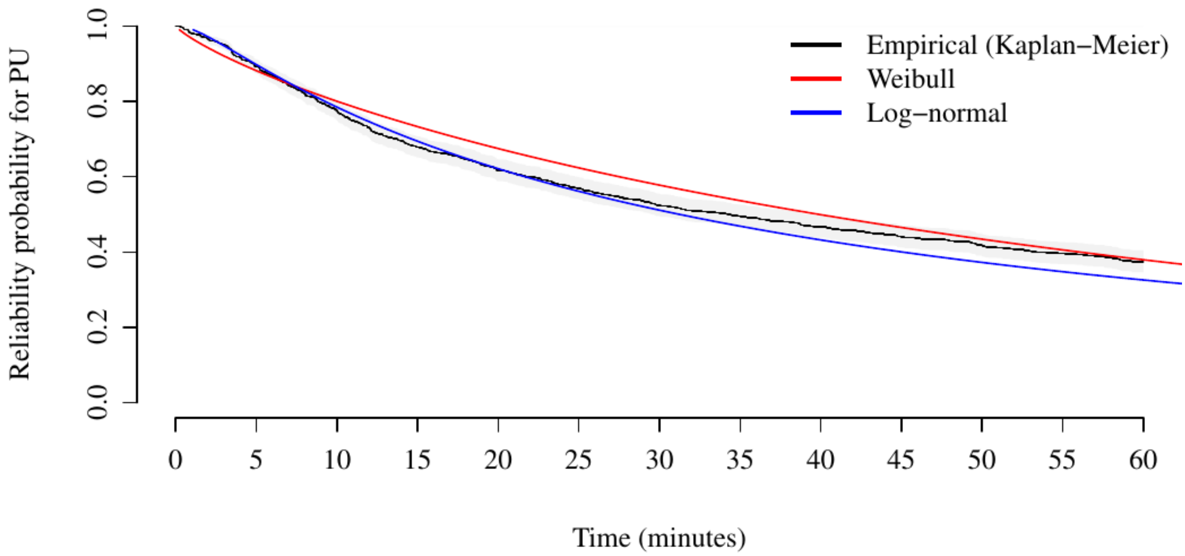

Figure F.6: Pasteurization Unit reliability plot.

F.7 Labeller 1 - LB1

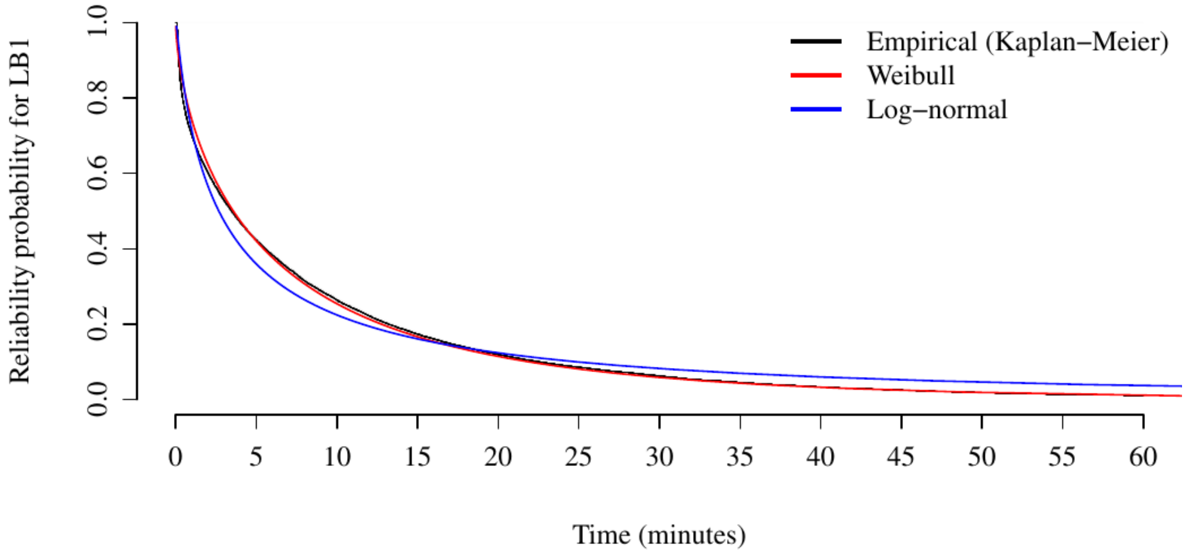

Figure F.7: Labeller 1 reliability plot.

F.8 Labeller 2 - LB2

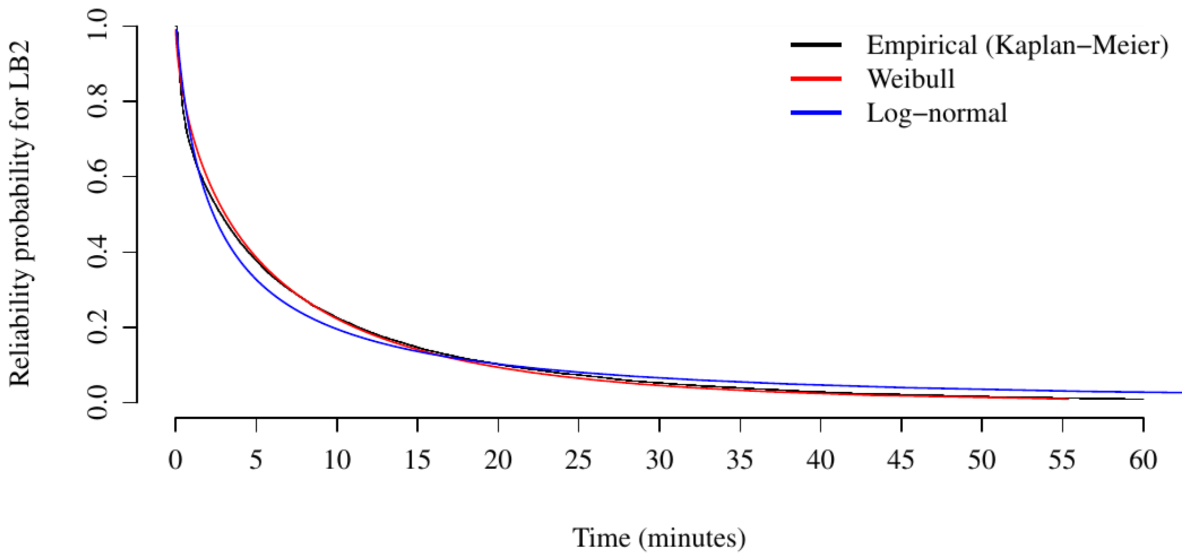

Figure F.8: Labeller 2 reliability plot.

F.9 Recrater - RCR

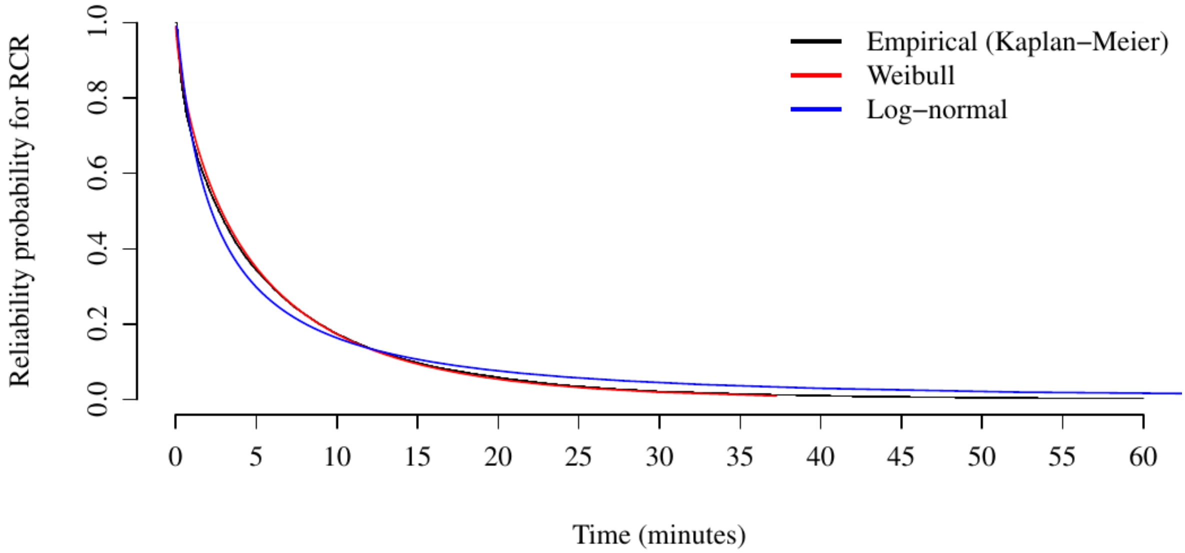

Figure F.9: Recrater reliability plot.

F.10 Palletizer - PL

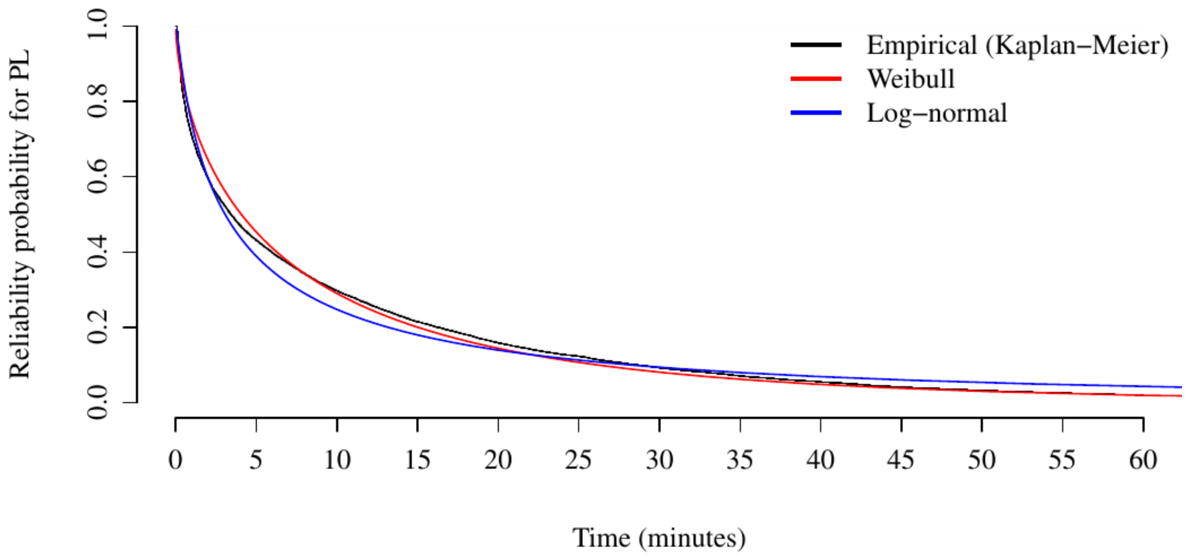

Figure F.10: Palletiser reliability plot.

Appendix G: Line A Maintainability probability graphs

G.1 Depalletizer - DPL

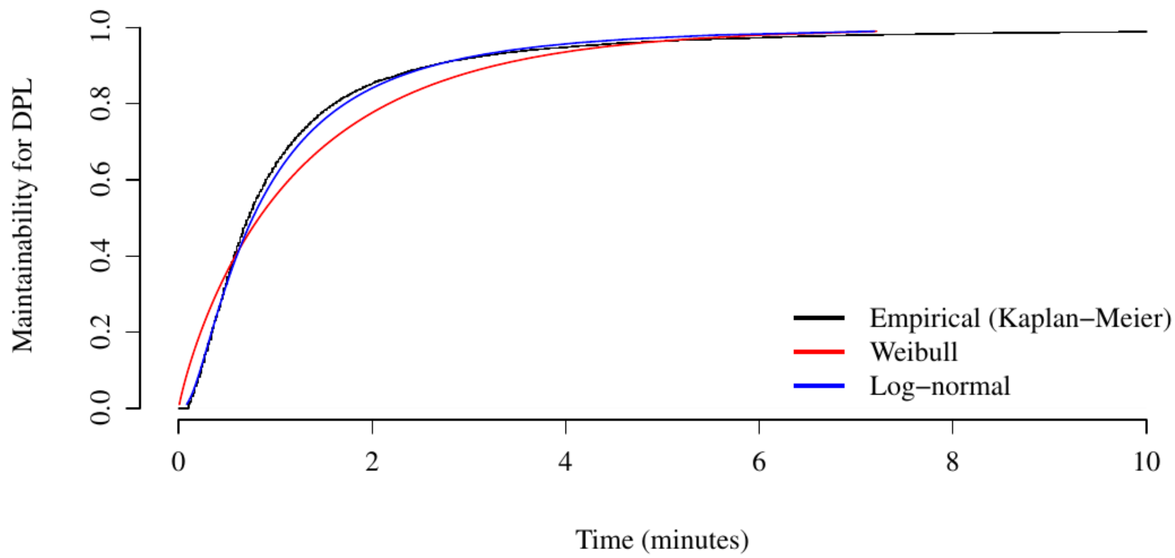

Figure G.1: Depalletizer maintainability plot.

G.2 Decrater - DCR

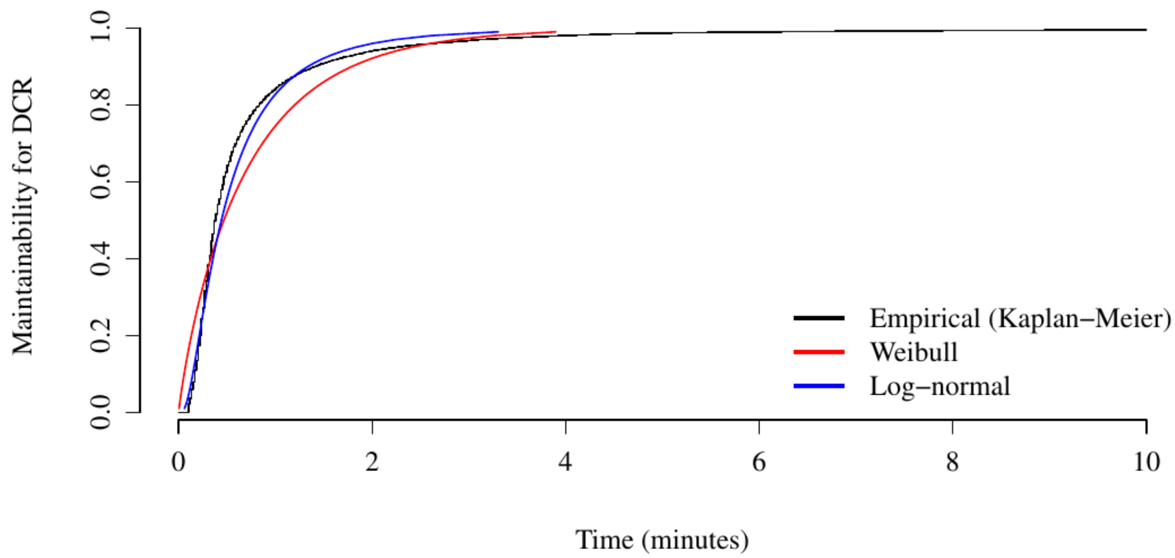

Figure G.2: Decrater maintainability plot.

G.3 Bottle Washer - BW

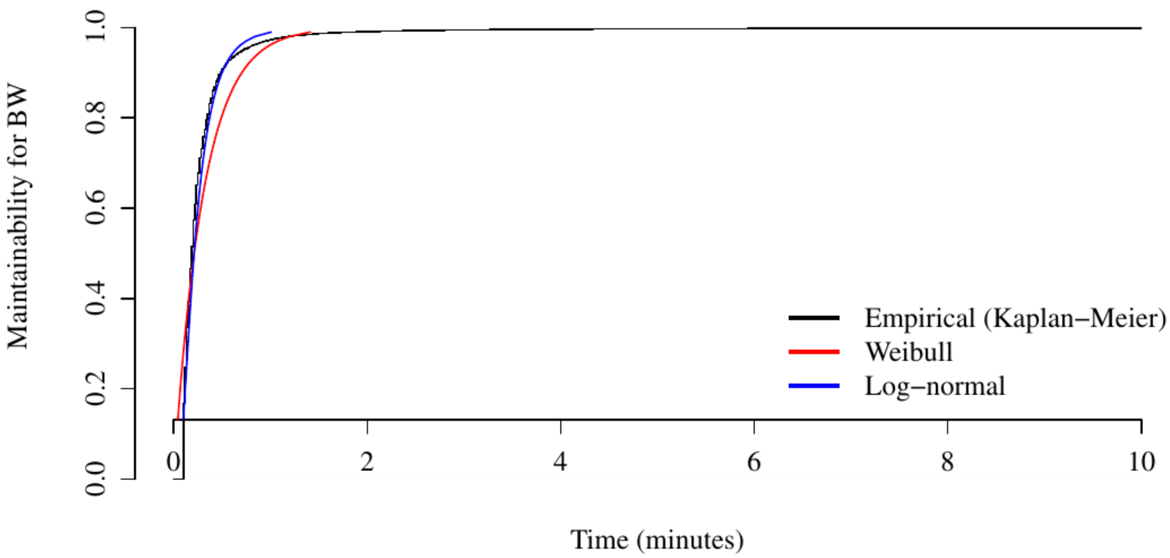

Figure G.3: Bottle Washer maintainability plot.

G.4 Inspector Unit - IU

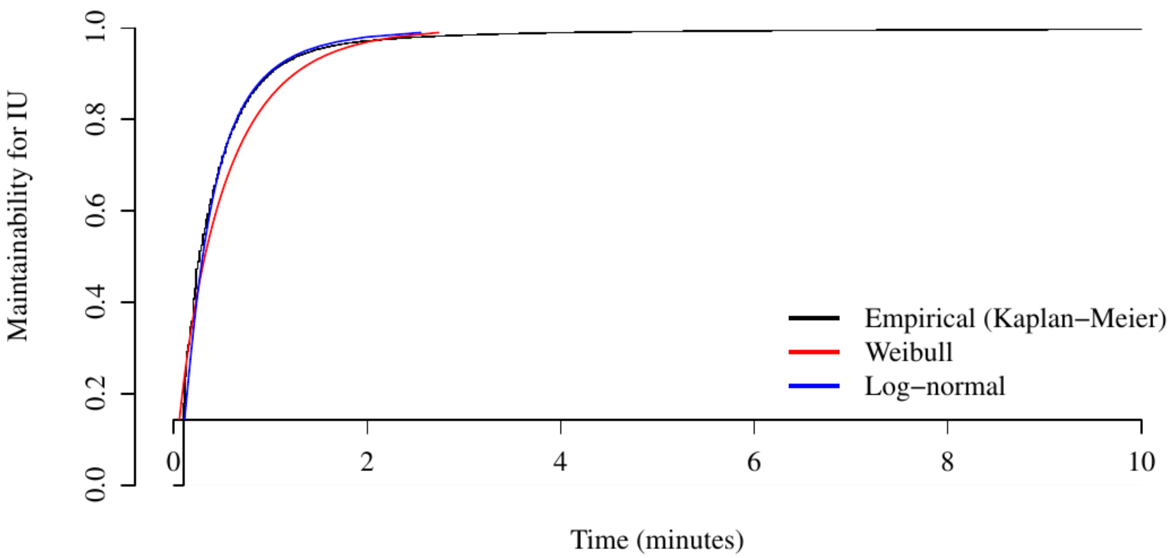

Figure G.4: Inspector Unit maintainability plot.

G.5 Filler - FL

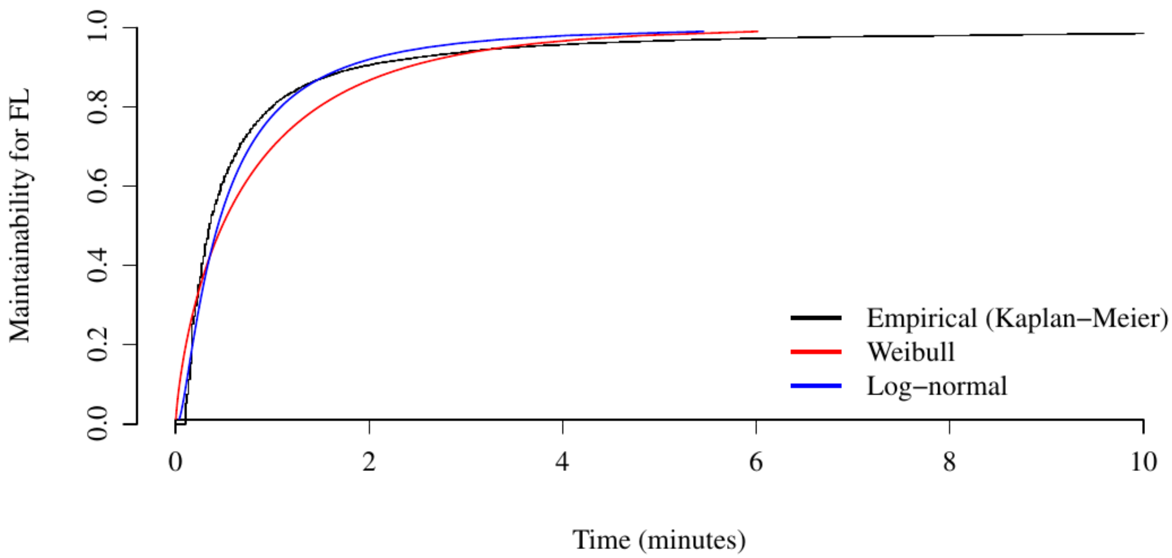

Figure G.5: Filler maintainability plot.

G.6 Pasteurization Unit - PU

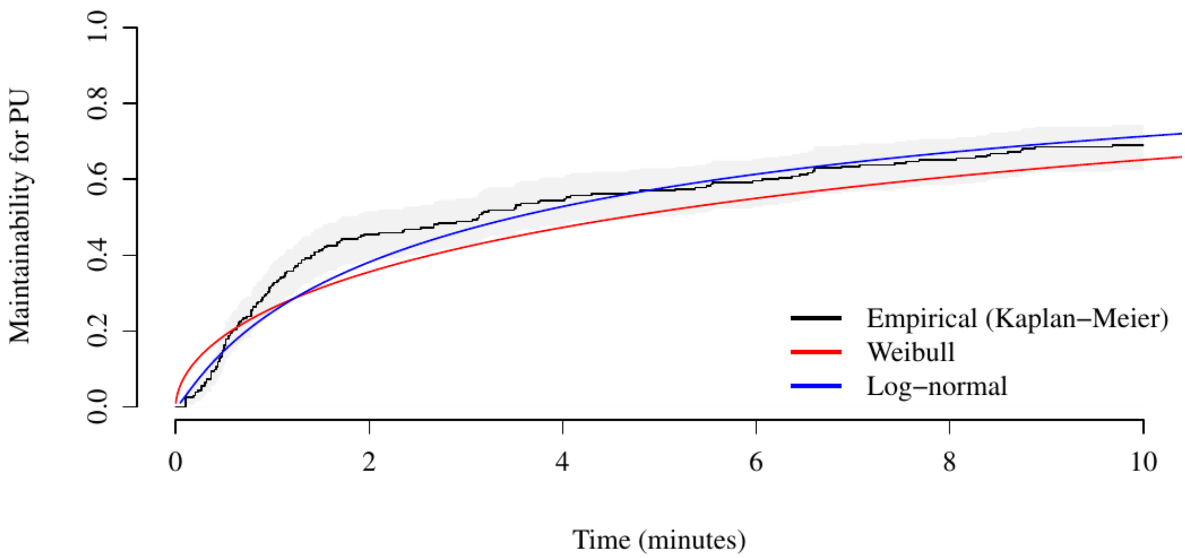

Figure G.6: Pasteurization Unit maintainability plot.

G.7 Labeller 1 - LB1

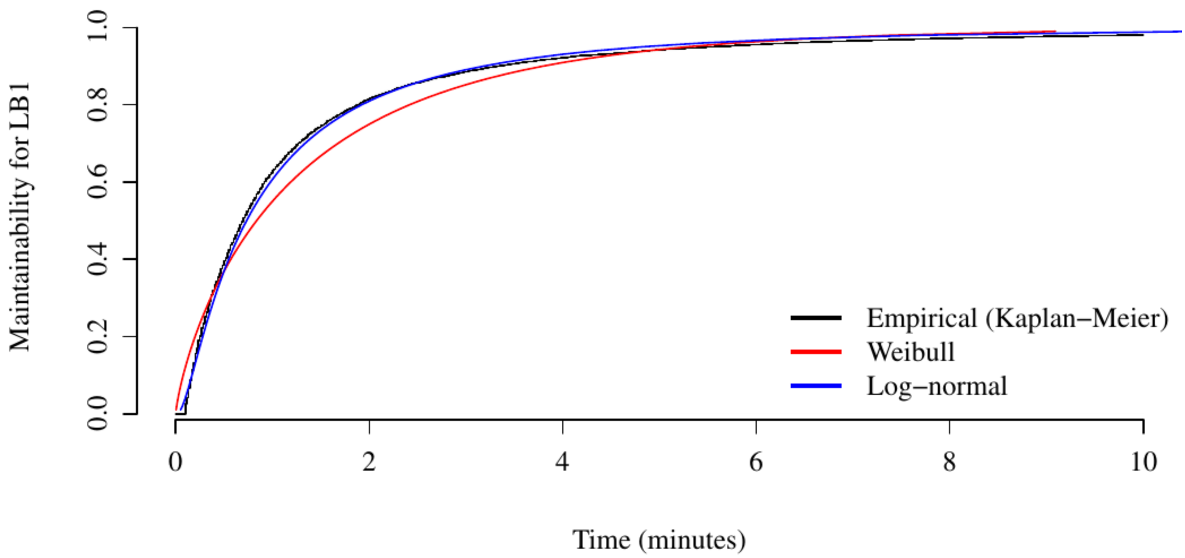

Figure G.7: Labeller 1 maintainability plot.

G.8 Labeller 2 - LB2

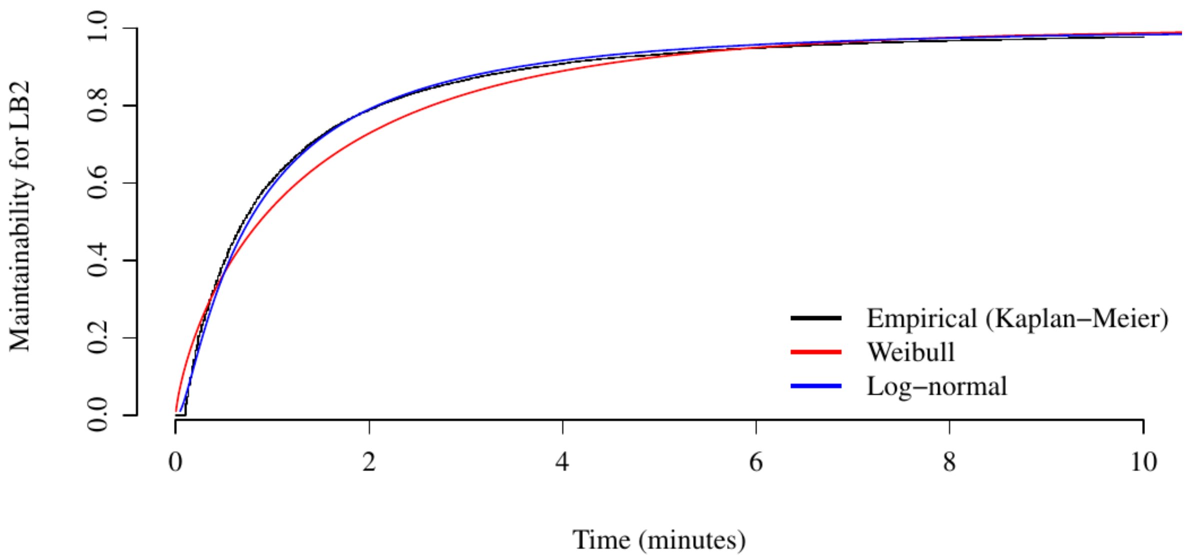

Figure G.8: Labeller 2 maintainability plot.

G.9 Recrater - RCR

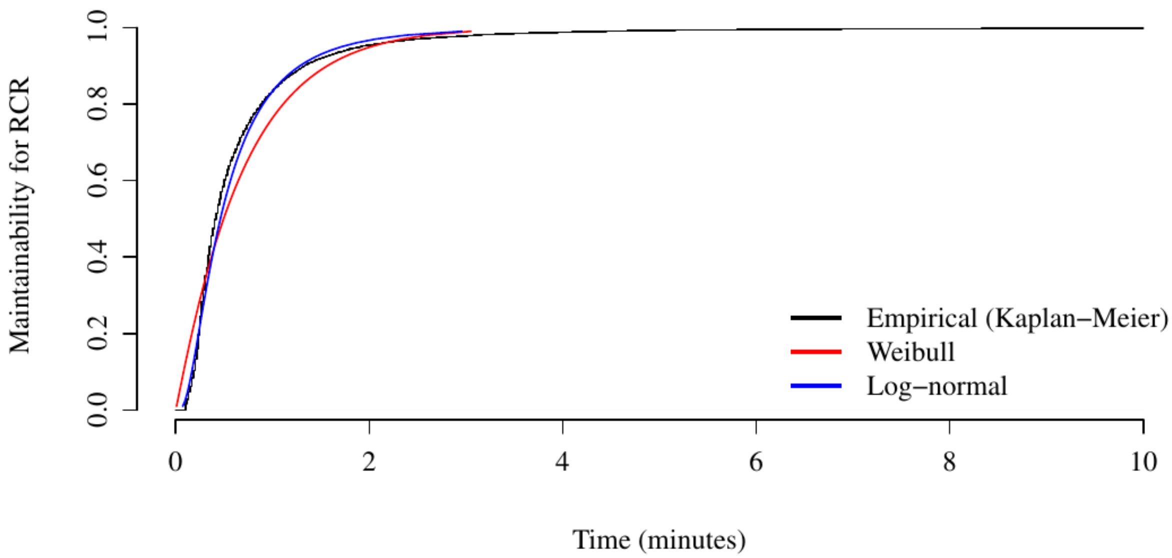

Figure G.9: Recrater maintainability plot.

G.10 Palletizer - PL

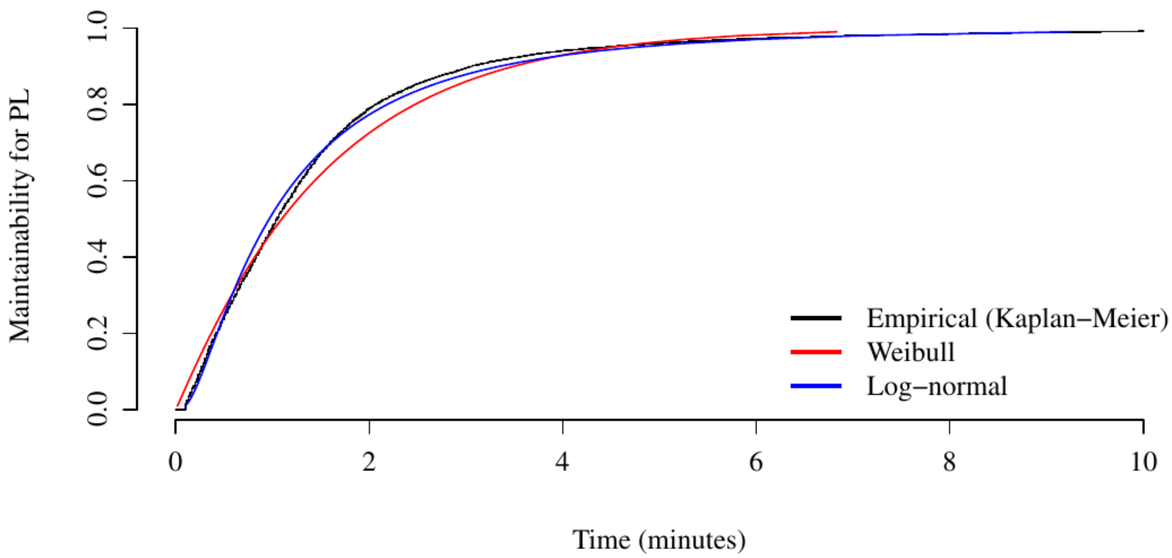

Figure G.10: Palletiser maintainability plot.