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Investigating net ideal cycle time estimation and efficient buffer allocation for Body-in-White production lines

by

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Abstract

This thesis makes a significant original contribution to the field of production economics. This contribution is two-fold and is relevant to Body-in-White (BIW) production line design. In the automotive industry, a BIW refers to the first step in the production of a vehicle, i.e. the basic structure. First, a new bottom-up method is proposed to estimate the Net Ideal Cycle Time (NICT), which is the main metric used for the production line design. Once a BIW production line has been built, the (maximum) capacity is fixed, and the throughput is therefore limited by the equipment specified during the design phase. Unfortunately, the state of practice to estimate the NICT is a basic heuristic that does not account for production variation. A mini-case study is used to demonstrate the insufficient consideration of uncertainty in the state-of-practice method. This thesis challenges the current estimation approach by proposing an alternative that assumes that the actual production throughput follows a Weibull distribution. The proposed model is derived and estimated from empirical data. The estimation results of the proposed model are then compared with the actual results of the production line used in the mini-case study, in terms of the throughput and financial investment. The results suggest that BIW production lines have traditionally been designed with insufficient capacity, resulting in the planned throughput rarely being achieved. On the other hand, increasing the design capacity implies a higher initial investment. This thesis demonstrates that the higher investment required is offset by reduced throughput losses, resulting in more reliable planning and returns. This is done by comparing the investment figures of the two models as well as the realistic expected throughput of each model. The second contribution to new knowledge is an efficiency evaluation method based on the efficient frontier that is proposed to measure the buffer system design efficiency encapsulated within the BIW production line based on multiple design objectives. The design of the complex buffer system is a challenging task, and finding efficient solutions to minimise the cost and maximise the throughput is a priority. Unfortunately, the state of practice is to focus purely on maximising the throughput, while the cost and space usage are considered to be the results of the buffer system, rather than the objective. This thesis considers the well-known Buffer Allocation Problem (BAP) and the individual objectives that are relevant in BIW buffer design, and demonstrates how the design objectives compete against one another. This thesis proves that there is no optimum buffer solution, but rather several efficient solutions. The proposed method is an efficient frontier that can be navigated and used to combine the objectives into a multi-objective solution, where the trade-offs and competition for location are studied. Full enumeration is used to create a complete buffer landscape that visually displays all the buffer solutions in terms of specifically selected multiple objectives. The frontier is tested using two real BIW production lines. The results suggest that the buffer systems for both BIW production lines can deliver greater throughput and remain more cost efficient, while minimising the space and Work-in-Process (WIP), indicating that neither line is on the efficient frontier. To conclude, this thesis demonstrates how the efficient frontier can be utilised to assist decision-makers in delivering more efficient buffer solutions in practice.

Acknowledgements

I want to thank my Father in heaven for blessing me with all that I am. All the Glory to God.

This thesis is dedicated to Rhodé and Tristan. Your patience and support was immense, and without you, this thesis would not have been possible. I will never forget that you allowed me to pursue this dream; I am forever in your debt. You were my inspiration, and I love you, always.

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Contents

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Acronyms

A	Availability
AF	Finish
AIC	Akaike's Information Criterion
AIEC	Automotive Industry Export Council
BAM	Buffer Allocation Model
BAP	Buffer Allocation Problem
BB	Centre Floor
BG	Under Body
BIC	Bayesian Information Criterion
BIW	Body-in-White
CDF	Cumulative Distribution Function
CMS	Cellular Manufacturing Systems
CSV	Comma-separated values
CTP	Cycle Time Problem
FMS	Flexible Manufacturing Systems
GDP	Gross Domestic Product

HB	Rear End
IPS-T	International Production System - Technical
HOP	Hang-on-Parts
KPI	Key Performance Indicator
KG1	Framing 1
KG2	Framing 2
KG3	Framing 3
LL	Log likelihood
LSL	Lower Specification Limit
MT	Mean Throughput
MTT	Mean Throughput Target
MTTR	Mean Time to Repair
MTBF	Mean Time Between Failures
NAT	Net Available Time
NICT	Net Ideal Cycle Time
NDF	Normal Distribution Function
NP	Non-polynomial-time
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
P	Performance
PLC	Programmable Logic Controller

P-P	Probability-Probability
Q	Quality
Q-Q	Quantile-Quantile
SD	Standard Deviation
SOP	Start of Production
SOS	System out of Sequence
SRi	Side Frame Inner
SRm	Side Frame Middle
SRa	Side Frame Outer
TDV	Total Daily Volume
TP	Throughput
TT	Takt Time
USL	Upper Specification Limit
uph	units per hour
VB	Front End
VCTR	Virtual Cycle Time Restriction
WIP	Work-in-Process

Chapter 1

Introduction

The problem background and motivation for this thesis consist of a first-hand account of the problems experienced during the design and implementation of a Body-in-White (BIW) production line. The purpose is to ensure that when the seven-year cycle of this production line is repeated, that the problems that have occurred during the design and implementation phase will be eliminated.

The automotive industry is an enormous industry that plays a significant role in global economics. In 2015, more than 90 million light vehicles were sold worldwide, and it is predicted that sales will increase and exceed the 111 million mark by 2020 [63]. According to one of the biggest auditor companies in the world KPMG [64], the automotive market is far from saturated, and growth, especially in emerging markets, will continue for the next few decades. This increase in sales means an obvious rise in production activities. Original Equipment Manufacturers (OEMs) with existing production facilities in these emerging markets will have the major strategic advantage of a direct link from the production facilities to the market. A country such as South Africa, which is currently ranked as the second largest emerging market [64], will play a significant role in both production and sales in the future. The automotive manufacturing industry in South Africa is a well-established and very important business sector. This industry and its contribution to the South African economy have grown rapidly over the past few decades and PricewaterhouseCoopers

[94] states that this growth will continue over the next ten years.

1.1 Automotive manufacturing industry in South Africa

The automotive manufacturing industry in South Africa employs a monthly average of 29,715 people, with a further employment of 82,790 people in the automotive component manufacturing sector [87]. The Automotive Industry Export Council (AIEC) reported in their 2015 Automotive Export Manual that this industry contributed approximately 7.2%, or R3,796.5 billion (ZAR, South African rand) to the total Gross Domestic Product (GDP) [67], confirming the importance of this industry to the South African economy. To date, there are eight light vehicle and sixteen heavy commercial vehicle manufacturers operating in South Africa. These OEMs are all involved in producing units for the local or export markets, or both. In 2014, 276,873 units were exported from South Africa, earning a total of R115.7 billion. Table 1.1 gives a comprehensive overview of all the major performance indicators achieved in 2014.

The impressive economic contribution of this industry in South Africa is not by chance. The units produced in South Africa are of very high quality, especially in the light vehicle manufacturing sector. Since the early 2000s, BMW and Mercedes-Benz have featured often in the top ranks of the prestigious J.D. Power awards [15, 82]. The J.D. Power awards serve as a guide for finding the highest ranked products or services in the USA. All J.D. Power circle ratings are based on the opinions of consumers and customers from a variety of industries who have used or owned the product or service being rated [56]. In 2015, BMW South Africa was awarded the platinum award for the world's best plant, which is the highest quality award that any production facility can achieve. The high quality output of the local production facilities has ensured that there is a large international market for units from South Africa. It is important that these production facilities produce high-quality units at a reliable rate to ensure their sustainability.

However, the problem in South Africa is not the quality, but rather the quantity,

Table 1.1: Performance indicators of South African automotive manufacturing industry in 2014 (adapted from Lampbrecht [67])

Indicator	**Performance**
South Africa's Gross Domestic Product (GDP) Broader	R3,796.5 billion
Broader automotive industry contribution to GDP	0.072
Vehicle and component production as % of South Africa's manufacturing output	0.302
Average monthly employment by vehicle manufacturers	29,715
Automotive component sector employment Capital	82,790
Capital expenditure-vehicle manufacturers	R6.92 billion
Capital expenditure-component sector	R2.7 billion
Total South African new vehicle sales	644,504 units
Total South African vehicle production	566,083 units
South Africa's vehicle production as % of Africa's vehicle production	0.68
South Africa's global vehicle production ranking South	24th
South Africa's global vehicle production market share	0.0063
Total automotive export earnings	R115.7 billion
Automotive export value as % of total South African export value	0.117
Number of export destinations	148
Number of export destinations with export values more than doubling year-by-year	25
Top automotive country export destination in rand value terms	Germany
Total South African vehicle exports	276,873 units
Total value of vehicle exports	R70.0 billion
Top vehicle export destination in volume terms	UK
Total value of automotive component exports	R45.7 billion
Top automotive export component category in rand value terms	Catalytic converters
Top automotive trading partner in rand value terms	Germany
Top automotive trading region in rand value terms	EU
Top country of origin for total automotive imports in rand value terms	Germany
Top country of origin for vehicle imports	India

of production output. Achieving constant high throughput rates in South Africa is not always an easy task, especially when considering the political and socio-economic conditions. Activities such as strikes and power outages cause production facilities to lose volume, which has dire financial implications. It is critical that the automotive production system itself does not contribute to any further volume losses.

1.2 Automotive production system: How a vehicle is born

In 2008, a German OEM launched a new light vehicle project for their existing production facility in South Africa. An example of a new light vehicle project is illustrated in Figure 1.1. It can last 6–12 years and is divided into three main stages: the three year *planning stage*, one year *installation stage*, and 1–7 year *series production stage*. The series production time period varies with the product and OEM. This thesis focuses on BIW production line design, which mainly occurs during the planning stage, or, more specifically, during the project premise phase and system design and simulation phase. It is during this stage that most of the important decisions about the specific production line are made. OEMs will usually give much attention to this phase to ensure that correct decisions are made.

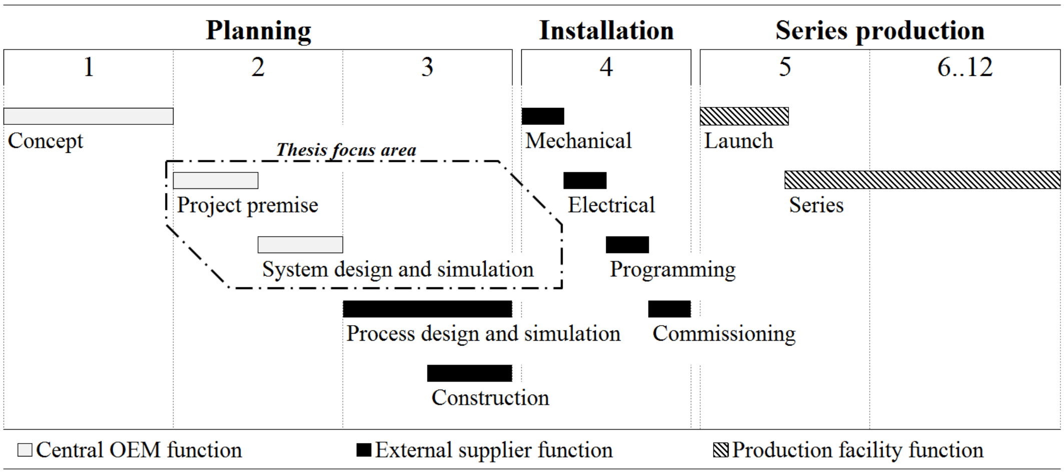


Figure 1.1: Twelve year light vehicle project life cycle for production facility.

The new project in South Africa was a successor product project. A successor product is a product that succeeds the current product; for example, the successor to the Audi B8 (2009–2015) product, commonly known as the Audi A4, was the B9 (2015–2021), i.e. the new Audi A4. The Audi C7 (Audi A6) would not be considered a successor model because the architecture of the A4 and A6 are not compatible. Therefore, it would not be possible to integrate the A6 into the production line for the A4, or at least it would be extremely complex and expensive. A successor product is normally integrated into a production facility's running production lines because it aids in reducing the required capital investment of the project. This allows for the maximisation of profits, which is one of the main reasons why successor products are normally chosen for production facilities. For the South African project, the number of changes and their level of complexity varied throughout the entire light vehicle manufacturing process. This manufacturing process, which is illustrated in

Figure 1.2, is divided into three sub-processes.

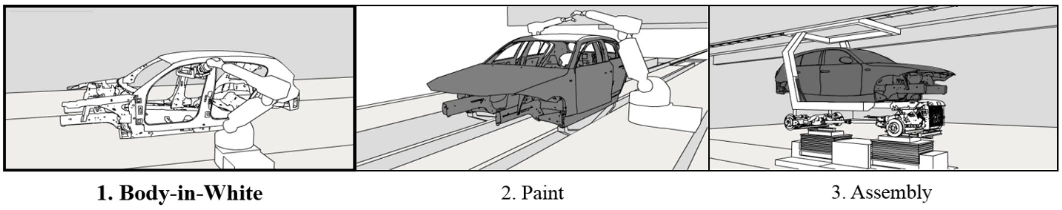


Figure 1.2: Light vehicle manufacturing process [14]

BIW: The first step in creating a light vehicle is to create its steel structure or skeleton. This is done by joining metal parts. The finished product is an unpainted silver greyish body with a plain metal form. The body is referred to as 'white' because of the absence of paint, indicating that the body is still clean, hence the name 'Body-in-White'. The BIW process is sub-divided into six main process steps, as illustrated in Figure 1.3. Five of the six process steps are parallel production lines.

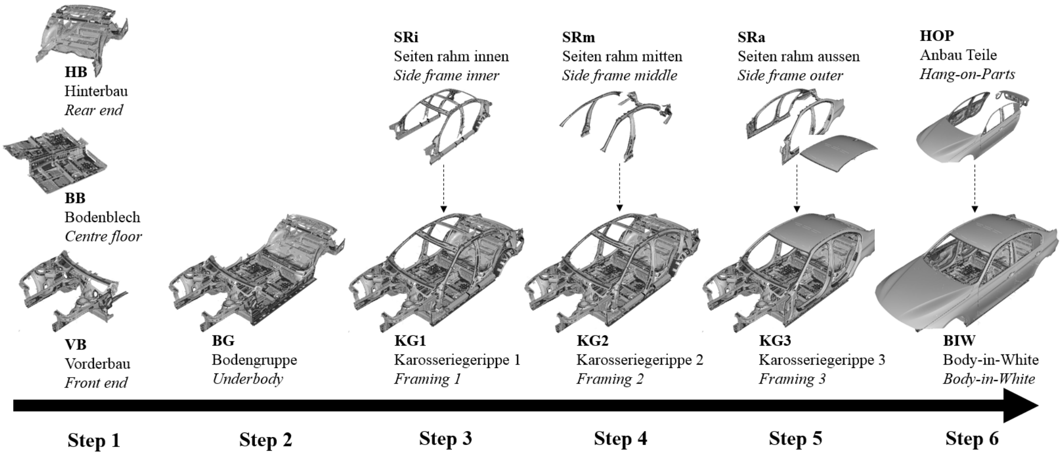


Figure 1.3: Six main process steps of BIW process

Paint: The next step is the paint process, where the BIW moves through several chemical and paint processes. These processes include metal cleaning, the application of corrosion protection, and the painting of the complete body. The final product is known as the painted body.

Assembly: As with the BIW and paint processes, there are several processes in the final manufacturing step. The assembly line is responsible for fitting the painted body with standard vehicle components, such as carpeting, seats, and the engine. The final product is the completed light vehicle that is ready for shipment to a customer.

In the South African project, the BIW process was the most affected by the complexity and quantity of the changes. Integration into the existing production lines was considered risky because of the abnormal architectural and structural differences between the two products. As previously mentioned in this thesis, we focus on the **BIW** process (Figure 1.3) during the **planning stage**, with an emphasis on the *project premise phase* and *system and design phase* (Figure 1.1).

1.3 BIW automotive production system: Planning stage

The project's *concept phase*, which is the first step in the planning stage, started in South Africa in the midst of a worldwide recession. The sub-prime lending problem in the USA initiated worldwide credit restrictions, which caused sales in the automotive industry to decline [11]. This decline in sales had numerous negative effects on current and new projects. The financial pressure forced additional investment restrictions onto new projects. The integration options for the new project in South Africa were limited because of these restrictions. During the *concept phase*, the project team had to achieve a basic three-point strategy: a) the development of a run-out plan for the current product, b) development of an integration plan for the two products, and c) development of a launch plan for the new product. The overall strategy gave the project team their initial direction. By the end of 2008, these three strategies were defined for the South African project.

In the first quarter of 2009, as planning moved into its second year, automotive sales plummeted to a thirty year low [11]. The automotive manufacturing industry, which is also the economic backbone of Germany [124], was severely affected by this lack of sales, causing German OEMs to tighten their budgets further as capital dried up [52]. This crisis created an extremely tight budget for the BIW project team. The changes to the BIW production line covered almost 80% of the entire project scope. More than 50% of the required BIW production lines had to be new, whereas complex integration was required for the rest of the production lines. The tight financial budget forced the Germany OEM to search for alternative methods to reduce their investment in the new BIW project.

By mid-2009, the *project premise phase* was concluded, and the project premise for the BIW project was defined. The goal of a project premise is to provide engineers and planners with concrete information and definitions that can be used during the design and planning process, ensuring that all of the team members are working towards the same common design. Table 1.2 provides a comprehensive overview of a typical premise sheet, with the responsibilities for each specific premise defined.

Table 1.2: Overview of project premise sheet with responsibility attached to each premise.

No.	Premise	Responsibility
1	Project title and description	Strategic team for new projects
2	Number of units required over life	Strategic sales analyst
3	Launch curve	Strategic sales analyst
4	In-house assemblies	Strategic team for new projects
5	Assemblies to purchase	Strategic team for new projects
6	Production facility location	Strategic team for new projects
7	Integration	BIW product integrator
8	Structures	BIW structure planner
9	Layouts	BIW process planner
10	Material flow	BIW process planner
11	Secondary functions	Production facility management
12	Conveyors	BIW structure planner
13	Working time and shift model	Production facility management
14	Throughput target	Strategic team for new projects
15	**Net ideal cycle time**	**BIW system design engineers**
16	Overall equipment efficiency (OEE) target	Strategic team for new projects
17	**Buffer system**	**BIW system design engineers**
18	Technology standards plant engineering (mechanical/electrical)	BIW technology standards engineer
19	Process engineering	BIW process engineers
20	Maintenance of data	Production maintenance
21	Value orientation	BIW process planner
22	Ergonomics	BIW process planner
23	Logistics	BIW logistics planner
24	Geometry/measurement	BIW geometry planner
25	Inspection equipment	BIW quality planner
26	Audit/quality management	BIW quality planner
27	Training	Production facility training team

There are two premises, the throughput target and Overall Equipment Effectiveness (OEE) target, that heavily influence two further premises, the Net Ideal Cycle Time (NICT) and buffer system design, which in turn heavily influence the overall production line design of the BIW facility. Estimating the NICT and buffer system design is the focus of this thesis.

Estimating NICT : The throughput target, or more specifically the Mean Throughput Target (MTT), defines the speed or rate at which the production line must produce units. The MTT, expressed in units per hour (uph), is a top-down figure that is estimated based on the expected sales over the lifetime of a specific product divided by the working hours of the specific production facility. For example, if the expected sales of a new product amount to 420,000 units over 7 years, based on the assumption that there are 250 working days in a year, a total of 240 units per day is required. The MTT is set according to the production facility's shift model; for example, for a 2 × 8 h operation, it is set to $\frac{240}{2\times 8} = 15$uph. The physical size and layout of the BIW production line is determined by the amount of equipment that is required to complete a process step. The amount of equipment is determined by the time available to complete the work content as specified by the product requirements. More available process time means less equipment, and vice versa. This process time is known as the cycle time, and is interchangeably referred to as the speed of the BIW production line. The maximum speed or NICT of a BIW production line is expressed in seconds (s) and calculated using Equations (1.1) to (1.3) [8, 111] :

$$TT = \frac{NAT}{MTT} \tag{1.1}$$

where Takt Time (TT) is the required time (in seconds) (s) needed to produce one unit to achieve the required MTT when the OEE is set at one. Net

Available Time (NAT) is the available time, in this case one hour, or 3600s. However, the OEE of a BIW is not set at one, but, in reality, normally ranges between 0.8 and 0.9. A final calculation is required to compensate for this efficiency loss [111]:

$$\begin{aligned} NICT &= \frac{OEE \times NAT}{MTT} \qquad (1.2) \\ &= TT \times OEE \qquad (1.3) \end{aligned}$$

This method for estimating NICT is standard in the automotive industry and was used for the South Africa project. The MTT for the BIW project was defined as 15uph. The NICT was estimated to be 204s.

Buffer system : The second premise, the OEE target, is another top-down calculated figure. An OEE of less than one indicates that the production line is not reliable, and that system losses will occur as a result of either availability, performance, or quality variations. An OEE of 0.85 is considered to be a world-class value [17], and it is used as the standard target for the reference OEM. Using Equation (1.4), the OEE can be calculated as follows:

$$OEE = A \times P \times Q \qquad (1.4)$$

where the world-class OEE is based on the assumption that the availability (A), performance (P), and quality (Q) of the production line will be 0.9, 0.95, and 0.99, respectively. The OEE target is an absolute indicator of the required efficiency of the equipment. Buffers are used to compensate for the OEE losses. A buffer system compensates for process variation in the production line by adding empty spaces where the Work-in-Process (WIP) can be stored temporarily. The goal of a buffer is to ensure uninterrupted production during unforeseen stoppages such as those that result from line adjustments and machine breakdowns. A larger buffer allows the production line to operate for a longer time during these stoppages. The Buffer Allocation Model (BAM) defines the required location and size of the buffers inside the production line. BIW system design engineers will search within the physical constraints of the production line for a BAM that will achieve the OEE target. Solutions are based on the results of previous projects and experience, i.e. heuristics. The project in South Africa was assigned an OEE target of 0.85, and the BAM was designed to achieve this value.

The *system design and simulation phase* started in the third quarter of 2009. In this planning step, the theoretical performance of a BIW production line is simulated, evaluated, and optimised until the MTT and OEE targets are achieved. In the South African project, two potential cost-saving measures on the commercial side underwent final evaluation in parallel with this phase. The first measure was to use a new Chinese supplier for the *installation stage*. Several risks were identified during this evaluation period. The new Chinese supplier had no work experience on the specific German OEM, and would be subject to a major learning curve. There was uncertainty regarding the Chinese supplier's ability to adhere to all of the OEM's design requirements and specifications. The second measure was the reuse of production equipment from other existing BIW production facilities that had reached their end of life. The reuse of equipment from project to project in the same production facility is common for BIW production lines, but equipment from completely different production lines in different countries had not been reused prior to this. The final evaluation phase was concluded, and both measures were approved. By the end of the fourth quarter in 2009, the *system design and simulation phase* were complete. The results indicated that the new production line would be able to adhere to the specifications of the planning premise. The speed of the production line, the machine sizes, and the buffer system were defined.

The year 2010 marked the final year of planning, and the system design and simulation phase was succeeded by the more detailed *process design and simulation phase*. During this phase, the external suppliers for the project were officially contracted. The main goal of the external suppliers was to design and simulate the production line at the process level. Figure 1.4 exemplifies the simulation of a process.

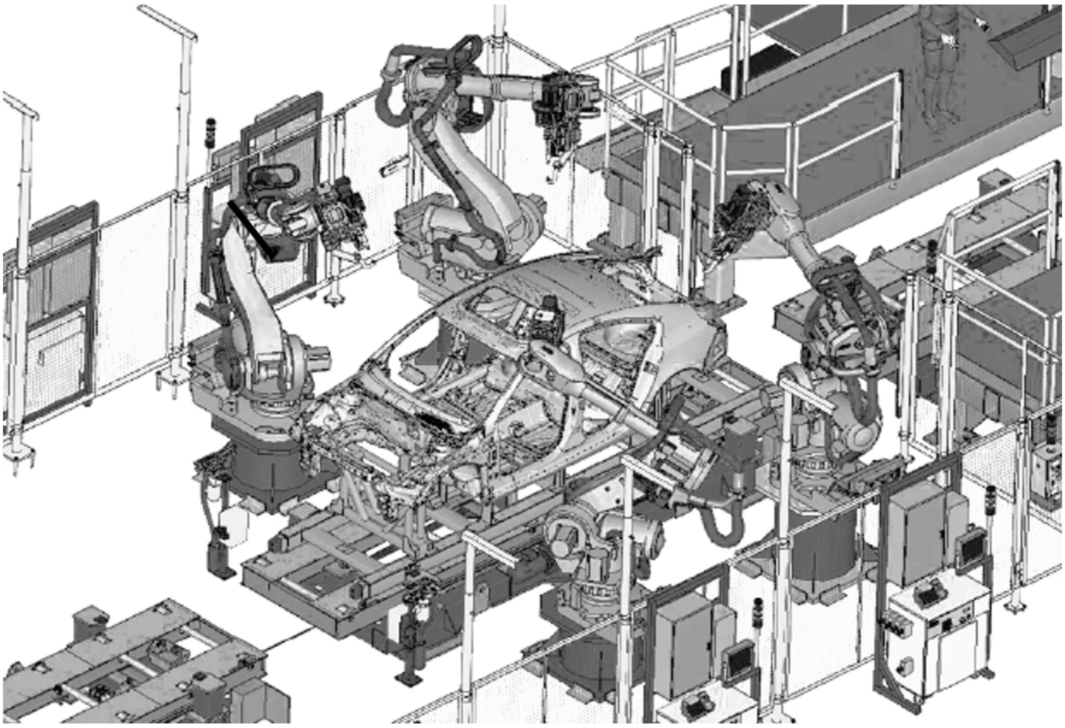


Figure 1.4: Example of detailed simulation of KG3 process line [26].

In this example, a KG3 unit is placed inside a production cell on top of a welding fixture between four industrial robots. The first step in this phase is to design the entire production cell in detail, including the welding fixture. A welding fixture is a special clamping unit that holds parts or assemblies stable during welding or gluing. This ensures that parts do not move during the welding or gluing process, which guarantees that a precise geometry and weld integrity is achieved. The second step following the design is the simulation. In this step, the location holes of the KG3 are compared to the location pins of the welding fixture. An exact match is required to confirm that the unit fits the fixture. The final step is to verify that the industrial robots can reach all the welding or gluing points, and that they can complete the process within the specified NICT.

In mid-2010, the Chinese supplier fell behind schedule with the simulation. Special actions were taken to assist the Chinese supplier to reach important milestones; however, most efforts failed. However, the *construction phase* started on time. The Chinese supplier was able to begin constructing the welding fixtures that had already been checked and signed-off by the OEM. The simulation was not on track to meet the deadline, and the OEM was forced to take extreme measures. The entire unfinished simulation content was moved to an alternative supplier to assist with increasing the simulation speed. Although the alternative supplier had made very good progress by the end of 2010, the critical target was not achieved. This meant that the installation of the BIW production line would start without confirmation that the new process was actually working. This had never occurred in the history of this specific OEM.

1.4 BIW automotive production system: Installation stage

In the beginning of 2011, the Chinese supplier shipped all of the constructed welding fixtures and tools from China to South Africa. The *mechanical installation* phase started only a few days behind schedule. The major concern at this stage remained the high degree of uncertainty regarding the functionality of the production line. Finally, the simulations were completed one month into the installation and showed that the production line would function.

The focus quickly shifted to the *electrical installation* phase, and by the second quarter of 2011, the installation stage was progressing far better than first anticipated. Unfortunately, this did not last. Most major automotive markets had stabilised and returned to normal levels after the recession, and sales were increasing relatively quickly. The South African production facility, which was still producing the predecessor in parallel to the new project, received a request to increase volume and build additional unplanned units for the predecessor's market. The requested volume would enable the production facility to achieve a record year in terms of units. The decision by the OEM and production facility to accept and produce these units was made almost instantly. This caused numerous unforeseen problems. All of the efforts and resources were allocated to the production of the predecessor, with very little focus on the new project. It was planned that at least half of the maintenance personnel would help the Chinese supplier to finish the installation phase. This would have increased the installation speed and ensured that the maintenance personnel were trained in the early stages on the new production technologies.

Further misfortune followed. During an unplanned installation audit, it was discovered that the Chinese supplier was six weeks behind schedule with the electrical installation. This led to a considerable contractual disagreement between the Chinese supplier and its electrical sub-contractor. This disagreement caused the project to lag even further. Unable to break the deadlock, the Chinese supplier ended the contract with its electrical sub-supplier. The electrical installation was not completed. The Chinese supplier was unable to find a new electrical sub-contractor within the allowable time frame. The only remaining option was to hire freelancers. This addition of freelancers from all over the world added a new complex dimension to the project. There were suddenly more than ten different nationalities on the installation site. Thus, there were more than ten different languages being spoken on-site. Amidst these communication problems, the Chinese, South Africans, Germans, and the new freelancers attempted to complete the project. By mid-2011, the *programming* phase started. The objective of this phase was to program all of the industrial robots and Programmable Logic Controllers (PLCs) to autonomously operate the production lines.

In the last quarter of 2011, it was clear that the project deadlines would not be met. The project was under extreme pressure. The *commissioning phase*, which was the last part of the installation phase, involved the testing of the entire production system. This phase could not start because the programming of the industrial robots and PLCs had not been completed. The Start of Production (SOP) date drew increasingly closer. The SOP is a fixed date and is the most important milestone in a project, with the project required to deliver units starting on this agreed-upon date. The last chance for the team to catch-up was during the South African holiday season in December.

1.5 BIW automotive production system: Series production stage

The SOP for the new project was planned for the middle of January 2012, with a *launch* phase spanning three months. It is normal for a project to have a launch phase spanning three to six months. The launch phase is the first phase of the *series production* stage. During this phase, machines are slowly brought up to speed. This is an opportunity for the production line to slowly mature while attempting to achieve its OEE target. After the launch phase, it is expected that the production line will perform at full speed.

After four years of hard work and preparation for the new project, the moment of truth finally arrived. The BIW production team was ready to start the new BIW production line for the first time. The target for the first week was 25 units, i.e. five units per day, which was not a highly demanding target for a 15uph production line. This was a complete failure. By the end of the first week, not even one unit had left the BIW Finish (AF) line.

The lines had not yet been completely commissioned; the maintenance personnel were not trained; and the Chinese supplier had returned to China. A significant challenge awaited the BIW production team. It was two weeks before the BIW production team was able to produce the first good unit. The daily volume target was increasing daily. Although the performance of the production line was increasing, the rate of increase was considerably less than that of the increasing daily target.

In the second quarter of 2012, the *launch* phase was over. At this stage, the production lines were supposed to be producing at full capacity. However, this was not the case. The BIW production team had made good progress, but remained in a difficult situation after only three months of production. They needed to improve the lines over the weekends; however, the lack of output resulted in weekends being allocated for additional production to compensate for the lost volume during the week. The most obvious problem in the production line was that the Mean Time Between Failures (MTBF) was low, and the Mean Time to Repair (MTTR) was very high, indicating that the Availability (A) of the line was not achieved:

$$A = \frac{MTBF}{MTBF + MTTR} \tag{1.5}$$

The exact cause of the problem was unclear. It may have been a result of the maintenance personnel not receiving the required and planned training, the reuse of equipment from older production facilities with inferior machine availability, the poor quality of the project delivered from the Chinese supplier, or a combination of all of these. The root cause of the problem was not obvious. One additional issue that raised considerable concern was the NICT. The actual cycle time of the production line was well within the planned specification. Yet, during times with almost no production stoppages, the production line still failed to achieve the planned MTT.

The BIW production team was plagued with breakdowns. A breakdown is defined as an unplanned production stop during the normal production time. The most common breakdown in the BIW environment is spot welding errors, because this is the most common joining technology used on a BIW production line. There could be between 5,000 and 8,000 spot welds on a finished BIW.

The spot weld process is illustrated in Figure 1.5. A spot welding gun is connected to the arm of an industrial robot. It has two copper electrodes connected

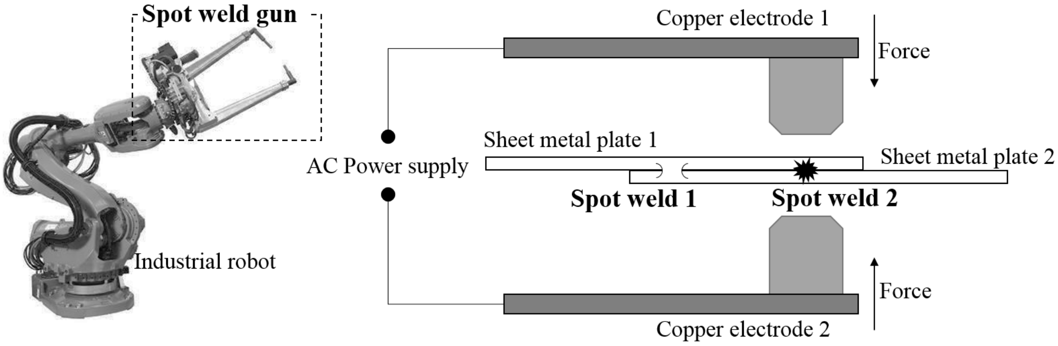


Figure 1.5: Spot welding process.

to either side of the gun. The gun is moved by the robot in such a way that the two steel plates are located between these two copper electrodes. The first step in welding is to press the two copper electrodes towards each other with a high force, typically 3.0–6.0kN. This grips the steel plates in the same manner as pliers. In the second step, a very high current is sent through the copper electrodes. The current causes a high temperature that instantly melts the steel. This entire process is executed in less than 2s.

Many BIW specialists refer to the BIW production line as ‘The Kid’. This is because, similar to a child, time is required for the BIW production line to grow and mature. As in parenting, hard work, discipline, and very good decision-making are required to mature a production line. The BIW production line in South Africa was not considered a kid, but, rather, a problem child. The fight for maturity continued for the next twelve months.

In mid-2013, the BIW management team was changed. A highly experienced BIW manager was relocated from Germany to South Africa to solve the production problems. He brought with him a team of German production specialists. The function of these temporary specialists was to analyse the production line and propose solutions to increase the throughput. Three key solutions were identified: a) further training of maintenance personnel, b) reduction of the NICT, and c) increased buffers. Weekend production was soon cancelled, and the specialists were allowed inside the production line to make the required improvements.

The greatest opportunity for production line improvement presented itself in the middle of the third quarter of 2013. Metal workers in South Africa went on strike, and the BIW production line was stopped for eight weeks. This was a major opportunity to improve the production line. Three international automation specialist suppliers were immediately contracted to assist with the improvement of the production lines. These three suppliers focussed only on NICT reduction. The local engineers focussed on increasing the buffer sizes between the six main BIW processes. The NICT was reduced by 10%, while the buffer sizes were increased by 1300% between Front End (VB) and Rear End (HB).

After this eight week strike, the BIW production team was presented with a second chance to determine whether their efforts, which were conducted at great cost, had succeeded. The entire production network was focused on South Africa. In the first week of October 2013, the BIW production line was restarted. For the first time in almost two years, it succeeded in achieving the daily volume target for an entire week. The improvements were immediately visible. The production targets were achieved for the first time in the project. Finally, the twenty month launch was over.

1.6 Problem statement and research questions

After the success of the 2013 project in South Africa, BIW system design engineers were left with a serious question: although the actual system was not the same as the original system design, how was it possible to deliver the same throughput? The BIW system design engineers identified two key issues that were the most likely causes of the difference between their theory and practice. Unfortunately, these two potential problems, the estimation of the NICT and the buffer system design, were never formally investigated. There are always new projects, and BIW system design engineers move very quickly from one project to the next, never having the chance to reflect deeply on previous production line designs or problems. It would be ideal to allocate small time windows between projects to address any problems or concerns that arose during the project, as a sort of *lessons learned* approach.

There are several concerns when considering the current method to estimate the NICT. First, the lack of research surrounding NICT estimation suggests that the current method has not yet been investigated in detail. Knowledge and an understanding of this method are limited, aside from the fact that it has been used for a very long time. In short, this method has not been challenged or critically evaluated in either practice or theory. Furthermore, the current method is highly static; there is no provision for uncertainties, and it does not allow or consider any process variations caused by real production lines that are not included in the OEE losses. Therefore, the current method focuses considerably more on theory than it does on practice. Finally, there is currently no alternative method to estimate the NICT. This means that BIW system design engineers are limited to utilising this one method for NICT estimation. Having alternative methods would not only provide more options, it would also contribute to a better understanding of the current method.

The second problem in South Africa was the buffer system, which was inadequate in supporting the production system, and also very difficult to expand as a result of physical space constraints. The buffer system was designed only for larger assemblies such as Under Body (BG) and KG3 units. Expanding the buffer system required considerable additional space, as well as high-cost conveyor systems. Buffer systems must enable a production line to achieve its target OEE. Ideally, they must be as small as possible and inexpensive; the WIP should be limited, and the location should hold some strategic advantage for future expansion. Yet, this is not the method used in practice. Heuristics, based on project experience, is the most common method employed by BIW system design engineers when designing BIW buffer systems. The focus is purely on achieving the target OEE, followed by some simulation-based optimisation to increase the efficiencies of the initial designs. There is no focus placed on other objectives that are considered important for a BIW production line design.

The project in South Africa was considered to be a victim of misfortune; the case was closed, and the questions remain unanswered.

1.7 Research objectives

To prevent a repetition of the project situation in South Africa, it is important to revisit these questions and provide adequate answers so that we can truly understand the faults of this BIW production line. Therefore, this research is divided into two sections.

In section one, the current method of estimating the NICT is studied, critically evaluated, and challenged. Anomalies are highlighted, described, and finally explained. The next issue addressed is the fact that the current NICT estimation method does not cover the process variation found in a practical production environment. This gap is closed by understanding how uncertainties can influence the estimation accuracy by specifically narrowing, quantifying, and explaining the variation, creating an opportunity to improve the current method. The primary intent of this section is to develop an alternative method to estimate the NICT. This will provide BIW system design engineers with at least two options when estimating the NICT. The objective is to define a new method based on empirical data to estimate the NICT, which then encapsulates the uncertainties in the estimation process by basing the NICT on the actual performance characteristics of a relevant BIW production line. The proposed method will be benchmarked against the current method in terms of the throughput and financial investment using the reference production line.

The second section of this research deals with buffer allocation, specifically with the BIW production line in mind. The research first studies the Buffer Allocation Problem (BAP) in general to understand and give context to buffer system design in BIW production lines. Next, the important buffer design objectives and requirements for a BIW production line are studied and defined. The competition for location and trade-offs are explained. The objective is to create a method for evaluating the efficiency of a BIW buffer system design based on multiple objectives using the efficient frontier. The proposed method will compare and benchmark existing production lines to evaluate their buffer system efficiencies.

Both topics are infamous for inducing strict expansion constraints on the basic blueprint of an entire BIW production line. It is the purpose of this research to better understand the questions and answers by providing BIW system design engineers with better methods to estimate the NICT, and establishing an evaluation tool that assists in decision-making for BIW buffer system design.

1.8 Research design

Creating new or improved methods and models is not only important for BIW system design engineers, it is also a highly important goal in design research. Manson [77] stated that design research includes usage and performance analyses of designed artefacts with the purpose to understand, explain, and improve the behaviours of their aspects. Therefore, following a design research philosophy can first ensure that the entire research process and the results produced during the work on this thesis are considered *research*, and second, that the deliverables can also be used in practice, providing BIW system design engineers with these improved design methods and models. Although the end-objectives for both BIW design issues are the same, new methods or models, the paths differ.

1.8.1 Estimating NICT

Estimating the NICT is a specialised subject, and for the purpose of this research, it can be confined to production systems. Therefore, the majority of the focus will be placed on critically reviewing the literature on the cycle time for production lines. The goals are to understand what has previously been studied and how the proposed study fits into the greater scope of cycle time research, and then to clearly confirm that what this research is trying to achieve has not previously been attempted. The literature review contains an in-depth analysis of the current method, including a discussion of the mathematical functions that make up this method and an investigation of the throughput distribution. The purpose of the literature review is to provide a solid theoretical base from which the new work can start.

The major contribution of this research is the development of a new method for estimating the NICT based on empirical data. The empirical data of a real BIW are studied to understand and completely define the throughput distribution of a practical BIW production line. This allows the research to highlight the differences between theory and practice, enabling a clear direction for further investigation and exploration. The aim is to understand the difference between theory and practice, and to quantify the differences and provide them with concrete definitions. Understanding the differences between theory and practice enables the research to search for an alternative method to compensate for the gap between them.

The main objective is to develop a new estimation method that considers the empirical throughput distribution of an actual BIW production line. The proposed method is classified according to Pidd [93] as *modelling for investigation and improvement*. Pidd [93] stated that the aim of these types of models is to bring a more defined rationality and consistency to processes that are too complex for humans to understand without model support. The proposed method will reduce the risk of incorrect NICT estimation by allowing for uncertainty in the estimation process, which is currently not possible with the state of practice method. The reduction in risk confirms that an improvement from the state of practice method to the proposed method was achieved. To conclude this subject, a comparative evaluation of the two methods is conducted, taking into account how the new method potentially influences important factors such as the financial investment and physical space requirements.

1.8.2 BAM for BIW production line

Unlike the estimation of the NICT, that of the BAP is a very well-explored research problem. The first step in this work is to study the BAP and the current methods that are used to solve it. The aim of this study is to establish what research has been conducted on BIW production lines in particular, as well as to determine multi-objective methods for solving the BAP to provide a solid base to start the proposed research.

The main enabler of this research is the exploration and understanding of the important BIW production line requirements regarding buffer design. Through simulation, which is later justified, the effects of using buffers in different production locations are studied. This is followed by a discussion of buffer types and their costs, or more specifically, the possible locations for their use inside a BIW production line and their potential costs. Next, an in-depth look at product size is undertaken to establish how the buffer space can be minimised by finding efficient buffer configurations to minimise the physical footprint of the buffer system. Next, in this section, the WIP and its relationship with buffer systems is studied. Once the four subjects are understood, an efficient solution is proposed.

It is important that the solution of this section be evaluated. A model is developed based on the proposed efficient solutions. The pinnacle of this research is achieved when the new model is compared to two real BIW production lines. This is done through simulation, and the evaluation criteria are based on the four important BIW production line requirements using a multi-objective approach. The results provide insight on how the capabilities of the proposed efficient solutions can improve the buffer design in practice.

The proposed model is classified according to Pidd [93] as *routine decision support*. Pidd [93] stated that these types of models must assist, yet not replace, people making routine, repetitive decisions. Buffer allocation decisions in BIW buffer design is a repetitive task because there are many new projects each year for the different OEMs. The proposed model will assist BIW system design engineers with a variety of efficient solutions that they can use as references for finding the solution that will best fit their project in terms of a specific set of objectives. Finally, the output of this research is the generation of new knowledge through the creation of artefacts, with their effectiveness systematically and rigorously analysed.

1.9 Outline of thesis

The two BIW production line design issues, estimating the NICT and BIW buffer design, form the basis of this thesis.

First, chapter 2 is divided into two sections. In subsection one, the cycle time research domain is investigated. A comprehensive overview of the current research is provided, which, in turn, is critically reviewed. The cycle time research scope is defined, and an explanation is given of how the current subject, estimating the NICT for a BIW production line, fits into this framework. In subsection two, the BAP is explored. The research focuses on the problem by placing emphasis especially on the relevance of this problem in relation to BIW production lines, as well as multi-objective-based research. The research scope is again defined, with a clear indication of how the BIW production line fits into the bigger picture.

In chapter 3, the thesis focus shifts to understanding the throughput distribution of a BIW production line. The throughput data of the South Africa BIW production line are used to achieve this. Based on the defined distribution, a new method is proposed to estimate the NICT of a BIW production line.

The focus of chapter 4 is the study of the effect of multiple objective buffer system design for a BIW production line. First, the criteria for evaluating buffer system efficiency using multiple objectives are proposed. This chapter further focuses on how objectives compete with one another, and how trade-offs must be considered. The final output of this chapter is a proposed efficient frontier for the BIW production line.

In chapter 5, the frontier from chapter 4 is evaluated. The frontier is used in two simulation experiments where the new model of efficient solutions is benchmarked against two real production lines. A comparative evaluation is the main output of this chapter, which confirms the hypothesis defined earlier in the chapter. It is proven that the frontier assisted in providing better solutions that increased the throughput of both BIW production lines, while decreasing their cost, space, and WIP.

Finally, chapter 6 provides the conclusion, along with a brief research agenda.

Chapter 2

Literature review

Net Ideal Cycle Time (NICT) estimation and buffer system design are two highly important design steps in the Body-in-White (BIW) planning stage. The NICT is independent of the buffer design; however, the inverse is not true. The buffer design is affected by the NICT because lower cycle times demand larger buffers. The buffer size of a BIW production line is typically measured in hours. BIW production facilities normally require at least an hour of buffering, e.g. between the Front End (VB) and Under Body (BG) lines. This means facilities with low cycle times, e.g. 45s, will require a buffer size of 80 VB assemblies to sustain an hour of production, whereas facilities with higher cycle times, e.g. 300s, will require a buffer size of only 12 VB assemblies. Although these two parameters are related, they will be treated as two separate and independent BIW design parameters in this research to ensure that each topic is understood fully on its own.

2.1 Estimation of Net Ideal Cycle Time

2.1.1 Overview

There are two important cycle time types that are used for BIW production lines: the Takt Time (TT) and NICT. The TT time is the average cycle time that a BIW production line must attain to achieve its Mean Throughput Target (MTT), whereas the NICT is the shortest cycle time, which is determined during the design of the BIW production line. Thus, there is a time window to allow for efficiency losses. The NICT is the TT influenced by the Overall Equipment Effectiveness (OEE), and is calculated using Equation (1.3). For example, a BIW production line planned at 15units per hour (uph), with an OEE of 85%, has its takt time at point A (240s) and NICT at point B (204s), as illustrated in Figure 2.1.

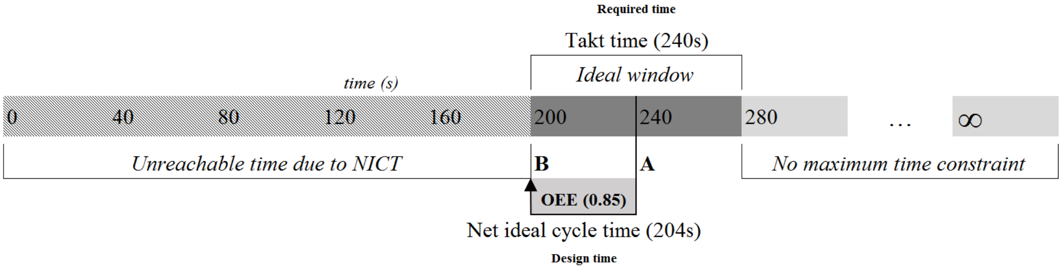


Figure 2.1: Net ideal cycle time.

Therefore, the NICT defines the minimum cycle time, or maximum speed at which the BIW production line can operate. However, there is no defined minimum speed, which translates to an undefined maximum time.

2.1.2 Cycle time in general

Cycle time research can be categorised into four main categories: *type*, *phase*, *goal*, and *methods*. Figure 2.2 illustrates this research domain by means of a morphological cast. The estimation of the NICT is plotted in the foreground to indicate the role of this topic in the current research domain.

Category one, type, deals with the application of the research. Researchers are either developing methods to *optimise* [34, 65] the cycle time of a system, or attempting to *estimate* [81, 129] the cycle time based on the production output. The limitations of cycle time research become clear when moving into the phase category. The focus of cycle time optimisation is purely *series production* systems; surprisingly, this is also true for cycle time estimation. The biggest industry focus of the phase category is the semi-conductor industry [3, 4, 34, 54, 65, 92, 112, 118, 136].

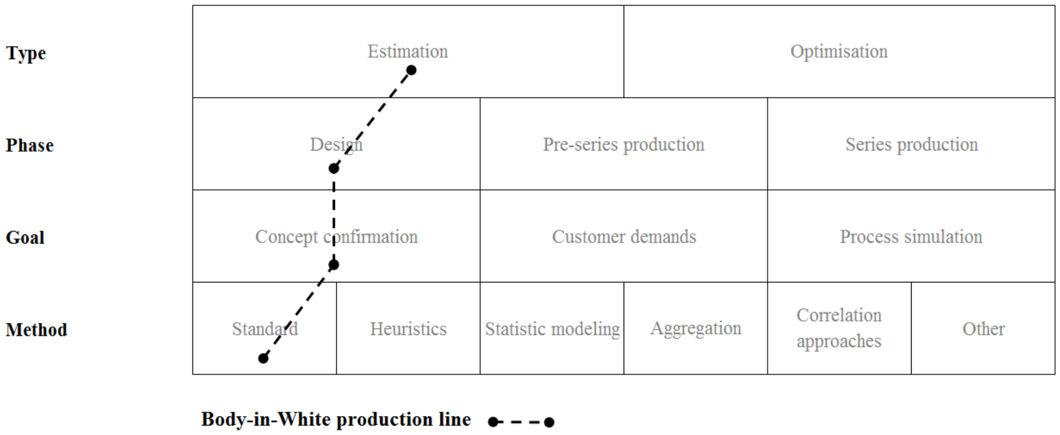


Figure 2.2: Cycle time research domain, including BIW configuration.

The common objective is to develop methods that can estimate the cycle time of either *pre-series production* [72] or *series production* [3, 136] systems to facilitate accurate output predictions. The results are intended to be used to compare system capabilities with customer demands and calculate whether the current system can meet those demands. Research on the *design phase* is difficult to find. This is unexpected because it should be the main focus of cycle time estimation for many production line types. Fortunately, there is a slight deviation from this focus area [83], where the relationship between the cycle time and production throughput is considered. It has been suggested that the cycle time throughput percentage of the production system could be used for strategic planning purposes. Simulations can then be used to test theories. In [129], the main assumption of their research was the use of a generalised gamma distribution to represent the underlying distribution of the cycle time. The use of a gamma distribution is interesting because distributions related to the cycle time are not often mentioned in the literature. Almstrom [8] and Stamatis, D [111] defined the state of practice method used to estimate the NICT. However, rather than assume a specific distribution uncertainty, they assumed that there was no uncertainty.

The goal and methods categories are dependent on the type and phase categories. This poses a problem because the critical phase category renders this type of research irrelevant to BIW production lines because there is no focus on the design phase. There is clear evidence that cycle time research has been conducted. However, a consideration of the four main categories, and all of the possible path combinations, shows that this research is clearly incomplete, particularly for the design phase of BIW production lines.

2.1.3 Cycle time estimation for BIW

The most relevant information providing insight into NICT estimation is the unpublished work of Langer [68]. Langer has spent approximately the last forty years in the automotive industry, working for various major Original Equipment Manufacturers (OEMs) in France and Germany. His involvement with BIW production lines occurs specifically during the design phase. Langer is included as an information source in this thesis for two reasons. First, credit must be given to Langer because it would be inappropriate to take credit for any knowledge, work, thoughts, and experiences that did not originate from this study. Second, some subtle suggestions from Langer are merely used in this thesis as a guide to expose tacit knowledge, and are not exhaustively detailed as recommended by Walker [123]. As a practitioner of BIW production line design, it is important to consider tacit knowledge, especially in this thesis where there is a strong connection between theory and practice. Langer explained that the actual recorded cycle times of BIW production lines follow the same distribution as the actual throughput, e.g. a normally distributed throughput has a normally distributed cycle time. This is because, in the core concept, their equations are identical, but their expressions differ.

There are currently no publications available that define the throughput or NICT distribution for a BIW production line. As a first attempt and only because it is an easy starting point, we will assume for the next part that the throughput distribution of a BIW production line is normally distributed and apply the three-sigma rule to it, as illustrated in Figure 2.3.

A normal distribution is described by its mean and standard deviation. The

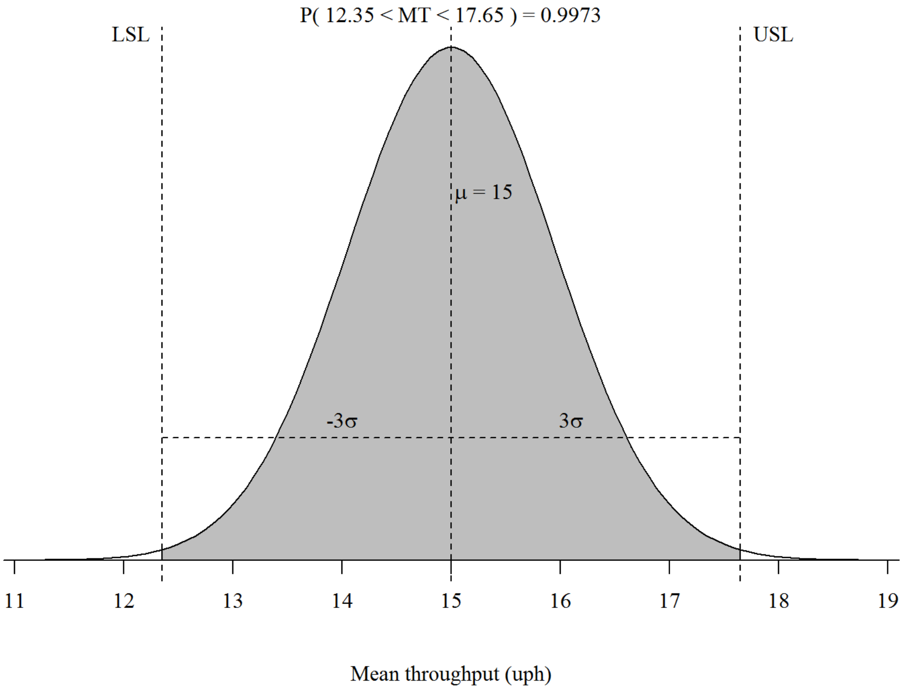


Figure 2.3: Throughput distribution of BIW production line fitted into normal distribution using three-sigma rule as starting point.

three-sigma rule is applied to determine the allowable deviation of the mean. The three-sigma rule is used in probability theory and mathematical statistics to account for the fact that 99.73% of all values should fall within three standard deviations above and below the mean [89]. The three-sigma rule is explained by equation 2.1:

$$P\{\mu - 3\sigma < X < \mu + 3\sigma\} = 0.9973 \tag{2.1}$$

For this to be true, using the example of a 15 uph line, the standard deviation for the actual throughput should be a very ambitious 0.95 uph. Whether the application of the three-sigma rule is correct can, for now, be considered irrelevant, because the purpose of the application is only to navigate through some basic ideas. Accordingly, the main goal is to determine whether this is an achievable and realistic target. The assumption of a normal distribution creates a unique and interesting situation. Because the throughput is now assumed to be normally distributed, this means that there is a performance window with a set Upper Specification Limit (USL) and Lower Specification Limit (LSL), to which the BIW production line should adhere 99.73% of the time. The USL and LSL can be calculated using Equations 2.2 and 2.3, respectively:

$$USL = \frac{NAT}{NICT} \tag{2.2}$$

$$LSL = MTT - (USL - MTT) \tag{2.3}$$

where NAT is the net available time for production.

The BIW production line is unable to produce more units than the USL, because this is the speed for which the line was designed; in other words, it is the equivalent of the NICT expressed in units per hour instead of cycle time. This also means that the BIW production line should not produce below the LSL because this will skew the distribution to the left and cause the mean to decrease. This concept is illustrated in Figure 2.4.

Figure 2.4 further illustrates how the throughput correlates with the cycle time. The Virtual Cycle Time Restriction (VCTR) is the equivalent cycle time for the corresponding LSL. This concept is further summarised in Table 2.1.

Table 2.1: Relationship comparison between throughput and cycle time for BIW production line with MTT of 15uph and OEE of 0.85.

Throughput (uph)		**Equivalent cycle time (s)**	
LSL	12.35	VCTR	291.5
MTT	15.0	TT	240.0
USL	17.65	NICT	204.0
Mean	15.0	**Mean**	245.2

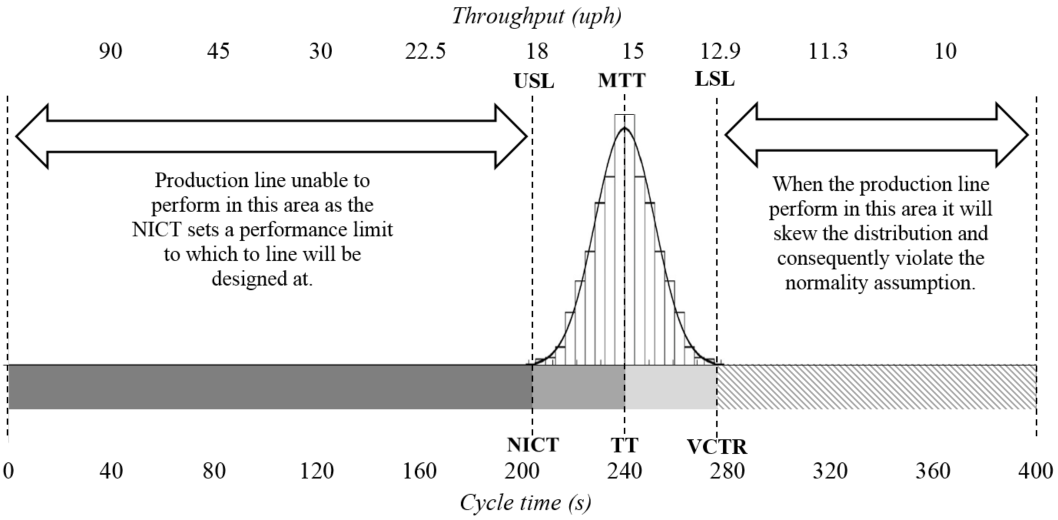


Figure 2.4: Normal distribution performance window for BIW production line with MTT of 15 uph and OEE of 0.85.

Although the above example is not completely realistic, it does highlight an important clue about the expected distribution, namely that it could be a right-truncated distribution. It is common for truncated distributions to occur or arise in industry [84, 134]. The above example is right truncated because there is a restriction by the USL that prevents values from being recorded beyond this point. Figure 2.5 illustrates the right truncation for a BIW production line with a MTT of 15uph and an OEE of 0.85, with a normal distribution throughput with standard deviations of 1,2, and 3.

It can be noted that the mean will decrease from the required 15 uph as the standard deviation increases. A simulation with the right-truncated function from the R [96] package `truncdist` [?] was completed 1000 times for each standard deviation (1–5) to investigate how much the mean decreases when the standard deviation increases. The results are displayed in Table 2.2.

Although it seems highly unlikely that the throughput distribution of a BIW production line will be normal, the actual distribution type is still unknown. The current method of estimating the NICT provides no clarity in this regard. A better understanding of the throughput distribution of a BIW production line will provide

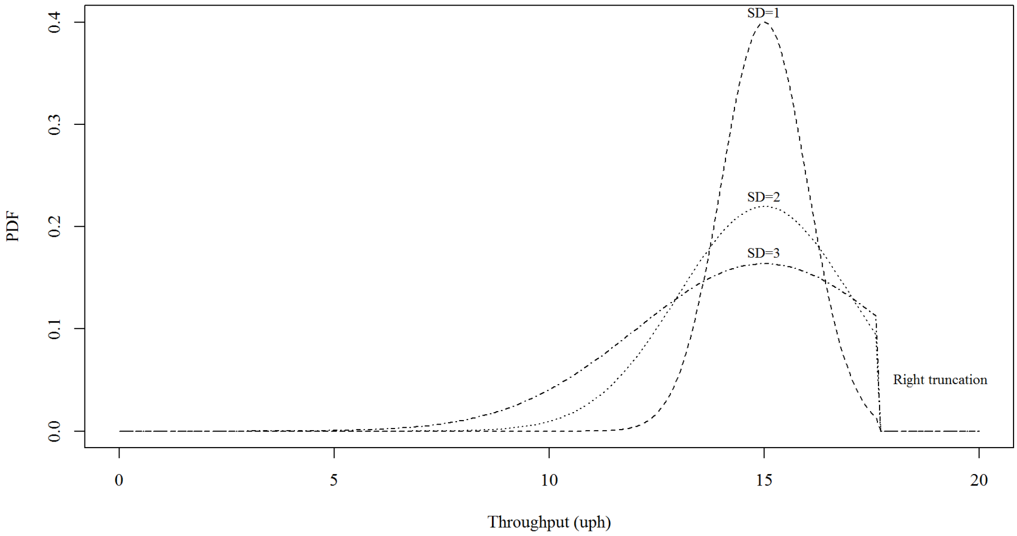


Figure 2.5: Right-truncated normal distribution for BIW production line with MTT of 15 uph and OEE of 0.85.

assistance in creating an improved method that estimates the NICT more accurately.

2.1.4 Conclusions

Although there has been some research regarding the estimation of the NICT, there are still unexplored areas in this research field. There are some hints that the throughput of a BIW production line will not follow a normal distribution, and it seems somewhat unrealistic to assume that it would because the performance might drop below the LSL. It is necessary to gain a better understanding of this subject, and studying the empirical data of a real BIW production line could provide much-needed information regarding the estimation of the NICT.

Table 2.2: Decrease in mean effect for BIW production line with MTT of 15uph and OEE of 0.85, with right-truncated normal distribution as standard deviation increases.

Standard deviation	**Mean throughput (uph)**	**SD of simulation**
1	14.99	0.98
2	14.63	1.70
3	14.00	2.31
4	13.28	2.91
5	12.55	3.46

2.2 BIW buffer allocation

2.2.1 Overview

Buffer systems are critical to in BIW production lines, as well as in the majority of all production lines. As Langer [68] states: *"Buffer does not produce anything, but without buffers, you will not produce anything"*. The importance of buffer systems can be explained using a very simple 1061 industrial robots production line example. Industrial robots have an availability in the range of 0.995–0.997 for spot welding (Figure 1.5), which is influenced by several factors. In this specific instance, an availability of 0.995 was used. The variation is caused by BIW specific conditions, such as the amount of new equipment vs. the amount of reused equipment. New equipment has a higher availability, set at 0.997, whereas that for reused equipment is lower and is set at 0.995. The question is asked: *"when considering a BIW system without any buffers, what would the BIW utilisation be for a system with 1061 robots, where the availability of each robot is set at 0.995?"*. This is answered using Equation (2.4):

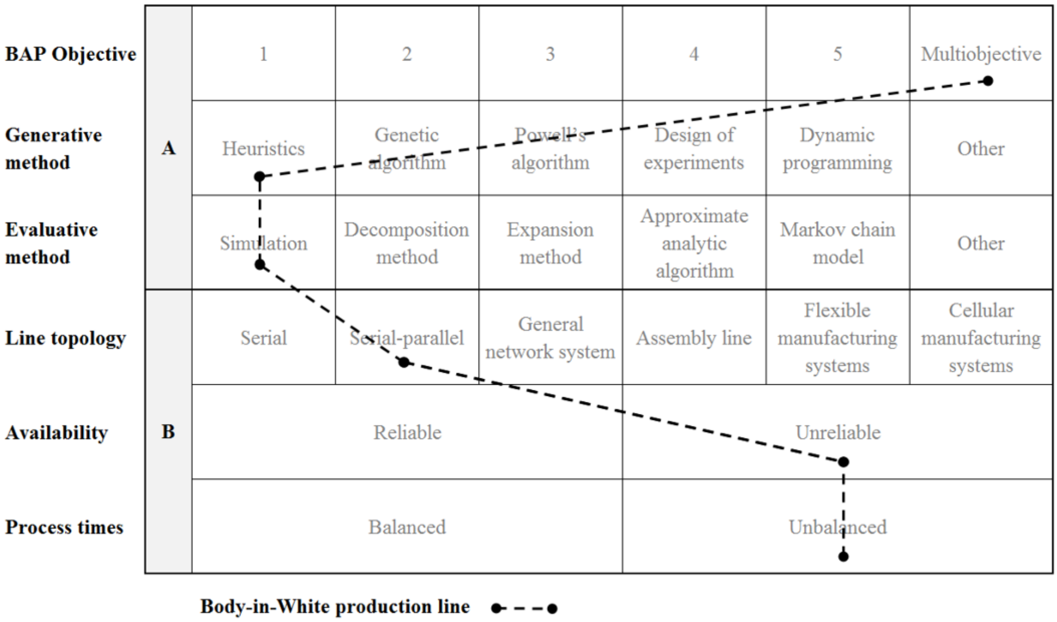
$$U_{BIW} = A_{IR}^{n} \tag{2.4}$$

where U is the utilisation rate of the BIW, A is the availability of each industrial robot, and n is the total number of industrial robots. When considering this example, the utilisation of this specific BIW is calculated using 0.995^{1061}, and is equal to 0.049. It is assumed that all of the industrial robots are utilised in series. However, this is clearly unrealistic, and it is certainly not the case for a BIW production line. Nevertheless, it is evident from the results that this project would not be able to produce any real output without a buffer system. The inclusion of a buffer system increases the throughput, because it increases the OEE of the production line.

2.2.2 Buffer Allocation Problem

Designing a buffer system for a BIW production line is a difficult task. The challenge is to design an efficient buffer system with the best possible Buffer Allocation Model (BAM) to support multiple objectives that are relevant to the requirements of the BIW production line. The optimisation and solving of this BAM for production lines with specific objectives is also known as the Buffer Allocation Problem (BAP). Demir et al. [39] defined the BAP as an NP-hard combinatorial optimisation problem and initially divided it into three separate problems: *Problem 1 (BAP1)*: Determine the maximum throughput rate for the production system given a fixed amount of buffers [27, 35, 36, 60, 62, 78, 86, 108, 114, 120]; *Problem 2 (BAP2)*: Determine the minimum buffer size for the production system to achieve a specific throughput rate [1, 10, 24, 36, 45, 69]; *Problem 3 (BAP3)*: Determine the minimum average Work-in-Process (WIP) for the production system given a fixed throughput rate and buffer size [5, 13, 71, 79, 97, 107, 132, 133]. The BAP has been expanded over the last few years, and two additional problems can be added to the list: *Problem 4 (BAP4)*, which is concerned with the maximum profit [41, 42, 78, 100, 104], and *Problem 5 (BAP5)*, which contains a variety of smaller specific topics with the goal of solving a specific single objective [1, 30, 80, 116, 131]. In this thesis, the BAP will be explored in terms of multiple objectives. Thus, we have the following: *Problem M-O (BAPM-O)*: Determine an efficient BAM for a production line using multi-objective criteria to evaluate the solution.

The BAP research domain can be divided into two sections, each consisting of three categories. This research domain is illustrated via the morphological cast in Figure 2.6. The six individual categories create the framework in which researchers generally classify their specific BAP research. The BAP for our BIW production lines is plotted in the foreground to explain the role of this subject in the current research domain.



BAP Objective	**A**	1	2	3	4	5	Multiobjective
Generative method		Heuristics	Genetic algorithm	Powell's algorithm	Design of experiments	Dynamic programming	Other
Evaluative method		Simulation	Decomposition method	Expansion method	Approximate analytic algorithm	Markov chain model	Other
Line topology	**B**	Serial	Serial-parallel	General network system	Assembly line	Flexible manufacturing systems	Cellular manufacturing systems
Availability		Reliable			Unreliable		
Process times		Balanced			Unbalanced		

Figure 2.6: BAP research domain, including BIW footprint.

Section A deals with the objective and solution methodology of the BAP, whereas *section B* describes the specifics of the production line that is considered (*line topology*, *availability*, and *process time*).

The main goals of section A are to define a clear objective and specify the method of achieving this objective. BAP research generally follows the same approach, using an iterative process to solve the targeted problem, as illustrated in Figure 2.7,.

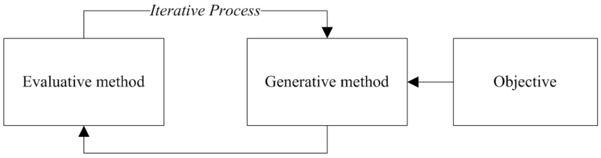


Figure 2.7: Iterative process to solve BAP

The *generative method* (constructive heuristics) is used to generate a possible solution for a specific objective. In this research, the evaluative method plays a more prominent role because this is where the new multi-objective criteria are introduced during the design of a BAM for a BIW production line. The main generative method for this research is *heuristics* [108, 119, 133]. The required solution should allow for practical experience and historical project information, and should be multi-objective compatible. Thus, heuristics is a very appropriate method because it can consider the combination of these complex objectives. Other methods such as *dynamic programming* [40, 55, 128], *meta-heuristics* [41, 42, 61, 62, 69, 86, 95, 114, 127]), and *Powell's algorithm* [32, 75, 76, 117] do not allow for the specific input requirement stated in this research.

The *evaluative method* is used to evaluate the generative method. The current BIW standard is *simulation*. Further, simulation is the most popular evaluative method in BAP research [10, 27, 60, 62, 88, 97, 108, 114]. Simulation is the most feasible method for testing complex BIW production line designs in terms of the interface, ease of use, speed, and cost. However, simulation is not the only evaluative method used by researchers. There are interesting alternative methods available, such as the *decomposition method* [35–37, 46, 78, 85, 86, 104], *generalized expansion method* [5], *approximate analytic algorithm* [25, 49, 55, 59, 107], and *Markov chain models* [22, 51, 53, 91, 120, 135], along with some *unique* individual methods [1, 13, 45, 79, 95, 133]. Simulation is used as the main evaluation method for this research for two main reasons. First, simulation is well supported by the industry. Thus, this method is more developed commercially and receives far more design input from customers such as OEMs and academics, ensuring a high quality method. Second, simulations can be used to model highly complex resources such as the conveyors in manufacturing systems, which is not possible with other methods [125].

Section B defines the specific production line and its characteristics. The fourth category of the BAP research domain, the *line topology*, is subdivided into six production line topologies. The line topology defines the actual production line configuration studied, and it is clearly defined in almost all of the research. The most common topology is the *serial* production line [1, 25, 27, 35–37, 60, 62, 78, 97, 104, 119, 120], which is illustrated in Figure 2.8. The S characters in the circles denote production *stations*, while the B characters in the blocks represent the *buffer* areas. This type of topology is the most basic production line type studied in the BAP domain. The most basic assumption with this line type is that the first station is never starved, while the last stations are never blocked, which is also the case when simulating a BIW production line. The greatest advantage of studying this basic topology is that it provides a very good understanding of how buffering affects the behaviour of the production line throughput in various locations. Although there are some similarities between a BIW production line and the *serial* production lines, the BIW production line has different additional parallel processes. The parallel process flow creates a larger number of and more complex solutions for the BAP in a BIW production line.

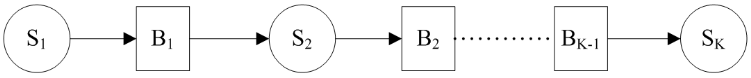


Figure 2.8: Serial production line topology.

A topology that is somewhat similar to that of a BIW production line is the *serial-parallel* production line [10, 32, 41, 42, 45, 61, 79, 85, 86, 95, 101, 108], which is illustrated in Figure 2.9. The BIW production line is illustrated in Figure 2.10.

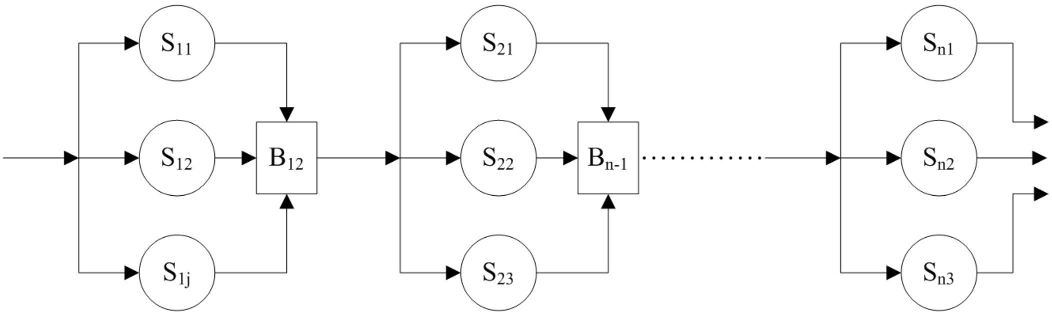


Figure 2.9: Serial-parallel production line topology.

A visual comparison of the parallel stations in series shown in Figures 2.9 and 2.10 shows an easy connection between the two. The BIW production line BAM illustrated in Figure 2.10 is derived from the BIW production line process steps,

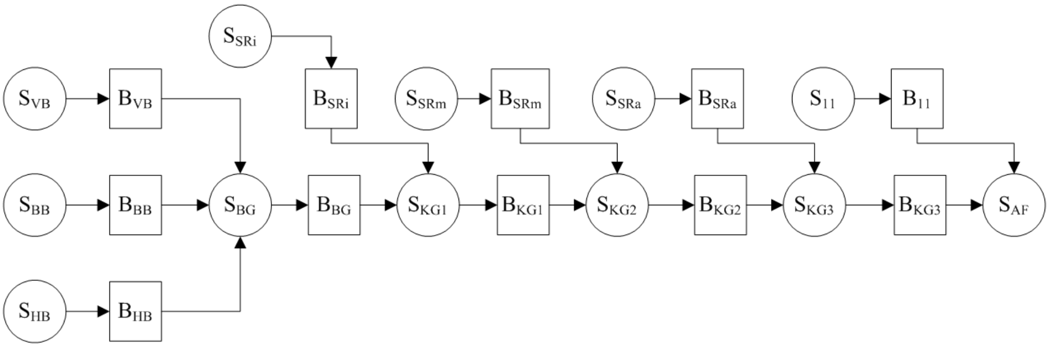


Figure 2.10: BIW production line topology.

which were defined earlier in Figure 1.3. Although the BIW production line is categorised as this topology type, no exact match was found in the literature. Research tends to be focussed on queuing networks [32] or tandem production lines [42], where there are two or more serial lines in parallel. These line types do not follow the serial-parallel topology of BIW production lines, where the parallel and serial processes are mixed together. The topology of the BIW production line is unique. For instance, *general network systems* [28–30, 71, 73, 95, 117, 131], as illustrated in Figure 2.11, only deal with queuing systems in general, and the absence of mixed parallel and serial processes is also evident. *Assembly* production lines [9, 13, 16, 24, 86, 103, 113, 114, 121] tend to be highly serial orientated, while an *Flexible Manufacturing Systems (FMS)* [30, 66, 110, 115] and a *Cellular Manufacturing Systems (CMS)* [5–7, 30, 70], as illustrated in Figure 2.12, vary too much in terms of structure.

Although the BIW production line topology is very important to solve the BAP accurately, it is not the only important criterion. The next category in the BAP domain deals specifically with the availability of a production line. This category is split between *reliable* [6, 7, 19, 20, 29, 30, 50, 76, 80, 102, 110, 117, 135] production lines, meaning lines with 100% availability, and *unreliable* [1, 10, 13, 27, 36, 37, 45, 60, 62, 79, 86, 88, 97, 108, 114, 120] production lines, meaning lines without 100This split is unexpected because the initial assumption would be that any reliable production line would likely not require a buffer system because there would be no efficiency

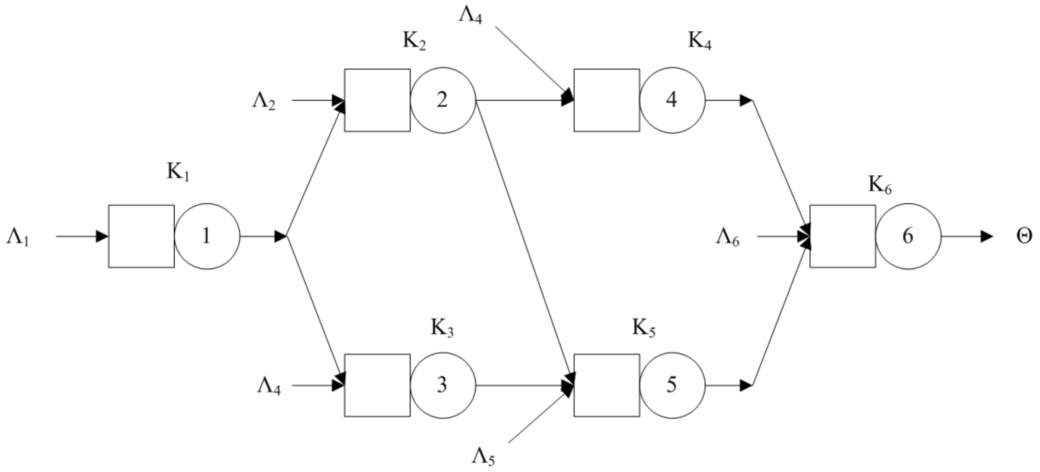


Figure 2.11: General network of queuing network with arbitrary topology.

losses. BIW production lines are notorious for breakdowns and efficiency losses, and are categorised as unreliable. There are a variety of assumptions regarding unreliable production lines. These focus mainly on the breakdown distribution of the production line, which can be an *exponential distribution* [47], a *cumulative distribution function* [100], or *normally distributed random variables* [121].

The next important research category in the BAP domain, the *process times*, is also a two-way split category. The category includes *balanced* [12, 46, 60, 70, 114, 122] production lines, where the cycle times of every station in the model are identical, and *unbalanced* [27, 37, 45, 62, 86, 108] production lines, where the cycle times differ by station. The BIW is categorised as unbalanced because the cycle times of the stations are different. It can be an advantage to have an *unbalanced* line, not because it is more realistic, but because it allows for a pull system. A pull system is a production line that runs faster at the end than at the beginning, i.e. it is continuously pulling for more units. The alternative system, a push system, is where the line runs faster in the beginning of the line and slower at the end. Thus, it is always pushing the output. The advantage of a pull system is that it motivates workers at the beginning of the BIW production line to work faster. There are normally more workers at the beginning of the production line than at the end.

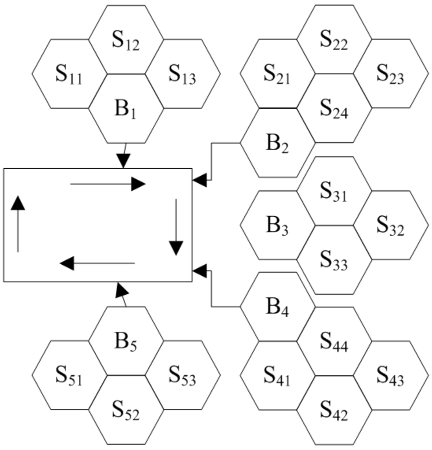


Figure 2.12: Cellular buffer topology model.

Considering balanced production lines has the advantage of allowing researchers to focus on the buffer behaviour of the production line, whereas a consideration of an unbalanced production line has the advantage of producing a more realistic result. Although both types of processing times are important, the main point is to define which type is considered based on the research objective.

2.2.3 Influence of buffers in the production line

Buffer systems usually have different effects on throughput depending the location of the buffer in the serial production line (Figure 2.8). This means that system designers will target the specific areas of the production line to place the majority of buffers. For example Lutz et al. [74] confirmed the placement of buffers in the middle of the production line using a tabu search method. The tabu search method is also a meta-heuristics method. The goal of the tabu search is to overcome the local optima. This popular method [27, 35–38] is based on artificial intelligence and the basic principles of operational research. Lutz et al. [74] uses five buffer storage areas spread evenly between machines. Each storage area has a buffer capacity of between one and seventeen. The results indicate that placing more buffers at the middle location increases the OEE. This same theory was confirmed several times in other research using different methods, including the *non-standard exchange vector* *algorithm* [59], *nested partitions* [105], and *genetic algorithm* [85].

There is one assumption that is common to all these contributions: the physical centre of the production line is also the logical centre. This appears to be a valid assumption; however, this is not the case for BIW production lines, or perhaps for other real production lines. The location of the equipment was not clearly defined in any of the available research. Consider the case of a five-station system, as investigated in Lutz et al. [74], with the equipment unevenly spread among the five stations. For example, 60% of the equipment is at station one, and stations two to five are each loaded with 10% of the equipment. The 'middle' needs to be defined. Further, it is necessary to determine the change in the distribution's impact on the throughput when the optimum location is still assumed to be position three. These questions are not answered by the existing research, and the uneven and unbalanced distribution of equipment, such as in a BIW production line, has not been explored. The research gap is filled by this thesis.

2.2.4 Reduction of WIP in buffer system

A popular research objective in the BAP is to reduce the WIP. Here, maximising the throughput is not the main objective. However, the BAP must be solved in terms of reducing the WIP without reducing the throughput.

Faria et al. [45] published a good article about the WIP in *serial-parallel* production lines. There are two key objectives that are addressed and valid for BIW production lines: reducing the lead times and production costs. The generative method used in their research was the canonical model. This was used to model the up- and downtime of the production cells. Three situations were modelled: the internal behaviour of the cell, behaviour of the cell's output, and behaviour at the buffer output. The processes were deterministic or quasi-deterministic. Faria et al. [45] explained that the probability density functions closely approximated the Dirac or step function. The WIP was successfully reduced and optimised. However, the assumption that the cost was reduced because the WIP was reduced was not completely true.

There are three assumptions regarding cost reduction that are incorrect when the WIP is reduced in a production line. First, it is assumed that a reduction in the WIP means a reduction in the cost, but the weight of the cost of the WIP through the various stages is ignored. Considering a BIW, the product grows as it moves through the six main process steps (Figure 1.3), which means that the value of the WIP also increases. Thus, the cost of ten WIP pieces in buffer station one could be less than the cost of one WIP piece in buffer station five. The optimum cost and WIP have not been determined. The same incorrect assumption is made in serial-parallel production lines [32] and serial production lines [44, 47, 49, 59, 113].

Second, the actual cost of the buffer system itself is ignored. This point has not been addressed in any current research. There are various types of buffer systems that could be used in a BIW production line. BIW buffer systems include stationary steel structures, which are normally used for small sub-assemblies. This type of buffer system is relatively inexpensive and is considered to be the most basic. The second main buffer type is an accumulating conveyor. This buffer system is used for larger sub-assemblies such as VBs and Rear Ends (HBs). This type of buffer system is more expensive and more complex; they are also used as transfer systems. Another common type of buffer system is a chain conveyor. This buffer system is used to transfer larger sub-assemblies such as BGs, Framing 3s (KG3s), and BIWs. This is the most expensive type of buffer system used for a BIW production line. This means that reducing certain conveyor types will result in an associated reduction in the required capital investment.

The third assumption involves the actual or physical space (volume) requirements of the WIP, which have been neglected by most researchers. The physical volume and space are severely limited inside a BIW production line. System designers would place an infinite amount of buffers inside the BIW if they had no space or cost requirements. This would allow the BIW to have an almost 100% availability. However, physical space requirements should be taken into account when searching for an efficient WIP solution because it is a real problem in BIW production lines.

This is a further gap in the current research that requires further investigation. Understanding the buffer types, assembly sizes, and WIP, along with developing a method for simultaneously optimising these parameters, will bring financial benefits to OEMs.

2.2.5 Conclusions

Dividing the BAP research into two sections with six categories creates an instant picture of the entire research domain. Multi-objective solutions are not very popular in current BAP research, particularly for specific topologies such us BIW production lines. The problem with current multi-objective BAP research is that it only attempts to solve BAP1. The remaining objectives (BAP 2–5) are considered to be secondary, and the solutions do not consider objective trade-offs. This is a problem because, as previously stated, the purpose of designing a BIW is not throughput maximisation, but rather BAP3, which is the reduction of the WIP.

There is a lack of understanding in terms of the BAP with regards to a BIW production line. Placing buffers exactly in the middle of a BIW production line could be a problem, because this might not be the logical middle point of the system.

In addition, the relationship between the buffers, WIP, and conveyors is not completely understood. There is a great opportunity to solve the BAP with these multiple objectives in mind.

2.3 Summary

There have been more research contributions related to the BAP than NICT estimation. For both topics, there are important questions that remain unanswered or unexplored, particularly when trying to relate them directly to a BIW production line.

Unfortunately, the state of practice to estimate the NICT is a basic heuristic that does not account for production variation.

Designing a complex BIW production line is a challenging task, and finding efficient solutions to minimise the cost and maximise the throughput is a priority. This is also true for the buffer system encapsulated within the production line. Unfortunately, the state of practice focuses purely on maximising the throughput, while the cost and space usage are considered to be a result of the buffer system, rather than parameters to be minimised as objectives.

Chapter 3

Estimating Net Ideal Cycle Time

Chapter 2 discussed the current method used to estimate the Net Ideal Cycle Time (NICT) and some of its shortcomings in relation to accommodating uncertainty. The current NICT estimation method, which is simply a multiplication, $\text{TT} \times \text{OEE}$, produces a defined scalar value that is used when installing the production line. If a Body-in-White (BIW) production line is designed based on this assumption, it is likely that the actual Mean Throughput (MT) performance will deviate from the estimated distribution. As previously mentioned, the assumption of normality is likely to be incorrect, and an in-depth understanding of the specific throughput distribution of a BIW production line is required to ensure that the theoretical NICT estimation can support the practical performance.

This chapter pursues two main objectives. The first objective is to define the throughput distribution of a BIW production line based on actual production data. The BIW production line of the South African project is used as a reference. The second objective is to develop a new method to estimate the NICT based on the actual throughput distribution and characteristics of a real BIW production line.

3.1 Defined throughput distribution of BIW production line

During the preparation of this thesis, the Original Equipment Manufacturer (OEM) of the South African project granted unrestricted access to all of the BIW production line data. Being provided with this valuable information made it possible to study the throughput distribution of a real BIW production line. All the data processing and analyses described in this chapter were conducted using the statistical computing software R [96].

3.1.1 Methodology

Collecting the data The production data of the reference BIW was collected for the years 2012–2015. Production information was recorded in real time in the reference BIW. Each unit produced triggered an incremental counter in the central database. At the end of each day, the total number of units produced, the date, the number of shifts, and the volume targets were saved. These data were exported to four (one for each year, *2012–2015*) Comma-separated values (CSV) files, each consisting of four columns (*date, number of shifts, volume produced, and target*) and approximately 300 data (*daily record*) entries. We refer to this data as *dataset 1* because it is our most basic level of information.

Processing the data Dataset 1 provides sufficient information for the daily MT to be calculated. The daily MT is very important because the data for the entire year provide us with the required throughput distribution of that year for the relevant BIW production line. The following equation is used to calculate MT:

$$\mathrm{MT} = \frac{\mathrm{TDV}}{8 \times \mathrm{shifts}} \tag{3.1}$$

where MT is expressed in units per hour (uph), Total Daily Volume (TDV) is the total daily number of units (volume) produced, and 'shifts' is the total number of shifts worked multiplied by the hours in a standard 8 h working shift, which gives the total number of hours worked on that specific day. The results of the MT calculation were added as an extra column to dataset 1. The amended dataset containing the MT information is referred to as *dataset 2*.

Cleaning the data Although dataset 2 could provide the throughput distribution of a real BIW production line, some data processing was required. According to the reference BIW management team, there are people performance variations during the week that can be linked to specific days. There is higher employee absenteeism on Mondays, Fridays, and Saturdays, which causes general performance issues that are not observed on Tuesdays, Wednesdays, and Thursdays. The production on Sundays also deviates from that of the high-performance days, but this is due to changes being tested rather than official production. This variation is also immediately noticeable when plotting the throughput distribution for all of the days, as illustrated in Figure 3.1.

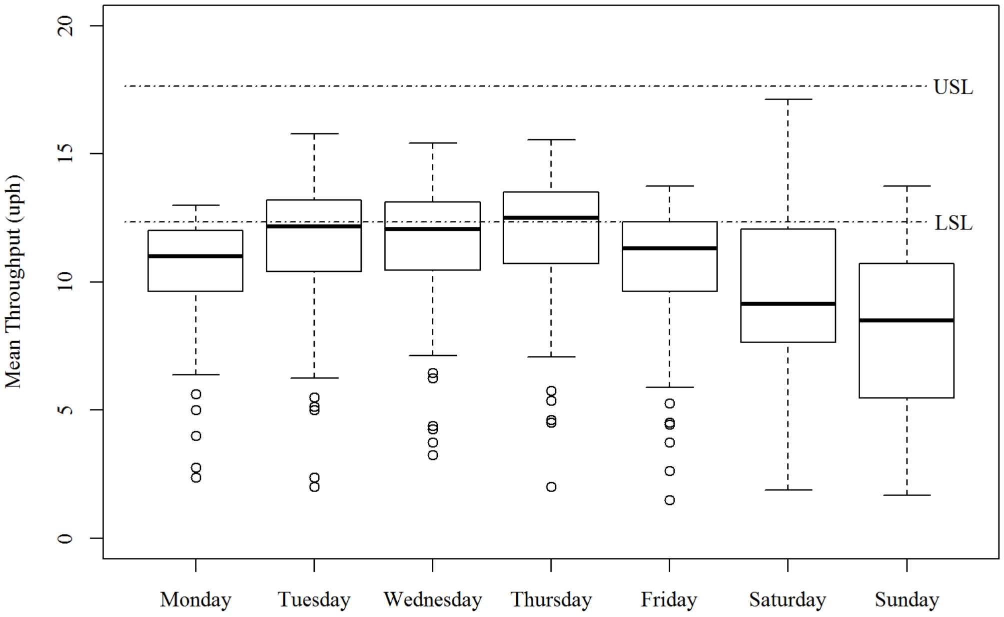
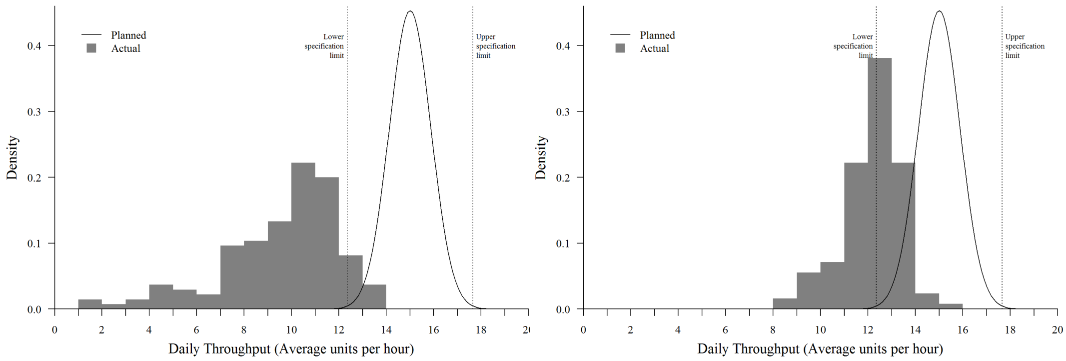


Figure 3.1: Average MT per day for 2012–2015.

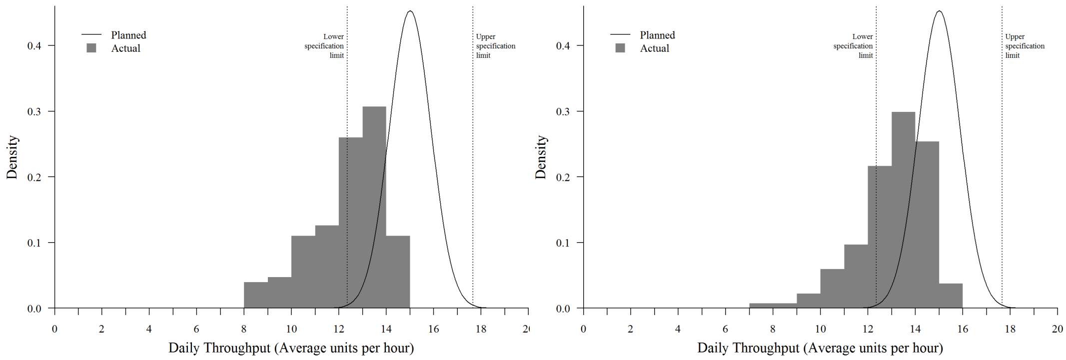
Consequently, Mondays, Fridays, Saturdays, and Sundays were removed from dataset 2 to ensure that this human behaviour did not influence the real performance results. The cleaned data are referred to as *dataset 3.*

Analysing the data and identifying the distribution As a starting point, the data of dataset 3 for each production year were plotted in a histogram with a reference line representing a normal distribution. The throughput distribution of the reference BIW production line for each year (histograms in dark grey) is shown in Figure 3.2 and compared to a normal distribution (line graph). The normal distribution was generated by setting the Upper Specification Limit (USL) to 17.65, which is the NICT estimation using the current method. The Standard Deviation (SD) was set at one. The normal distribution was added to the figures just to highlight the difference compared to the actual throughput distribution.



(a) 2012

(b) 2013



(c) 2014

(d) 2015

Figure 3.2: MT (uph) distributions of reference BIW production line from 2012–2015 (dataset 3).

Three observations are made. First, the reference BIW production line has never performed within the performance window delineated by the Lower Specification Limit (LSL) and USL(Figure 2.4). Second, the throughput distribution of the reference BIW production line does not appear to be normally distributed, and a lack of fit is observed. Third, there are significant performance differences between 2012 and the other years, confirming the difficult launch of the South African project in 2012. Annual improvements in the production throughput are visible from 2012 to 2015.

Dataset 3 was fitted and compared to a normal distribution using the R package `fitdistrplus` [33]. A table was produced to describe the kurtosis and skewness of the distribution for each of the years. The next step was to produce a Cullen and Frey graph. A Cullen and Frey graph provides an overview of or clue about which distribution the data could potentially fit. This graph was used to identify other distributions that may provide a better fit for our data. The above-mentioned R package includes three other functions that allow for goodness-of-fit tests: 1) the Log likelihood (LL), 2) Akaike's Information Criterion (AIC), and 3) Bayesian Information Criterion (BIC). The results of these functions must be compared to identify the best goodness-of-fit result. For the LL, the maximum result value indicates the best goodness-of-fit [48], whereas for the AIC and BIC, the minimum result values indicate the best goodness-of-fit [2]. In addition, four goodness-of-fit plots were generated to obtain a visual impression of the data: 1) a histogram and the theoretical densities, 2)a Quantile-Quantile (Q-Q) plot, 3) an empirical and theoretical Cumulative Distribution Function (CDF) fit, and 4) a Probability-Probability (P-P) plot.

3.1.2 Results

A comprehensive statistical overview of the reference BIW production line is produced in Table 3.1.

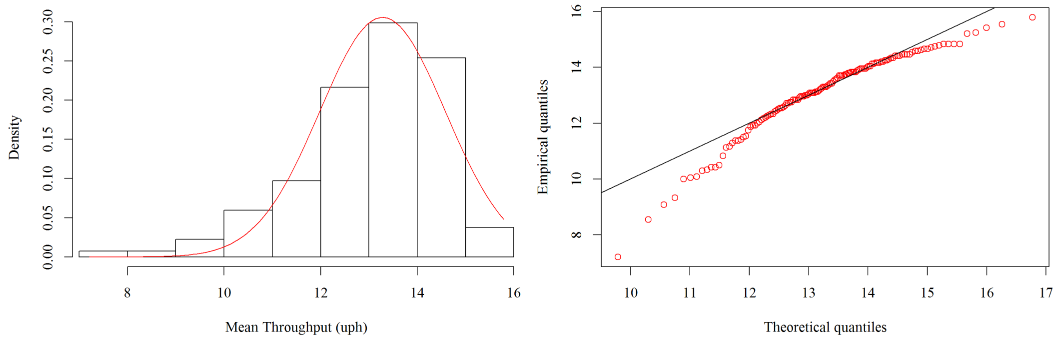
Table 3.1: Statistical overview of throughput of reference BIW: 2012–2015.

Parameter	*2012*	*2013*	*2014*	*2015*	*Mean*	*SD*
Shape estimate	4.82	11.36	10.66	11.49	9.58	2.77
Standard error of shape estimate	0.35	0.76	0.77	0.80	0.67	0.19
Scale estimate	10.52	12.73	13.03	13.69	12.50	1.19
Standard error of scale estimate	0.20	0.11	0.11	0.11	0.13	0.038
Min	2.00	8.17	8.42	7.21	6.45	2.61
Max	13.75	15.38	14.63	15.79	14.89	0.78
Median	10.33	12.27	12.83	13.29	12.18	1.13
Mean	9.64	12.19	12.40	13.08	11.83	1.31
Estimated standard deviation	2.52	1.27	1.50	1.50	1.70	0.48
Estimated skewness	-1.03	-0.65	-0.74	-1.11	-0.88	0.19
Estimated kurtosis	3.83	3.76	2.80	4.59	3.74	0.63

Table 3.1 reports the mean, median, skewness, and kurtosis of the observed dataset 3. The sample *skewness* is a measure of the data's asymmetry about its mean. Negative values are indicative of a skewed distribution. In all cases, the

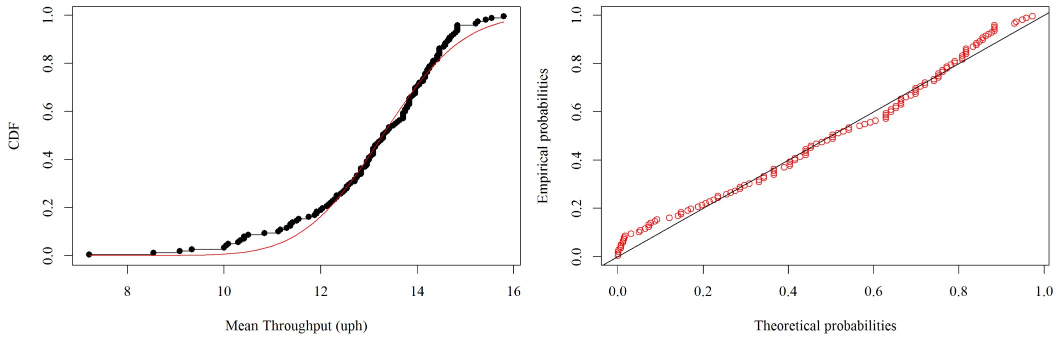
value is less than zero, confirming that the data are *not* symmetric about the mean. The *kurtosis* metric is a measure of the tailedness of the data. A higher kurtosis means that more of the variance is the result of infrequent extreme observations, as opposed to more frequent but modestly sized deviations. A kurtosis value of less than three (as in 2014) suggests that the distribution is *platykurtic*, meaning there are fewer and less extreme outliers than in a normal distribution with the same mean and standard deviation. This could be indicative of a production line that is under control. For the other three years, the kurtosis values exceed three, suggesting that the distributions are *leptokurtic* and contain more outliers than in the corresponding normal distribution.

The throughput distribution of the reference BIW production line was further fitted to a normal distribution in a goodness-of-fit test (Figure 3.3).



(a) Histogram and theoretical densities

(b) Q-Q plot



(c) Empirical and theoretical CDFs

(d) P-P plot

Figure 3.3: 2015 throughput data of reference BIW compared to theoretical throughput of normal distribution.

There are four sub-graphs in Figure 3.3, which are used to show the goodness-of-fit test results. Figure 3.3 represents the data for the year 2015. The data for 2013 and 2014 are similar, with 2012 showing significantly more deviation. Figure 3.3a shows the density plot. This graph gives only a visual impression of the goodness-of-fit. It is observed that the distribution does not appear to be normally distributed. Figure 3.3b shows the Q-Q plot. The goal of a Q-Q plot is to determine whether two data sets have a common distribution. The main focus of the Q-Q plot is to emphasize the lack-of-fit at the distribution tails. It is observed that the dataset is not sourced from the same populations, because the 'o' data points diverge from the reference line. Further, the two datasets do not have the same scale or distribution shapes, and the tail behaviours are not similar. Figure 3.3c shows the CDF plot. This plot further shows that the two datasets do not match by evaluating the gap created between the data points and the reference line in the first curve of the reference line. Figure 3.3d shows the P-P plot. As with the Q-Q plot, the P-P plot attempts to emphasize the lack-of-fit; however, it focuses on the centre of the distributions and not the tail.

The data points of the 2015 dataset diverge from the reference normal distribution. Considering all of the deviations from the reference data compared to the actual throughput data, it is concluded that the throughput distribution of a real BIW is *not* normally distributed.

Thus, the empirical data do not fit a normal distribution, and the correct distribution must be determined. The R [96] package `fitdistrplus` delivers a very important clue about the MT distribution of the actual BIW production line. The package allows for the classical descriptive statistics (minimum, maximum, median, mean, standard deviation, skewness, and kurtosis). A skewness-kurtosis plot based on the proposal by Cullen and Frey [31] is provided based on the function for the empirical distribution. Values for common distributions are displayed using this plot. This makes it possible to identify the distribution by attempting to fit the distributions to the data. Because the skewness and kurtosis are known to not be robust, this package also takes into account the uncertainty of the estimated kurtosis and skewness values for the data. In addition, a non-parametric bootstrap procedure based on Efron and Tibshirani [43] is performed. This bootstrap procedure allows the skewness and kurtosis values to be computed on bootstrap samples. This is achieved by constructing random samples with replacements from the original data set. Finally, this is reported on the skewness-kurtosis plot.

Figure 3.4 gives an overview of the 2015 dataset. The Cullen and Frey [31] graph indicates that the reference BIW dataset is a combination of beta, log-normal, gamma, and Weibull distributions. The datasets for 2012, 2013, and 2014 are similar.

The previously used procedure was applied to the datasets to test their goodness-of-fit to a specific distribution.

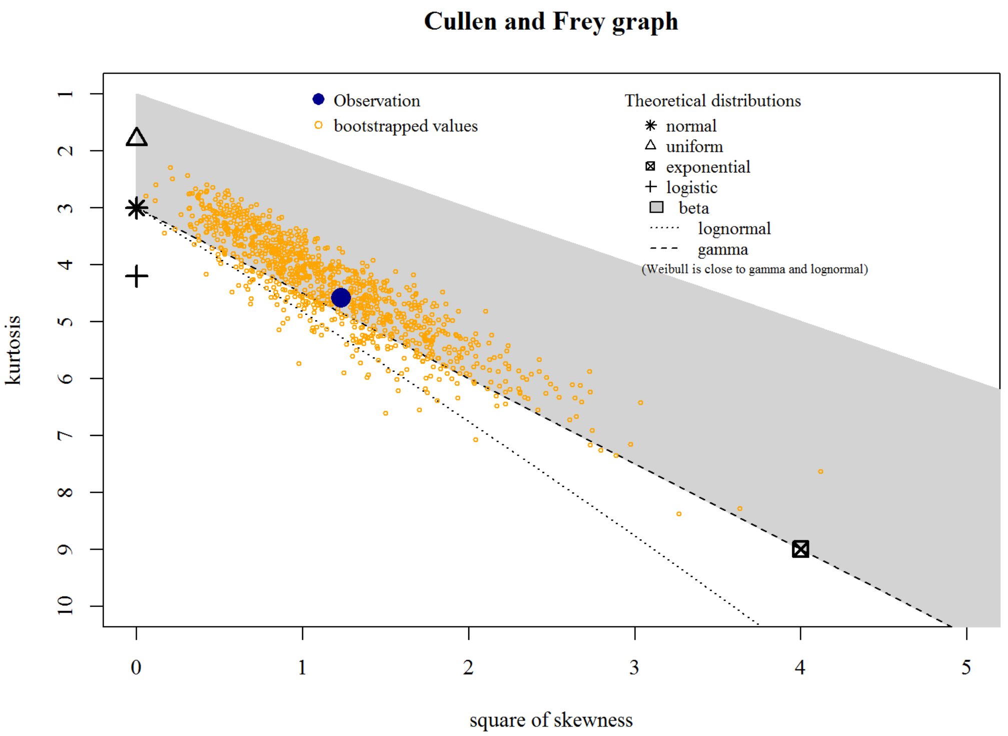


Figure 3.4: 2015 throughput data of reference BIW plotted on Cullen and Frey graph.

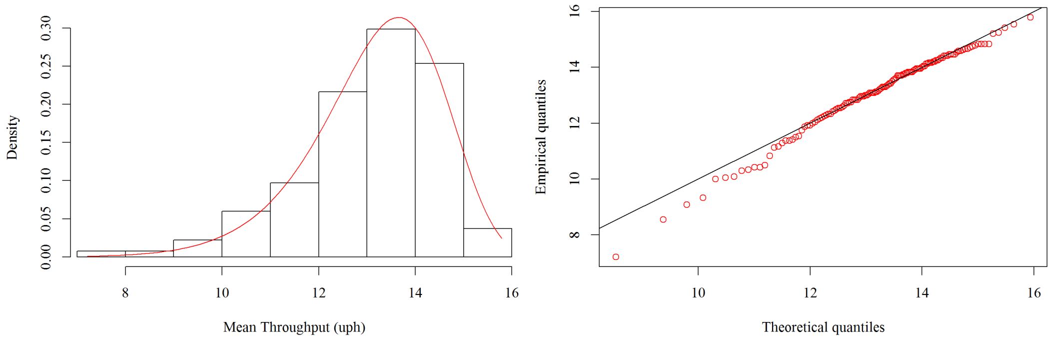
The Cullen and Frey reference graph consists of points, lines, and surfaces. According to Delignette-Muller and Dutang [33], normal, uniform, logistic, and exponential distributions can have only single skewness and kurtosis values, and are therefore represented by a single point. For log-normal and gamma distributions, more values are possible, and these distributions can fall anywhere on the given line. For a beta distribution, there is an entire surface of values where the distribution can lie.

Goodness-of-fit tests were conducted for the various distributions to determine the best match for the empirical data. The various distributions included the gamma, normal, Weibull, log-normal, exponential, and logistic distributions. All the distribution results were compared using the LL, AIC, and BIC. The results are listed in Table 3.2.

Table 3.2: Distribution goodness-of-fit results for all data (2012–2015) using various test distributions.

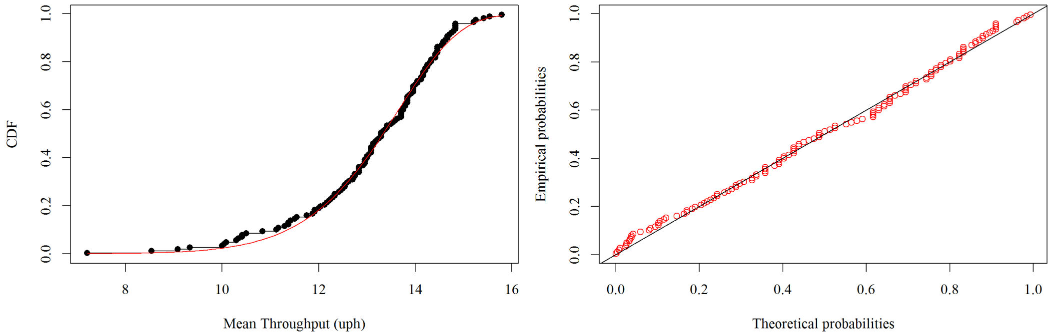
	2012			**2013**			**2014**			**2015**		
	LL	*AIC*	*BIC*	*LL*	*AIC*	*BIC*	*LL*	*AIC*	*BIC*	*LL*	*AIC*	*BIC*
Gamma	-362	727	733	-216	435	441	-238	481	486	-261	525	531
Normal	-320	644	650	-210	424	430	-233	469	475	-248	501	507
Weibull	**-313**	**630**	**636**	**-206**	**416**	**421**	**-224**	**451**	**457**	**-233**	**469**	**475**
Log-normal	-402	808	814	-219	443	448	-242	488	494	-268	541	547
Exponential	-446	895	898	-448	897	900	-453	908	911	-485	973	976
Logistic	-314	631	637	-207	417	423	-233	470	476	-241	486	492

Table 3.2 shows that the Weibull distribution performed the best in all of the goodness-of-fit comparisons. The high Weibull performance is further amplified and illustrated in Figure 3.5. A comprehensive visual overview of every distribution for every year is shown in Appendix A.



(a) Histogram and theoretical densities

(b) Q-Q plot



(c) Empirical and theoretical CDFs

(d) P-P plot

Figure 3.5: 2015 throughput data of reference BIW compared to theoretical throughput of Weibull distribution.

The visual fit of the Weibull distribution in Figure 3.5 is by far the most accurate fit for the data (*Dataset 3 from 2015*). It is clear from the Q-Q plot that the datasets have the same scale and distribution shapes, and the tail behaviours are similar, indicating a match. In the P-P plot, the centre lines are aligned and also very similar, again indicating a match. It can be concluded that the throughput of a real BIW production line is Weibull distributed, as proven by the goodness-of-fit test results. The results for all the years are also confirmed to be Weibull distributions.

The current NICT estimation method does not assume that the MT of a BIW production line is normally distributed; however, it does assume that the performance characteristics of all the production lines are the same because there is no parameter to change or adjust to represent a specific production line. This is a problem because numerous external factors such as union strikes, irregular human behaviour, and power outages are expected to influence the performance characteristics of a BIW production line, and yet these are currently ignored. It is highly unlikely that all of the BIW production lines will perform in the same manner. This means that when estimating the NICT for a specific BIW production line, the assumption is made that the specific production line is not unique and that any previous information regarding this production line is irrelevant. Because of these unconsidered external factors, this is a very dangerous assumption, and poses a problem.

3.2 Estimating NICT using Weibull distribution

A Weibull distribution is described using two parameters: the shape (k) and scale (λ). Once the Weibull parameters are known, it is possible, in theory, to calculate the NICT using a novel method based on the specific empirical data. The reference BIW production line provides a good idea of the requirement of its main characteristic, the shape. However, the scale must be incremented to increase the mean of the entire distribution to achieve the actual Mean Throughput Target (MTT).

3.2.1 Methodology

Estimating the shape: The shape of the reference BIW production line can be estimated by considering the mean shape for all normal years. The data from 2012, when they were struggling to launch, were omitted from the sample to ensure that this abnormal year was not considered in the estimation. By omitting the 2012 shape, the shape mean increased from 9.58 to 11.17, and the standard deviation simultaneously decreased from 2.77 to 0.37. The decrease in the standard deviation confirmed that the shapes for all three years were similar.

Calculating the scale: The scale of a Weibull distribution can be calculated using Equation (3.2) [130]:

$$\mu = \lambda\Gamma(1 + 1/k) \tag{3.2}$$

where μ is the mean, λ is the scale, Γ is the gamma function, and k is the shape of the Weibull distribution. The gamma function is an extension of the factorial function and can be expressed by Equation (3.3) [130]:

$$\Gamma(x) = \int_{1}^{\infty} z^{x-1} exp(-z) dz \tag{3.3}$$

where x is a positive integer. The estimated standard deviation for the Weibull distribution can be calculated using Equation 3.4 [130]. The estimated standard deviation can be used to compare the actual performance data from the real BIW production line:

$$\sigma^2 = \lambda^2[\Gamma(1 + 2/k) - \Gamma(1 + 1/k)^2] \tag{3.4}$$

where σ is the standard deviation of the distribution. We can now calculate the X_{th} percentile p, which is the percentage of observations that must fall within the Weibull distribution, using Equation (3.5) [130], which is also the USL:

$$t_p = \lambda[-ln(1 - p)]^{\frac{1}{k}} \tag{3.5}$$

The NICT for the BIW production line can now be derived as follows:

$$NICT = \frac{NAT}{\lambda[-ln(1-p)]^{\frac{1}{k}}} \tag{3.6}$$

where *Net Available Time (NAT)* is equal to 3600 s, and p is the pth percentile, in our case a value of 0.999, meaning that all production days during the year are considered. The value of 0.999 in this calculation is an assumption. The USL can be decided for example by a negotiation between the designers and the manufacturing engineers as proposed by Kao [58]. Figure 3.6 demonstrates the negotiation range and flexibility of what is on offer from the proposed method.

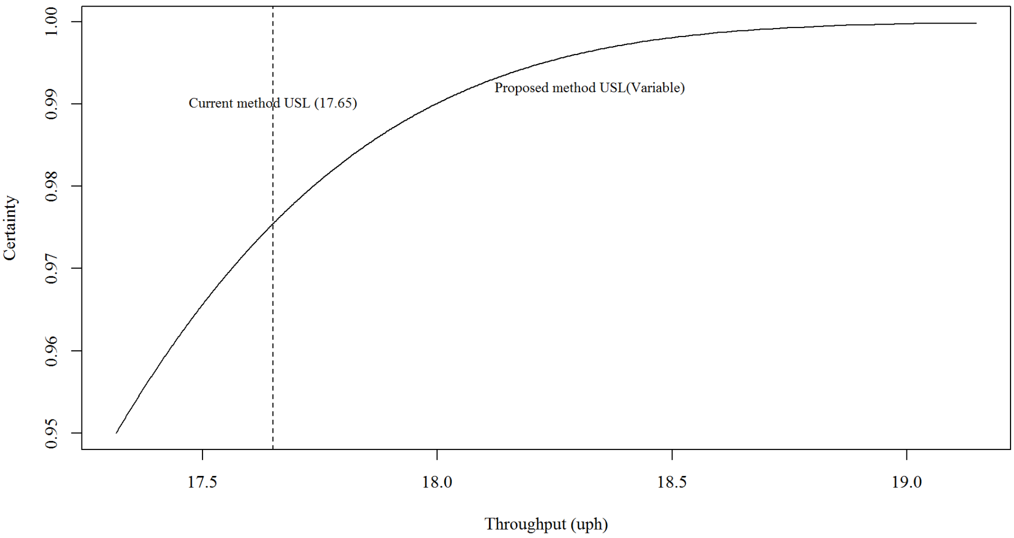


Figure 3.6: An USL comparison and negotiation range between the current and the proposed method.

Equation (3.5) is equivalent to the standard `qweibull`(p, k, λ) function in R [96].

3.2.2 Results

To benchmark the proposed method, a re-estimation of the South African BIW production line NICT was conducted. First, as previously mentioned, the shape of the Weibull distribution was estimated to be 11.17 using the mean shape value for 2013–2015. In the next step, Equation 3.2 was used to determine the scale, which in this case was 15.69. Then, the expected standard deviation of 1.608 was calculated, and the results were found to be consistent with the actual data, showing a good correlation between the theory and practice. The final step was the estimation itself, which resulted in an NICT of 192.93 s and a USL of 18.66uph. The expected MT distribution is shown in Figure 3.7. The full code and example are available in Appendix D.

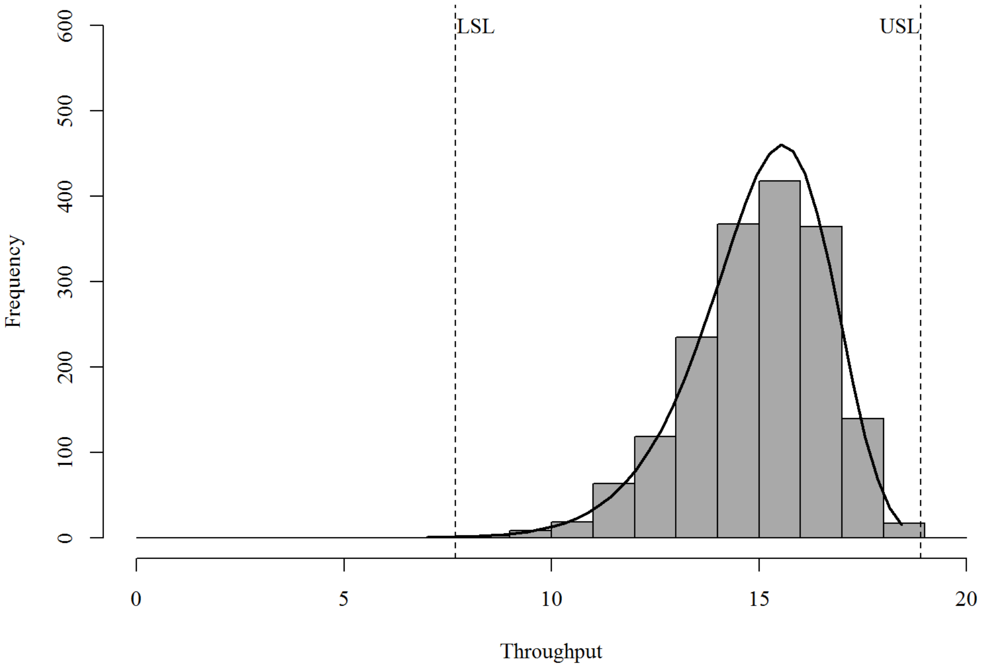


Figure 3.7: Expected MT distribution using new method based on Weibull distribution.

Using the proposed method results in an increase in speed (cycle time decrease) of 5.4%. Although the 5.4% increase for this specific example might seem small, it is an increase, which will result in a corresponding increase in equipment. For BIW production lines with different characteristics (shape and scale), there may be an increase or a decrease of any magnitude, indicating that the specific characteristics of any BIW production line are considered based on historical events.

A simple business case can be analysed to determine whether the expected losses outweigh the additional investment. For the South African project, the business case indicates that an additional investment for a faster NICT would have been more feasible.

3.3 Conclusions

The MT distribution of a real BIW production line was studied, and it can be concluded that the values are Weibull distributed, and not normally distributed as first assumed. A new method of estimating the NICT based on this Weibull distribution was further developed using this distribution as the base input for the NICT estimation.

This new method has several advantages over the current method used for estimating the NICT. First, the new Weibull method allows the NICT to be based on the characteristics of the relevant BIW production line for which it is estimated, allowing for a bottom-up approach. This increases the reliability because every BIW production line will have a unique NICT provided historical data are available, enabling a strong correlation between the theory and practice. Second, the relevant BIW production line will also receive a target image of its desired performance, as illustrated in Figure 3.7. This allows the relevant BIW production line to measure its performance against a target image, which will aid in either early performance variation detection or confirmation that the performance is on track.

The new method resulted in a 5.4% decrease in the NICT, which may differ for other BIW production lines. This 5.4% decrease likely means an equivalent investment increase of 5.4% to compensate for the faster production line. However, this 5.4% investment increase can easily be justified or rejected by comparing it to the expected losses due to the variation in the relevant BIW production line.

Finally, a new method was developed to estimate the NICT, which means that

BIW system design engineers now have two methods from which to choose. This will allow them to follow a top-down or bottom-up approach, depending on the situation. During this study, we successfully understood, explained, and improved the behaviour of the current method to improve NICT estimation; this means that this research complies with the requirements of Manson [77] for design research. The new Weibull method features a strong correlation between the theory and practice. It is more plausible, robust, and descriptive than the current method used for estimating the NICT.

Chapter 4

Efficient frontier for multi-objective buffer system design

Buffer systems help to minimise the effect of process variation by allowing for temporary storage areas before entering, while inside, and after leaving a specific production area. Buffer systems can be viewed in both a positive and a negative light. On the positive side, buffers limit losses in equipment efficiency, and increase the Mean Throughput (MT). On the negative side, buffer systems are expensive and considered to be *waste* in lean manufacturing. In addition, large buffer systems can mask performance problems, making it difficult for a Body-in-White (BIW) production team to efficiently analyse the production system and implement the correct improvement measures to attain better performance.

As the decision-makers and designers of production lines, we are faced with multiple and competing objectives. We want to maximise the throughput and achieve the Mean Throughput Target (MTT). This means that we want to increase the buffer sizes to account for and hedge against the inherent process variation. However, large buffers increase the costs in terms of the equipment and space. Therefore, this conflicts with the possible second objective of minimising the cost. First, this chapter studies the individual objectives independently to understand how each objective could potentially influence the Buffer Allocation Model (BAM) for a BIW production line. The different objectives are then used to demonstrate the spectrum of trade-offs that need to be considered. In multi-objective optimisation, this spectrum of trade-offs is referred to as the *efficient frontier*. In this chapter, the efficient frontier is created by considering multiple important objectives that are not necessarily considered when designing the buffer system, either in theory or in practice. The frontier uses multi-objective criteria to evaluate the efficiencies of buffer locations inside a BIW production line. Although four objectives will be considered for the efficient frontier, only two will be used on the efficient frontier because pre-emptive optimisation is considered, as described by Rardin [99]. These two objectives can then be graphically represented by comparing the production trade-offs.

The main deliverable of this chapter is a proposed efficient frontier for a BIW production line. In this chapter, we also demonstrate how the frontier can be navigated, as well as how the objectives can be combined into a single multi-objective solution, where the trade-offs and competition for location are studied.

4.1 Buffers in BIW production line

A BAM consists of two important parameters: the buffer *location*, which defines the location of the buffer in the production line, and the buffer *size*, which defines how many units of a certain assembly must be stored in each buffer location. There is a well-known heuristic, the *bowl phenomenon*, that was first introduced by Hillier and Boiling in 1977 [12] and defines the BAM for a production line.

According to the bowl phenomenon, to achieve the best MT performance, the buffer allocation should follow the shape of an inverted bowl, where the buffer sizes are the largest in the centre of the production line and decrease towards the beginning and end of the production line. This concept is illustrated in Figure 4.1 and has been successfully applied on several occasions [53, 62, 80, 109].

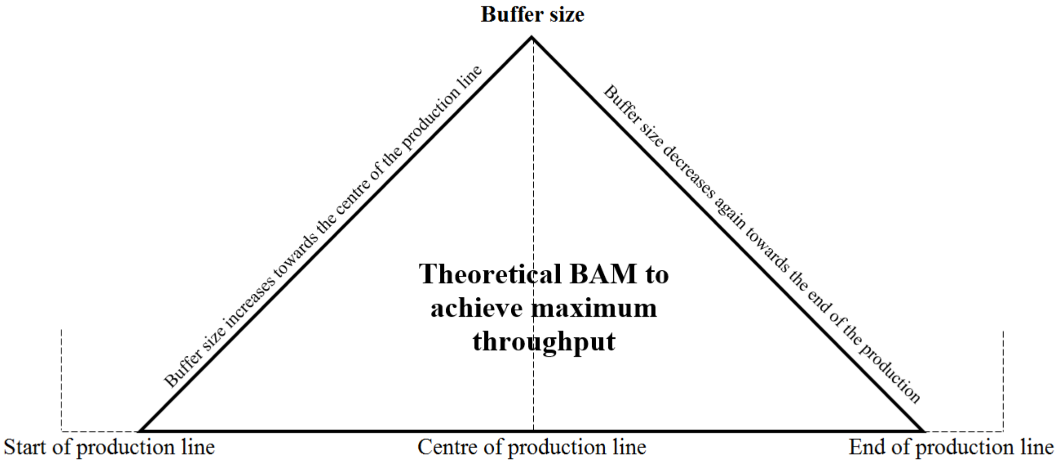


Figure 4.1: Bowl phenomenon.

The bowl phenomenon considers both the buffer location and size. The x-axis and y-axis in Figure 4.1 represent the buffer location and buffer size, respectively. The tip of the bowl represents the highest buffer size, which is located exactly in the centre of the production line. The Buffer Allocation Problem (BAP), which was studied in chapter 2, attempts to determine the exact shape of this triangle. Solutions with more buffers required in the beginning of the production line will cause the triangle to skew to the left, whereas solutions with more buffers required at the end will cause the triangle to skew to the right. In theory, there may be cases where the shape of the triangle becomes completely distorted as a result of an irregular buffer quantity distribution, such as a case where two buffer peaks exist just before and after the centre of the production line, with a big dip in the centre.

The buffer locations for a BIW production line can be divided into five distinct locations, which are illustrated in Figure 4.2 and marked as locations L1–L5. Location L1 provides unit storage for the three assemblies of the first process step of the BIW production line (Figure 1.3), namely the Front End (VB), Centre Floor (BB), and Rear End (HB) assemblies. Similarly, locations L2–L5 provide storage for the assemblies of BIW production steps 2–5.

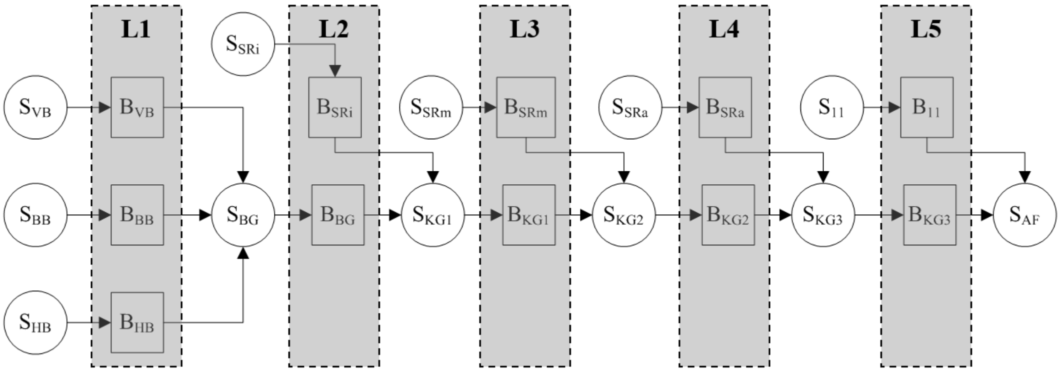
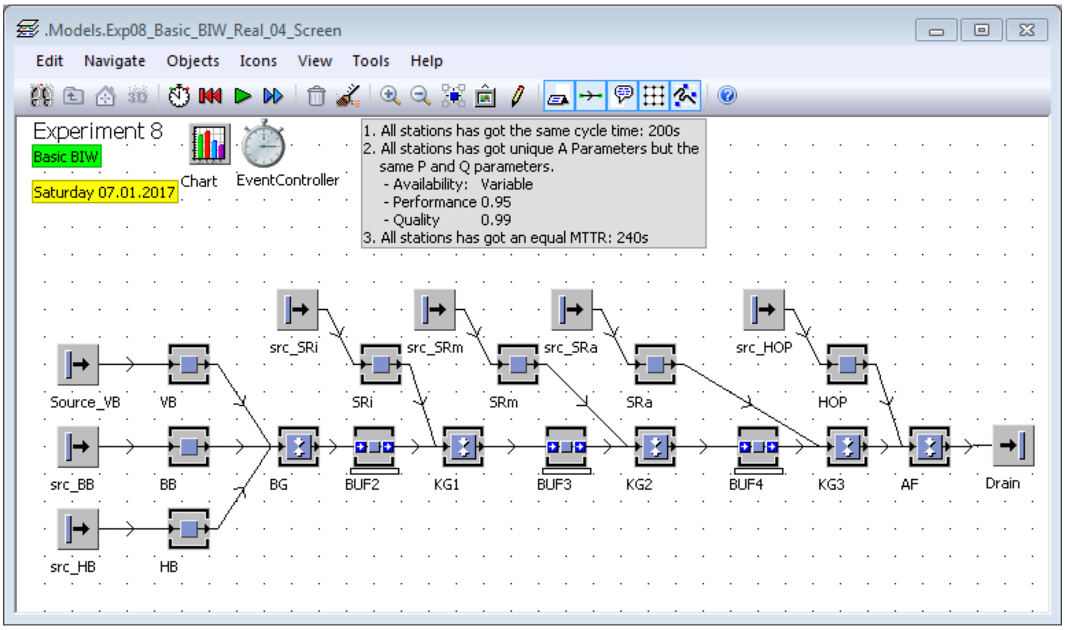


Figure 4.2: Five main buffer locations inside BIW production line.

In theory, this means that for a BIW production line, the highest buffer size must be at location L3 when considering that the BIW production line will adhere to the bowl phenomenon; this also means that locations L1 and L5 must have the lowest buffer sizes.

4.2 Experimental setup

As discussed in chapter 2, simulation is the most popular evaluation method in buffer research [18, 21, 98, 115, 126], particularly when heuristics [23, 57, 70, 108, 119] are used as a generative method. Simulation is also the de facto standard in the industry and was selected for this research. Simulation provides a visually intuitive and easily understandable interface; it is easy to use and is considered very reliable. Additionally, if the model is properly constructed, a strong correlation in practice is ensured. The simulation software used for this research was Tecnomatix Plant Simulation version 11 from Siemens AG [106]. Figure 4.3 shows an experiment that was executed using this software package.



1. All stations has got the same cycle time: 200s
2. All stations has got unique A Parameters but the same P and Q parameters.
   - Availability: Variable
   - Performance 0.95
   - Quality 0.99
3. All stations has got an equal MTTR: 240s

Figure 4.3: Experiment model set-up in Tecnomatix Plant Simulation.

The simulation software allows for a realistic duplication of a BIW production line buffer model by allowing the individual Overall Equipment Effectiveness (OEE) performance parameters to be set for each BIW production step (Figure 1.3). For the general availability parameters, a Mean Time Between Failures (MTBF) of 2427s and a Mean Time to Repair (MTTR) of 240s were used. The same availability were used in all experiments When comparing the models of the five main buffer locations of Figure 4.2 with the simulation model of Figure 4.3, the resemblance is noticeable.

Figure 4.3 can be divided into two sections. Section 1, the top third of the figure, shows when the experiment was executed and which OEE figures were used for it. Section 2, the bottom two thirds of the figure, shows the model itself. There are various building blocks and lines with various meanings. The *scr* blocks are source blocks. This is typically where single parts are loaded into the BIW production line. This research assumes that the source will never be starved, meaning that parts are always loaded in a timely manner. This was done to isolate the buffer behaviour from the human performance to make it possible to achieve the main objective of studying the buffer behaviour. There are a further two types of production blocks, block type 1 and block type 2. Block type 1 is a plain single station block such as VB or Side Frame Middle (SRm), where single parts are assembled to form an assembly. Block type 2 is an assembly block denoted by two white arrows, one pointing up and one pointing down, where sub-assemblies are merged into a larger sub-assembly. The buffer locations inside the line are denoted by the block with the two white arrows pointing to the right-hand side. The lines with arrows indicate the flow direction of the production line. Finally, the drain is the extraction point of the BIW and is the block on the extreme right of the figure. It is also assumed that the drain is never blocked for the reason mentioned for the sources. Further, the drain is the measuring point of the entire production system because this is the point in practice where units are officially recognised and counted as units.

4.3 BIW objectives in evaluating buffer configurations

There is currently no BAM available that BIW system design engineers can use to assist them with designing the buffer system for a BIW production line; the only references are the bowl phenomenon and existing production lines. The bowl phenomenon for a BIW production line could be invalid when specific performance objectives are added. In addition, it is highly implausible that any reference production lines were designed with specific BIW objectives in mind other than achieving the planned MTT.

According to the reference Original Equipment Manufacturer (OEM), there are four highly important performance criteria to which a BIW production line must adhere. This multi-criteria performance requirement can be defined as a request: *Design a BIW production line that will achieve its MTT while minimising the financial investment and physical footprint and while following a lean manufacturing philosophy.* The multiple criteria require a multi-objective approach to design the BIW production line.

It is important to understand the impact of each objective on the design of the BIW production line so that an efficient BAM can be recommended for a specific

BIW production line.

4.3.1 Mean Throughput

The first performance criterion is designing a BIW production line that achieves a target MTT. When a production line underperforms, sales are lost. When a production line overperforms, the financial investment was unnecessarily high. Both conditions will negatively affect the OEM. It is important to understand where buffers have the greatest influence on performance. Placing a large number of buffers in the BIW production line will certainly increase the performance, but it will also be costly. Therefore, objective 1 is determining the location where the buffer has the most positive effect on the MT of the BIW production line.

The MT was studied using the experimental set-up described in the previous section. The aim of this experiment was to determine the best location (where the MT is the highest) by evaluating the MT for each of the locations (L1–L5) shown in Figure 4.2. The main aim of the simulation experiments was to move several Work-in-Process (WIP) pieces, x, to different buffer locations to determine the influence on the MT of the production line. In these experiments, a total of 5, 10, or 50 WIP were simulated in the various locations. For example, when considering the batch of 50, it was first moved to location L1, while all the other locations were eliminated; the simulation was then completed and the results were recorded. The 50 WIP were then moved to location L2 while all the other locations were eliminated, and this process was repeated until all the buffer locations were tested. The aim of this simulation was to find which location as a single entity had the most positive influence on the throughput, which in turn helped with an understanding of the theory of buffer allocation within BIW production lines.

Since each simulation had inherent randomness in the production and availability characteristics, a total of 100 observations were conducted for each configuration. Each observation simulated 365 days of 24 h production.

Two experiment sets were considered. The first set of experiments, set 1, assumed that the availabilities of the BIW production steps were identical. In other words, it was assumed that each BIW production step used the same number of robots, which was not the case. This was done to confirm that the MT changed when buffers were moved from one location to the next. The second set of experiments, set 2, was executed using the actual availability of a BIW production line based on the actual robot distribution in terms of a real production line distribution. This was done to ensure that the real performance behaviour of a BIW production line was captured in the results.

The set 1 results for the 5 buffer quantities are shown in Figure 4.4, which uses a bar chart to illustrate how the OEE of the production line changes as the buffer moves from one location to the next. A solid black line is plotted in the foreground to create a reference back to the bowl phenomenon for ease of comparison. The results for the 10 and 50 buffer quantities are similar, with MT performances that were equally improved in all areas owing to the larger buffer sizes.

It is observed that placing the buffers at location L3 (Framing 1 (KG1) and Side Frame Inner (SRi)) had the greatest positive influence on the performance, whereas placing the buffers at location L5 (Framing 3 (KG3) and Hang-on-Parts (HOP)) had the lowest. See Appendix B for the detailed results of all of the experiments.

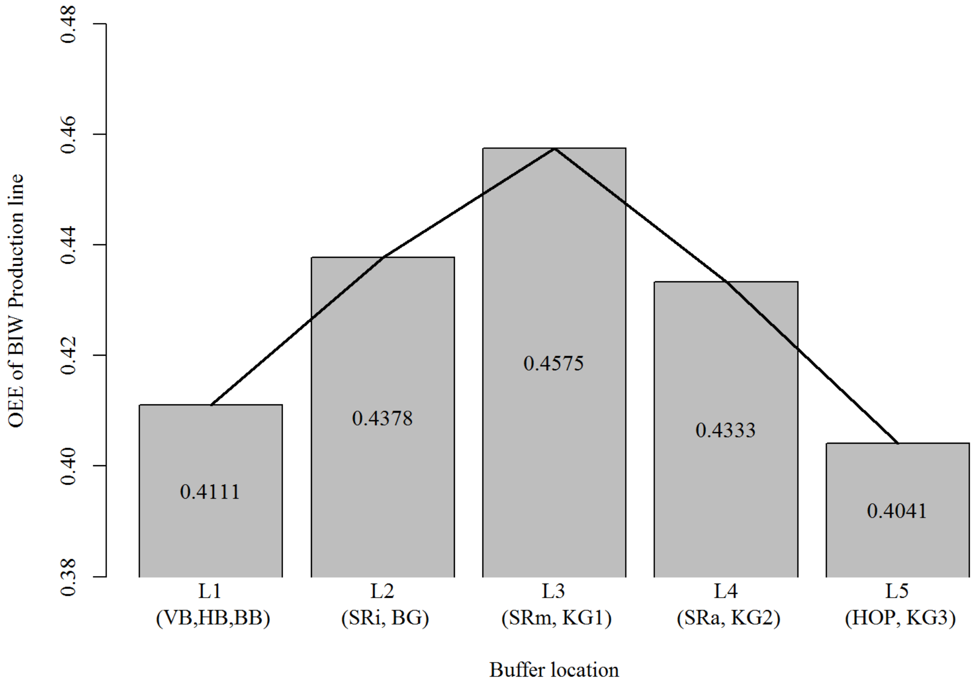


Figure 4.4: Observed bowl phenomenon for BIW production line.

The results from the experiment with set 1 further demonstrated and confirmed the presence of the bowl phenomenon. Therefore, the results for set 1 indicated that the bowl phenomenon is potentially valid for BIW production lines. This is mainly a result of using the same assumed availability figures for each assembly. The MT performed the best when the buffer was placed at location L3, and the MT performed the worst when the buffer was placed at location L1 or L5.

However, this changed for the experiment with set 2. There are normally more robots in the VB and HB areas than in any other area, indicating that the availability in these areas is lower compared to other areas. This means that buffers could help the MT because they support the lower throughput areas. The results of the experiments for set 2 are shown in Figure 4.5. The MT performance behaviours for sets 1 and 2 are different.

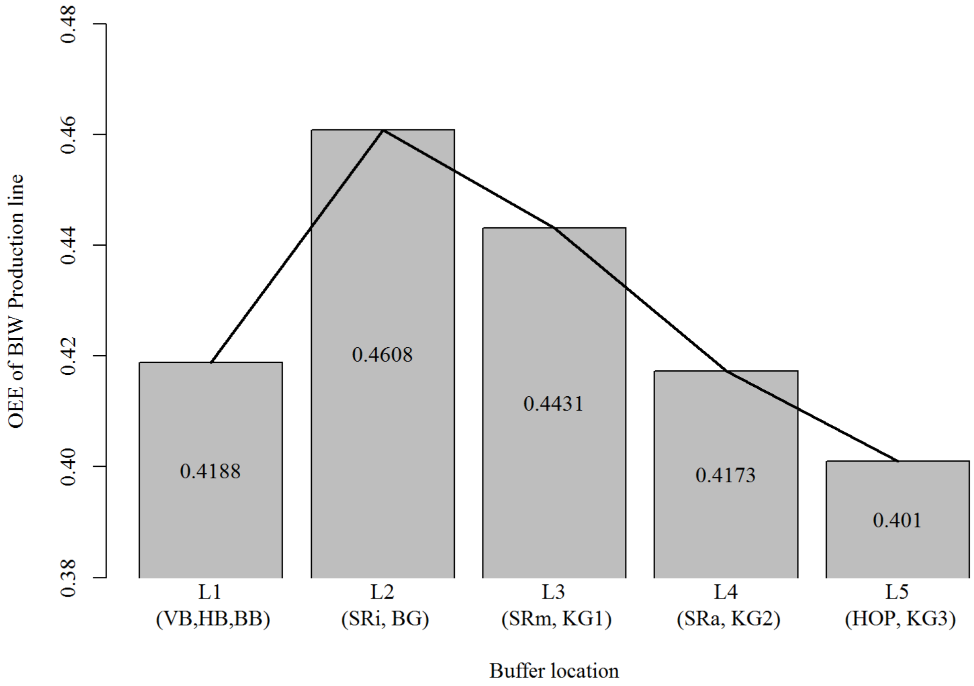


Figure 4.5: Left-skewed bowl phenomenon for BIW production line observed with realistic availability parameters.

The greatest difference between set 2 and set 1 is the increase in the OEE for the Under Body (BG) line, whereas the OEE in KG1 decreased. There is a further OEE reduction visible in most lines. The difference in availability between set 1 and set 2 is responsible for the change in results.

Although the triangle of the bowl phenomenon remains recognisable, it is skewed to the left. Based on the results for set 2, the realistic representation of a BIW production line, the largest buffer sizes should be used at location L2, followed by locations L3, L1, L4, and L5. The reason for the left skewness is the fact that 65% of the robots inside the BIW production line are found before this location and, therefore, can be much better utilised here.

Because set 2 more realistically represents the BIW line, it is concluded that targeting location L2 is the best option to achieve an efficient MT.

4.3.2 Cost

The second criterion is designing a BIW production line that requires the least amount of financial investment to realise. This is important because the products of OEMs need to be competitive in the market. A higher investment in the production line leads to a more expensive product. The production equipment design is defined by the Net Ideal Cycle Time (NICT), which was explored in chapter 3. This means that there is almost no way to reduce the investment in the equipment. The only opportunity for any major investment reduction or overspending lies within the buffer system. Understanding the types of buffer systems available and where they can be placed, as well as understanding their investment requirements, can create an investment reduction opportunity. Therefore, objective 2 is determining the best location to place buffers in terms of their application and cost.

In most cases, the buffer systems in a BIW production line are also used as material handling systems in the various process steps. This is the reason that most of the buffer types used in BIW production lines are also some sort of conveyor system to transport the assemblies from one process step to the next. The different buffer types have different shapes and sizes, with their own unique cost implications.

To date, there are eight types of buffer systems that can be used in BIW production lines. Each buffer type has unique parameters and serves a specific purpose. Table 4.1 gives an overview of these eight buffer types, including the possible buffer locations, and provides further details regarding the assemblies that they can manage.

The reference OEM of the South African project supplied a detailed database of the current buffer systems and types. The investment costs in the database were calculated using the average costs from different manufacturers and suppliers. This information is confidential. To retain this confidentiality, a base factor calculation was performed using the most cost effective buffer type. This was the base value. The database includes the single investment cost for every available buffer type, as well as the additional investment cost for any extra stations or meters that may be

Table 4.1: Different buffer types for BIW production lines and their applicable locations.

Buffer type	**L1**	**L2**	**L3**	**L4**	**L5**
Static steel structure for medium size assembly	VB BB HB	SRi	SRm	SRa	HOP
Static steel structure for full underbody (BG)		BG	KG1	KG2	KG3
Chain conveyor	VB BB HB	SR BG	SRm KG1	SRa KG2	KG3, HOP
Accumulating conveyor (2,0m width)	VB BB HB	SRi	SRm	SRa	
Longitudinal shuttle		BG	KG1	KG2	KG3
Steel plate conveyor for underbody (BG)		BG	KG1	KG2	KG3
Belt conveyor (6,5m)		BG	KG1	KG2	KG3
High-speed conveyor skid system (6,5m)		BG	KG1	KG2	KG3

required. The total cost was calculated using Equation (4.1):

$$TBC = IC_1 + (IC_2 \times x) + IC_3 \tag{4.1}$$

where TBC is the total buffer cost, IC_1 is the initial set-up investment cost, IC_2 is the cost per extra station or meter, x is the number of buffer units required, and IC_3 is the additional cost required.

Figure 4.6 shows a final overview of the cost per buffer type. There is also a comparison between the initial investment (1 unit), and the cost for 10, 20, and 50 buffer units per buffer area. The increase in WIP from 1, 10, and 20 to 50 gives an overview of how the investment cost increases for each buffer type when the buffer quantity increases. The total cost was calculated by assuming that only one specific buffer type was used for all of the WIP.

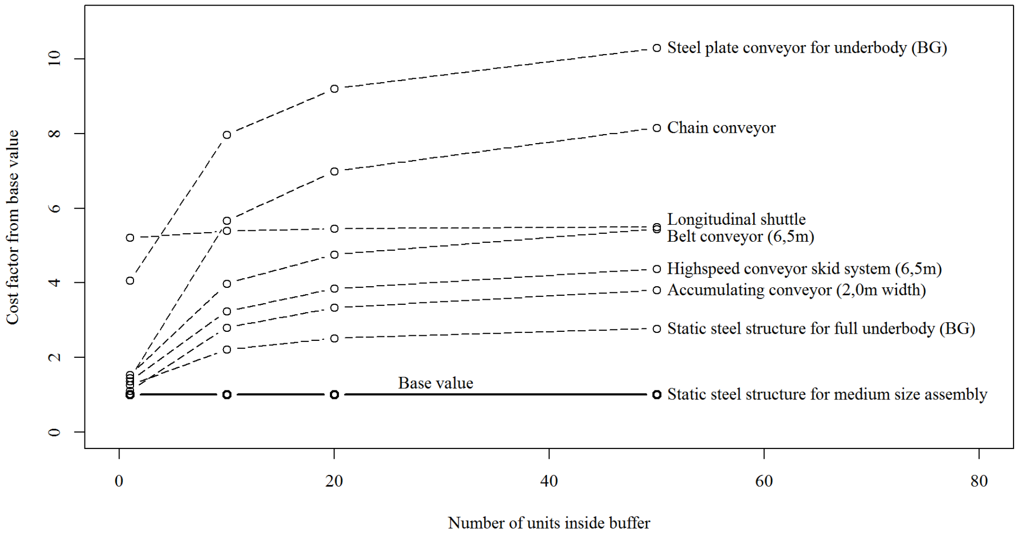


Figure 4.6: Different types of BIW buffer systems and their cost factors.

The base value for the comparison was the '*static steel structure for a medium size assembly*'. When considering a buffer type with 20 units, the investment cost for a '*static steel structure for a full underbody*' will be twice as expensive as the base value, and using 50 units for '*chain conveyors*' will be eight times more expensive than the base value. Six of the eight buffer types have similar increases in the investment cost when increasing the buffer size, becoming more expensive per station as the requirements increase. In contrast, two buffer types, '*longitudinal shuttles*' and a '*static steel structure for a medium size assembly*', stay fairly constant, with a low marginal increase.

In Table 4.2, a BIW production line is configured with 50 buffer pieces moving through locations L1–L5 to illustrate the most financially feasible locations for the buffers. This configuration is based on the information supplied by the reference OEM for two recent projects. The configuration was copied from production lines where accumulating conveyors were used at location L1, a high-speed conveyor skid system was used at location L2, chain conveyors were used at location L3, belt conveyors were used a location L4, and longitudinal shuttles were used at location L5. There are different and, perhaps, more cost effective solutions available. It is not clear why these exact buffer types were used, but it is assumed that the reference OEM had a technical basis for the specific selections. The buffer types were copied 1:1 to ensure that the cost factors of the buffer system were identical in theory and practice. It is the intent of chapter 5 to discuss how benchmarking was conducted and a stable information base was developed to allow a relevant comparison to be made at a later stage.

Table 4.2: Buffer configurations and cost factors

L1	**L2**	**L3**	**L4**	**L5**	**Buffer size**	**Cost factor**
1	1	1	1	50	54	10.94
1	1	1	50	1	54	14.56
1	1	50	1	1	54	17.36
1	50	1	1	1	54	13.66
50	1	1	1	1	54	13.35

The cost location results indicated that a buffer is less expensive at location L5, and that the cost objective will determine that more buffers are allocated in this area. This is in conflict with the first objective of maximising the MT, where the best location is determined to be location L2. Location L3 is the worst buffer location in terms of the cost; yet, it is the second best location if the MTT is to be achieved.

4.3.3 Space

The next criterion is designing a BIW production line using the least amount of space possible. This is important not only because area requires investment, but also because of future expansion. Physical space is a considerable problem in most BIW production line projects. The future expansion of production lines is vital for OEMs to be sustainable. It is universally accepted that future sales demand will increase [63] and that BIW production lines will require expansion to cope with the additional volume needed. Most production facilities border other facilities and have additional physical constraints. Thus, expansion limits exist for these production lines. As with the second objective, the only real opportunity for space optimisation lies within the buffer system. Therefore, the third objective is determining the best location to place buffers in terms of the physical area requirements.

Two popular products from the reference OEM were considered as references to determine the physical space requirements for the different phases of production based on the defined locations (L1–L5). The total size was calculated using Equation (4.2):

$$V = l \times w \times h \tag{4.2}$$

where V is the volume and size of the assembly expressed in m^3; and l is the length, w is the width, and h is the height of the relevant assembly, each measured in metres (m).

The different assembly sizes were combined based on their locations for comparison with each another. The total space for location L1, for example, was calculated using Equation (4.3):

$$V_{L1} = V_{VB} + V_{BB} + V_{HB} \tag{4.3}$$

where V_{L1} is the volume of location L1, V_{VB} is the volume of assembly VB, V_{BB} is the volume of assembly BB, and V_{HB} is the volume of assembly HB. The total space values for locations L2–L5 were calculated using the same logic.

Figure 4.7 provides the final results for each location. It is better for the BIW production line when a location requires less space.

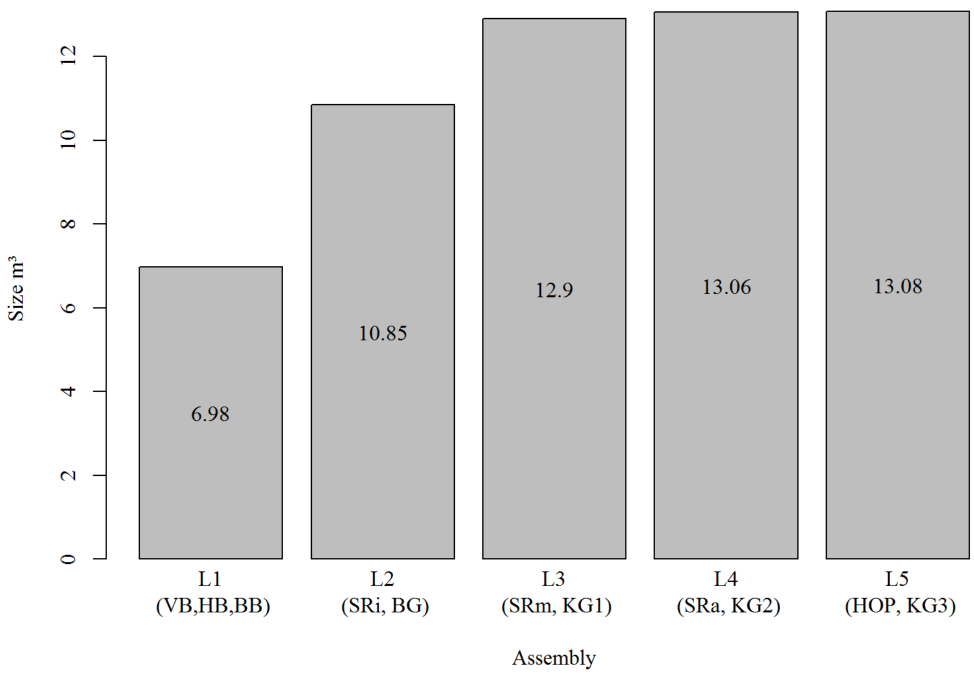


Figure 4.7: Sizes of BIW assemblies per location.

The previous logic was used again, where the entire WIP was moved from location to location, testing each location with the full quantity individually. Location L1 had the best performance in terms of the space usage, while the space usage at location L5 increased as expected as a result of the product growing and becoming the intended BIW. This means that an identical buffer amount at location L1 will use less space than in any other location, indicating that this will be the target location for this objective. Again, there is a big rivalry between locations. The most cost efficient location, location L5, becomes the worst location in terms of achieving the MTT and for space usage.

4.3.4 WIP

The final design criterion is to follow a lean design philosophy, which means minimising the WIP for the entire BIW production line. This is important for OEMs because lean manufacturing has the potential to improve product quality, reduce inventory, create more manufacturing flexibility, and improve the work environment in terms of safety. The fourth and final objective is determining a buffer solution where the WIP value can be minimised.

All of the relevant WIP information was provided by the reference OEM.

The WIP values were calculated using Equations (4.4)–(4.6):

$$WIP_x = PIU_x + MCU_x \tag{4.4}$$

where WIP is the cost per area x, PIU is the total product investment per unit, and MCU is the total material cost per unit.

$$PIU_x = \frac{PI_x}{upa \times a} \tag{4.5}$$

where PI is the total product investment per area x, upa is the total number of units that must be produced per annum, and a is the total number of production years expected, which in this case is seven.

$$MCU_x = SC_x + MC_x \tag{4.6}$$

where SC is the shipping cost per area x, and MC is the physical material cost per area. All the investment and cost figures were provided under a confidentiality agreement, and the results are displayed in terms of ratios.

Figure 4.8 shows the results for the total WIP value per area.

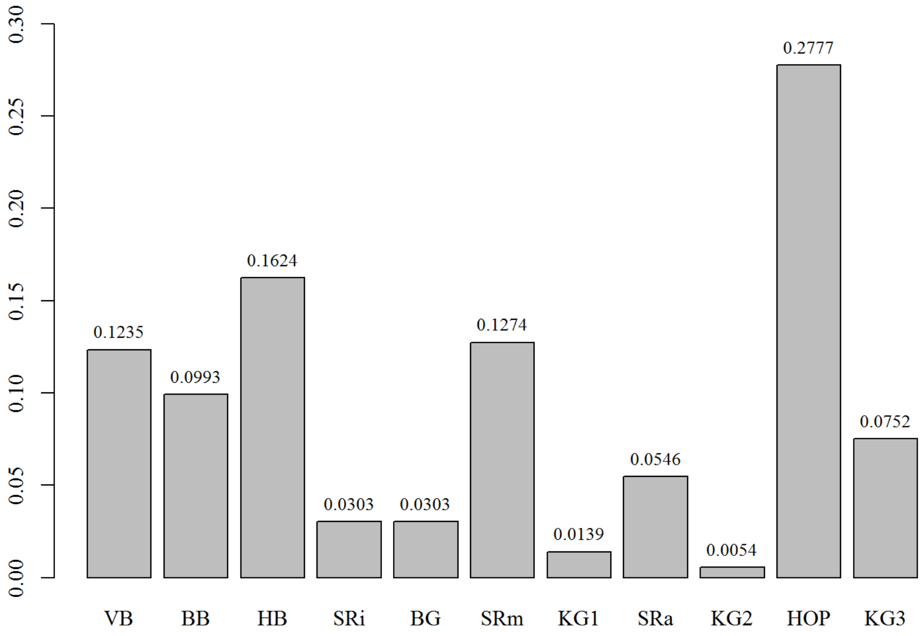


Figure 4.8: WIP value distribution of BIW assemblies per area.

The HOP is the assembly with the highest WIP value. The HOP is high because it includes all of the vehicle doors, the boot-lid, the bonnet, and the fenders. Other assemblies that also rank high are the VB, BB, HB, and SRm.

The WIP values for the different assemblies cannot simply be compared to each other as in Figure 4.8. Figure 4.8 only gives the WIP value per area. In real production, the total WIP value increases as the product moves through the production line. Thus, the WIP value is constantly accumulating with the product size. This concept is demonstrated by the waterfall model in Figure 4.9. The accumulated results are displayed in Figure 4.9.

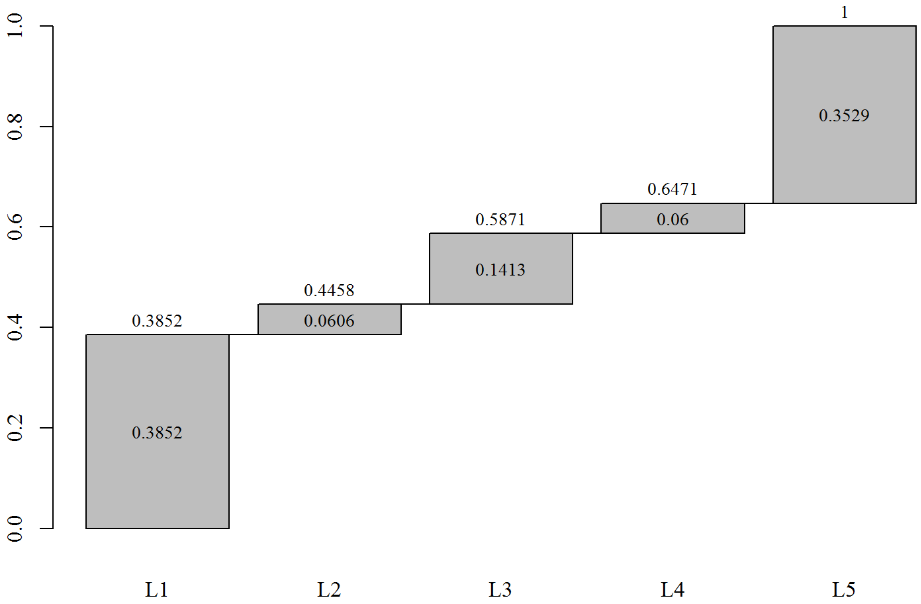


Figure 4.9: WIP value distribution of BIW assemblies per buffer location.

The previous logic was used again, where the entire WIP was moved from location to location, testing each location with the full quantity individually. The results indicate that location L1 has the highest individual WIP value. However, this is irrelevant because of the accumulation of costs during the production process. Therefore, the results indicate that the WIP value is the lowest at location L1, increasing continuously as the unit proceeds through the production system until location L5 is reached. In other words, the buffer at location L5 must be minimised (or no buffer should be used) because this specific location is the worst place to have a buffer in terms of the WIP. The results for the WIP and space are identical, which means that finding a good space solution will also result in a good WIP solution.

4.4 Dealing with multiple BIW objectives

So far, we have only dealt with assigning the WIP to single buffer locations. In this next section, we will deal with distributing the WIP through the various locations (L1–L5) and see how the results change. The preferred locations and buffer configurations are different for the four BIW production line BAM objectives. This means that, for example, when opting for a BAM design where the MT is to be maximized, the model will also automatically increase the buffer cost, space usage, and WIP, which has a negative effect on the other three objectives. Further, this means that an optimum solution does not exist for the BAM; there can only be an efficient solution because the objectives are competing against one another. However, according to Rardin [99], when using a multi-objective optimization model, there can be several efficient points on (solutions to) the model. Rardin described an efficient point as a feasible efficient solution if no other feasible solution scores at least as well for all of the objective functions and strictly better in one. These efficient points can be best described by the efficient frontier.

The efficient frontier is a collection of efficient points for a model, and in this thesis, it is plotted against the objective value space with axes corresponding to the objective functions instead of the decision variables [99]. The efficient frontier is constructed by optimising one objective, while parametrically varying the specified levels of the remaining objectives.

In the case of the BIW production line, there is a strong correlation between two of the objectives: the space and WIP. There is no correlation to the MT and cost. In this research, the efficient frontier was developed using the MT and cost objective to create the plots on this specified objective value space. Selecting these two objectives, as previously mentioned, is pre-emptive optimisation because these two objectives are considered by OEMs to be the most important in practice.

The MT and cost were chosen for the proposed research as examples because these would take priority in practice. However, this does not mean that the model cannot be used for the space or WIP. The beauty of the efficient frontier is that it allows decision-makers to choose which objectives they want to prioritise, which in turn can be plotted in any combination of objectives, allowing efficient solutions to be delivered.

The efficient frontier was created using the same experimental set-up. The following criteria and assumptions were used to define all of the points in the objective value space:

- The total buffer size of the entire production system was set at 20. A buffer size of 20 is workable and not too complex to simulate; further, it has a sufficient number of configurations to investigate the behaviour of the throughput in terms of different buffer configurations.
- Locations L1–L5 must be used for buffer storage as defined by the BIW production model from the previous sections.
- No location is allowed to have a zero buffer size. Thus, for location L1, the minimum buffer size is three, whereas the minimum at all the other locations is two. The minimum buffer sizes of three and two were selected because of the physical architecture demands of the BIW production line. There are always material handling systems between the different BIW sub-assembly areas (L1–L5), and these material handling systems automatically provide the BIW production line with a buffer system between these locations.

Using a total buffer size of 20, with five possible locations, where no location is allowed to have zero buffers, creates 715 possible buffer configurations for the entire production system. Each configuration was simulated 10 times. All the possible numbers of units across the five buffer locations were simulated, with the total number of buffer units in the system remaining at 20.

The results for the efficient frontier are given in Table 4.3 and Figure 4.10, with the complete results available in Appendix C.

Table 4.3: Buffer configurations and results for efficient frontier (in bold)

Exp. No.	L1	L2	L3	L4	L5	Mean volume	SD	MT	Cost factor
001	**3**	**2**	**2**	**2**	**11**	**114370.2**	**166.32**	**13.056**	**13.106**
002	3	2	2	3	10	114655.3	173.57	13.089	13.338
003	3	2	2	4	9	114669.3	173.671	13.09	13.57
004	3	2	2	5	8	114766.6	173.062	13.101	13.802
005	3	2	2	6	7	114766.3	173.347	13.101	14.034
006	3	2	2	7	6	114799.1	173.692	13.105	14.266
007	3	2	2	8	5	114792.5	173.074	13.104	14.498
008	3	2	2	9	4	114801.1	174.576	13.105	14.73
009	3	2	2	10	3	114778.8	173.566	13.103	14.962
...	...	...	...	...	...	...	...		...
220	3	11	2	2	2	115722.5	198.918	13.21	14.645
221	**4**	**2**	**2**	**2**	**10**	**116694.3**	**170.43**	**13.321**	**13.258**
...	...	...	...	...	...	...	...		...
385	4	10	2	2	2	117862.2	188.367	13.455	14.626
386	**5**	**2**	**2**	**2**	**9**	**119032.9**	**174.275**	**13.588**	**13.41**
...	...	...	...	...	...	...	...		...
591	**7**	**2**	**2**	**3**	**6**	**121679.7**	**168.618**	**13.89**	**13.946**
...	...	...	...	...	...	...	...		...
646	**8**	**2**	**2**	**2**	**6**	**122286.3**	**165.65**	**13.96**	**13.866**
...	...	...	...	...	...	...	...		...
661	**8**	**3**	**2**	**2**	**5**	**123031.4**	**165.471**	**14.045**	**14.037**
...	...	...	...	...	...	...	...		...
707	**10**	**3**	**2**	**2**	**3**	**123454.3**	**155.982**	**14.093**	**14.341**
...	...	...	...	...	...	...	...		...
715	12	2	2	2	2	122375.7	166.741	13.97	14.474

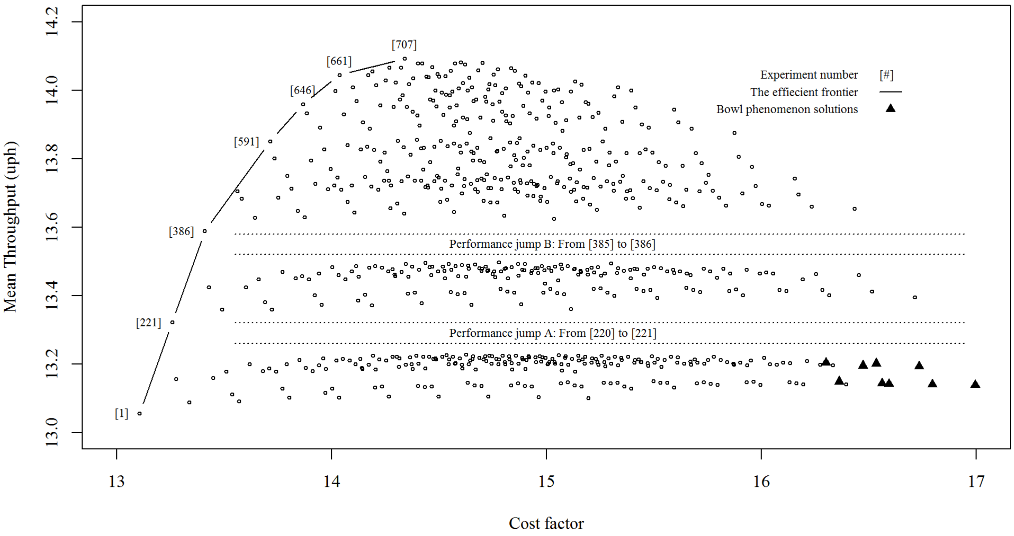


Figure 4.10: Efficient frontier for BIW production line BAM.

The efficient frontier comprises a total of seven efficient solutions (1, 221, 386, 591, 646, 661, 707). The lines between points are indications of other potentially efficient solutions. For the first three solutions (1, 221, 386) there is a steady increase in the MT when the total buffer cost also increases.

However, the MT flattens slightly between the next three solutions (591, 646, 661) until there is an evident flat-out from the last solution (707), indicating that any increase in the buffer cost will not result in much improvement in performance (MT) because the system is saturated beyond this point. The cost factor in Figure 4.10 is related to the basic costs for material handling systems and static buffer structures, as listed in Table 4.1 and shown in Figure 4.6.

There are also two performance jumps identifiable in Figure 4.10. These two performance jumps, marked *A* and *B*, are caused by increases in the buffer quantity at location L1. Performance jump A occurs when the total buffer size at location L1 is increased from three to four, and performance jump B occurs when the total buffer size at location L1 is further increased from four to five. This indicates that the buffer at location L2 is well-supported by that at location L1. This also indicates that the solution results in a greater output when the locations are combined compared to standing alone. The results further illustrate the competition for location by offering a better cost factor when the buffer sizes are increased at L5, which shows how the different objectives compete against each other and how certain trade-offs are required.

In Figure 4.11, the different efficient solutions are compared with each other.

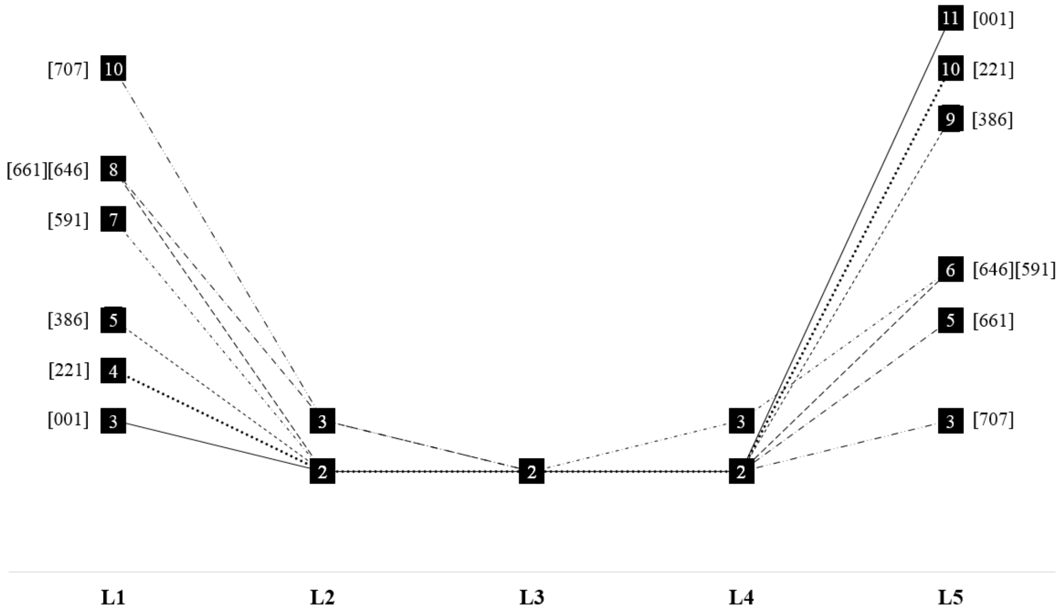


Figure 4.11: Efficient points of efficient frontier for BIW production line BAM.

It should be noted that for all seven efficient points, there are similar buffer configurations in terms of the size per location. In every single solution, the largest buffer sizes are found at the start of the production line at location L1 and/or at location L5. Locations L2–L4 have the smallest values. There is an almost symmetrical pattern around location L3 for all of the efficient points. This indicates that the most efficient solutions for the BIW production line are concentrated around location L1, which is an advantage for the space and WIP objectives, and location L5, which is an advantage for the cost objective. Moreover, there is not a single efficient point that allows for the maximum MT by allocating the most buffers at location L2.

The results indicate a definite pattern that follows a ‘u’ shape. This is interesting because this solution is the complete opposite of the bowl phenomenon. The ‘u’ shape solutions prove that when multiple objectives are considered, the results can be completely different from those based on the classical theories.

A further observation is made regarding the types of solutions that follow the bowl phenomenon. It can be seen that almost all of the worst solutions adhere to the bowl phenomenon theory, as indicated by a black triangle in Figure 4.10. This means that for BIW production lines, the worst solutions will be the bowl phenomenon solutions if multiple objectives are considered.

4.5 Conclusions

In this chapter, we evaluated the placement and size of buffers in a BIW production line using multiple, competing objectives. In the classic approach, referred to as the bowl phenomenon, the heuristics suggest that the largest buffer should be placed in the centre of the production line [12]. This chapter showed that this is only the case when the work stations for the line have equal amounts of equipment, and similar reliabilities. The efficient frontier resulting from the suggested multi-objective approach provided contradictory results and suggested that more buffers should be placed upstream when the cost, throughput, space, and WIP are considered. Several efficient points were identified; these can assist decision makers to determine the solution to implement, depending on which objective is a priority.

The efficient frontier defined in this chapter creates a solution that is completely different from that of the classic bowl phenomenon. This is not because the bowl phenomenon is incorrect. Rather, it is simply an indication of how solutions can change when multiple objectives are considered during buffer design. The further definition of the 'u' shape is a big hint to BIW system design engineers that more buffers must be allocated at the beginning and/or end of the production line. The next step is to evaluate this efficient frontier.

Chapter 5

Evaluating efficient frontier of BIW production line

The efficient frontier of a Body-in-White (BIW) production line offers multi-objective-based solutions that provide BIW system design engineers with a clear target line against which their designed buffer system can be benchmarked. However, the frontier defined in chapter 4 remains untested.

The purpose of this chapter is to test the frontier. This is achieved with the aid of two real production lines from the reference Original Equipment Manufacturer (OEM). First, the two production lines are plotted on the frontier objective space area. This is done for two reasons: to establish a visual impression of each production line and plot an absolute position from which further optimisation is possible. The next step is to identify efficient points on the frontier from which the existing production lines can be optimised by changing their actual buffer design. The production lines are then altered using the Buffer Allocation Model (BAM) of the selected solution, which means the total system buffer quantity remains constant, but the quantity per location is modified to fit the profile of the selected solution. The relevant values of the four objectives are recorded before and after the change. The results are analysed by comparing the before and after states of the buffer system's relevant objective values.

This chapter is divided into four sections. The first section plots the reference BIW production lines on the efficient frontier plot derived in chapter 4. In the second section, the first production lines are studied and altered. The third section studies the second production line, and the fourth section summarises and discusses the results of both production lines.

5.1 Referencing BIW production lines on efficient frontier

Two production lines are investigated. The first is a 15 units per hour (uph) production line with an Overall Equipment Effectiveness (OEE) of 0.85. This production line is referred to as BIW production line 1. BIW production line 1 has a total buffer capacity of 158 units. The second production line is a 13.5 uph production line with an OEE of 0.83 and a total buffer capacity of 103. This production line is referred to as BIW production line 2.

In Figure 5.1, both production lines are plotted and compared to the efficient frontier defined in chapter 4. The configurations for production lines 1 and 2 were established by scaling down the buffer setup from 158 and 103, respectively, to 20. This downscaling causes both lines to have the same total buffer size of 20, which is equal and comparable to the buffer configuration used to create the frontier.

The buffer configuration downscaling of production lines 1 and 2 was achieved using Equations 5.1 and 5.2, respectively:

$$B20_x = \frac{B158_x}{158} \times 20 \tag{5.1}$$

$$B20_x = \frac{B103_x}{103} \times 20 \tag{5.2}$$

where $B158$ and $B103$ are the buffer sizes at location x, and $B20$ is the result of the downscaling.

The downscaling results in production lines 1 and 2 having identical buffer configurations to experiments 401 and 506, respectively.

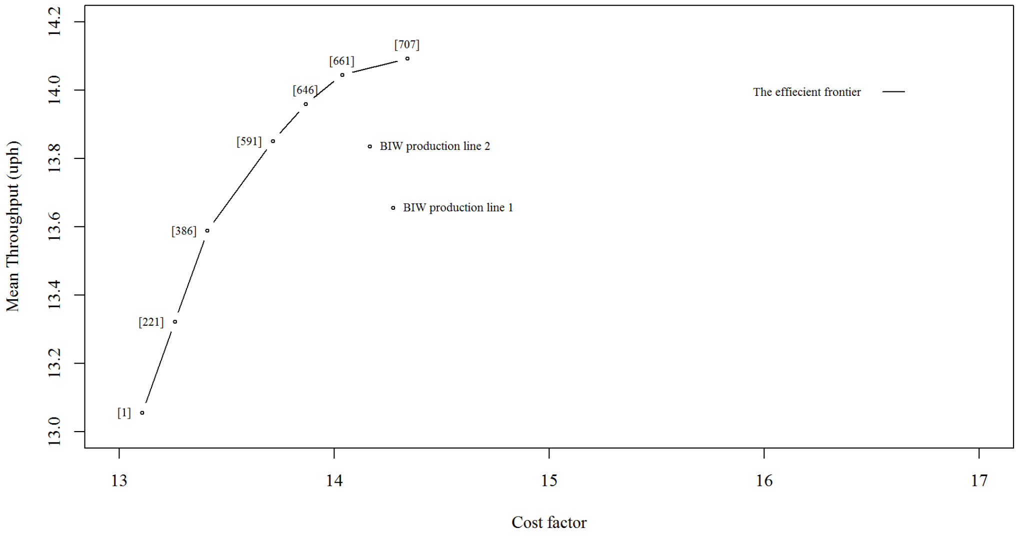


Figure 5.1: Reference BIW production lines on efficient frontier.

The downscaling allows the exact buffer configurations from both production lines to be plotted on the frontier graph. It is observed that both lines fall below the efficient frontier, meaning that they are both dominated, i.e. inefficient. In theory, if both production lines follow the same buffer configuration as either experiment plot 646 or 661, there would be an increase in the Mean Throughput (MT) and a decrease in the cost, resulting in a much better solution for the OEM. To test this theory, BIW production line 1 is modified with the buffer configuration of experiment 646, and BIW production line 2 is modified with that of 661. The expectation is that there will be an increase in the MT and a decrease in the buffer cost for each production line. The meeting of this expectation will confirm that the proposed efficient frontier is reliable and valid.

5.2 BIW production line 1

The first BIW production line under investigation is BIW production line 1. The line was designed in 2009–2010 and is the reference production line in chapter 1.

BIW production line 1, and later production line 2, will be referred to using one of two buffer configuration states, the *current state* and *comparative state*. The current state is the original state of the production line with its original buffer configuration, whereas the comparative state represents the modified buffer configuration for the production line in accordance with experiment 646.

5.2.1 Current and comparative BAM states

In the current state, the total buffer capacity of BIW production line 1 is 158. The 158-buffer capacity is distributed between locations L1 and L5, as illustrated in Figure 5.2a.

The buffer distribution of the BIW production line's current state has a 'w' shape, indicating that the majority of the buffers are located at locations L1, L3, and L5, with the majority at L5.

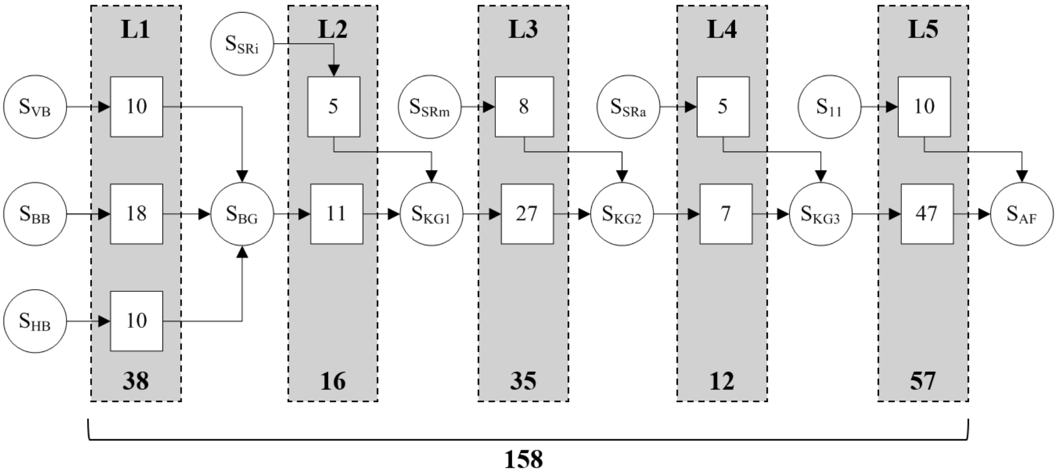
In the comparative state, the total buffer capacity of BIW production line 1 remains at 158; however, these 158 are redistributed according to the frontier buffer configuration of experiment solution 646.

To change the buffer configuration from that of experiment 646 to a relevant configuration similar to production line 1, it is necessary to upscale the buffer system. This is achieved using Equation 5.3:

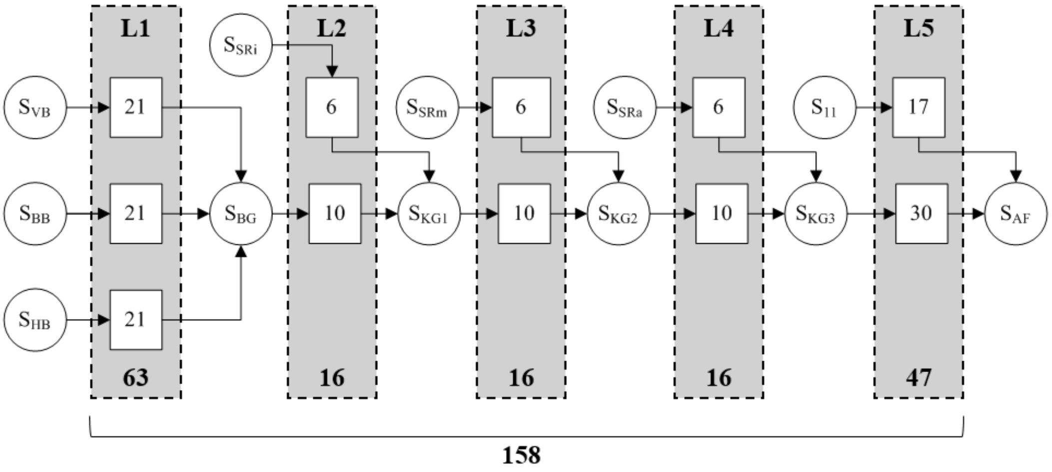
$$B158_x = exp646_x \times \frac{158}{20} \tag{5.3}$$

where $exp646$ is the buffer size of experiment 646 location x, and $B158$ is the result of the upscaling.

The final buffer model of the comparative state is shown in Figure 5.2b. The



(a) Current buffer configuration.



(b) Comparative buffer configuration.

Figure 5.2: Comparing buffer configurations of current and comparative cases for 158-buffer line with MT of 15.0uph and OEE of 0.85.

buffer distribution shape changes significantly from the ’w’ shape in the current state to a ‘u’ shape in the comparative state. This means that the buffer at the middle location (L3) was moved to the beginning (L1) and end (L5) of the production line. The change in shape confirms the successful transformation of the buffer configuration of production line 1.

It should be noted in Figure 5.2 that the internal ratios of the buffer systems were also changed. This was done arbitrarily because changing the internal configurations did not significantly affect the simulation results. Simulating all of the combinations is not realistic because the total number of possible solutions becomes so large that simulation becomes impractical.

5.2.2 Results

The results of each state, current and comparative, were recorded and are evaluated using the four important BIW production line objectives.

The first objective, the MT, provides an overview of the change in the throughput performance. The throughput results are obtained using the same experimental simulation set-up as discussed in chapter 4. The BIW production line was carefully re-constructed for the simulation with the assistance of the original BIW system design engineer from the original project. This means that reliable and accurate OEE data for the input parameters were used, including the availability, quality, performance, and Net Ideal Cycle Time (NICT).

The results of the simulations are listed in Table 5.1.

Table 5.1: MT comparison of current and comparative states of production line 1.

KPI	**Target**	**Status 1**	**Status 2**
MT (uph)	15	14.77	14.85

Table 5.1 confirms that there is an MT improvement from the current to the comparative state. This MT increase was expected and is an early indication that the frontier did assist in achieving a better result.

Objective 2 was to evaluate the buffer investment. The buffer cost was calculated by accumulating the total buffer cost per location. To ensure that the current and comparative configurations are comparable, identical buffer types are used for both states. Although changing the buffer types to more feasible types for the comparative state could potentiality further improve the total buffer cost, the decision was made not to do this. It was assumed that the BIW system design engineers chose the specific conveyor types based on specific technical reasons or constraints, and therefore these were not changed.

The results of objective 2 are provided in Table 5.2.

Table 5.2: Buffer cost comparison of current and comparative states of production line 1.

State	**L1**	**L2**	**L3**	**L4**	**L5**	**Cost factor**
State 1	3.61	3.60	7.58	4.14	5.51	24.44
State 2	4.00	3.60	6.46	4.44	5.50	24.00

The results indicate an improvement from the current to the comparative state, further confirming that the frontier assisted in achieving a better result. The cost factor is based on the data of Figure 4.6 for 20 buffer locations. This means, for example, that the total cost factor of 24.44 for the current state is 24.44 times more expensive than the *static steel structure for a medium size assembly*, as described in Figure 4.6. This cost factor was again chosen to ensure that the financial investment information of the reference OEM remains confidential.

The third objective is a buffer size comparison. The total space usage of each state was determined simply by adding all of the required assembly space per location based on the relevant state solution (Figure 4.7).

Table 5.3 gives an overview of the results.

Table 5.3: Space requirement comparison of current and comparative states of production line 1.

State	**L1**	**L2**	**L3**	**L4**	**L5**	**Total size**
State 1	265.24	173.60	451.50	156.72	745.56	1792.62
State 2	439.74	173.60	206.40	208.96	614.76	1643.46

For the third consecutive time, the results of the comparative state are better than those of the current state. The space requirement for the comparative state is reduced, indicating that the OEM requires less physical space if the comparative state is implemented instead of the current state. This a major advantage for the OEM because it improves the product integration flexibility, as well as the sustainability of the production line.

The final objective for assessment is the total Work-in-Process (WIP) value of each of the two states. The goal of this is to determine which state performs better in terms of a lower WIP value. Again, this was achieved by accumulating the total WIP value per location for each state (Figure 4.8).

The results are provided in Table 5.4. There is a visible improvement in the total WIP value for the comparative state compared to the current state; this is an indication that the modified BIW production line also has better results for this objective.

Table 5.4: WIP comparison of current and comparative states of production line 1

State	**L1**	**L2**	**L3**	**L4**	**L5**	**Total site**
State 1	14.64	7.13	20.55	7.77	57	107.08
State 2	24.27	7.13	9.39	10.35	47	98.15

There are improvements in each of the four objectives for production line 1 from the current to the comparative state, indicating that the modified buffer configuration performs better than the original configuration. These improvements are in accordance with the expected results.

5.3 BIW production line 2

The second BIW production line under investigation is BIW production line 2. This line was designed in 2015–2016, and its data were also provided by the reference OEM.

The line was designed based on a strict lean manufacturing philosophy. BIW production line 2 has an Mean Throughput Target (MTT) that is 10% lower than that of BIW production line 1, as well as a 33% smaller buffer size, indicating and confirming the trend towards the lean manufacturing philosophy.

5.3.1 Current and comparative BAM

The total buffer capacity for BIW production line 2 is 103. The 103 buffer units are also distributed between locations L1 and L5, as illustrated in Figure 5.3a.

Figure 5.3a provides an overview of the buffer capacities at locations L1 and L5, with the exact size per assembly.

The profile of BIW production line 2 is very interesting and quite different from that of BIW production line 1. The profile of BIW production line 2 has a ‘u’ shape, similar to the comparative state profile of production line 1. This is consistent with the efficient solutions of the frontier.

In the comparative state for BIW production line 2, the total buffer capacity of 103 remains constant, and the logic used for BIW production line 1 is used to redistribute the buffers. Figure 5.3b shows the results of the transformation. In the configuration change from the current to the comparative state, the profile remains a ‘u’ shape, but the ‘u’ is somewhat down adjusted, which again confirms the successful transformation.

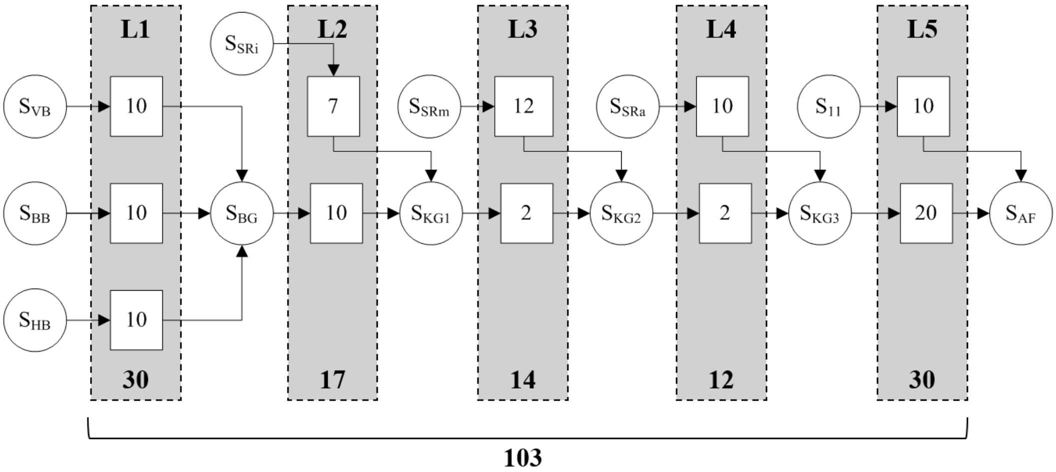
5.3.2 Results

The results of production line 2 are obtained using the same methodology as that used for production line 1.

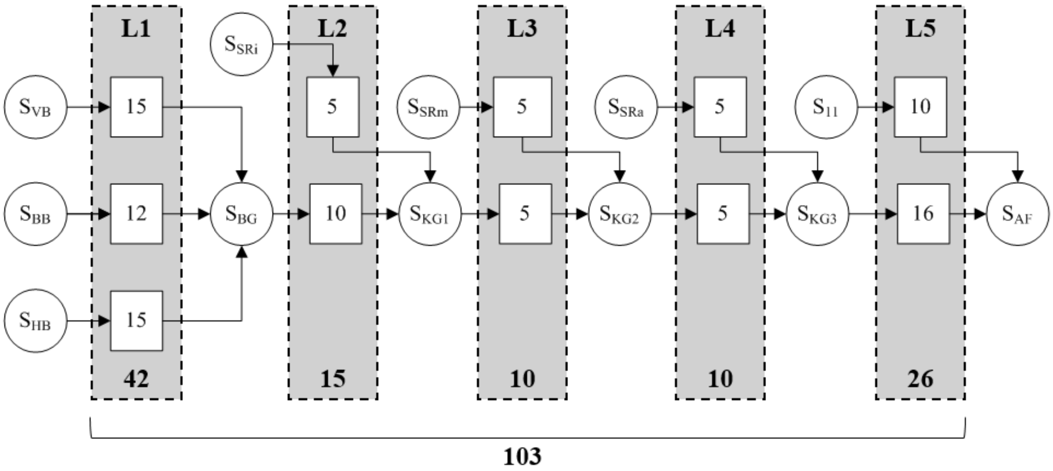
The MT results are listed in Table 5.5. As with production line 1, production line 2 shows an improvement in the MT from the comparative state to the current state.

Table 5.5: MT comparison of current and comparative states of production line 2

KPI	**Target**	**State 1**	**State 2**
MT (uph)	13.5	13.54	13.64



(a) Current buffer configuration.



(b) Comparative buffer configuration.

Figure 5.3: Comparison of buffer configurations for current and comparative cases of 103-buffer line with MT of 13.5uph and OEE of 0.83.

The rest of the objective results are given by Table 5.6. The overall results indicate that the buffer investment required for the comparative state is lower than that for the current state. This is a further indication that the new state performs better. In addition, the comparative state requires less space compared to the current state, and has a better WIP factor. This is further confirmation that these objectives are improved by using the frontier.

Table 5.6: Cost factor, space, and WIP comparison of current and comparative states of production line 2

	L1		**L2**		**L3**		**L4**		**L5**		**Total**	
	Cur	**Comp**	**Cur**	**Comp**	**Cur**	**Comp**	**Cur**	**Comp**	**Cur**	**Comp**	**Cur**	**Comp**
Cost factor	3.49	3.68	3.66	3.54	6.19	5.66	4.14	3.98	5.47	5.46	22.94	22.32
Space usage	209.40	293.16	184.45	162.75	180.60	129.00	156.72	130.60	392.40	340.08	1123.57	1055.59
WIP factor	11.56	16.18	7.58	6.69	8.22	5.87	7.77	6.47	30.00	26.00	65.12	61.21

In summary, and analogous to production line 1, the frontier contributes further to the improvement of all four important BIW objectives.

5.4 Summary

The final results indicate that both production lines studied improved with the use of the efficient frontier defined in the previous chapter.

Tables 5.7 and 5.8 provide a summary of the results.

Table 5.7: Results summary of current and comparative states for production line 1

Objective	**Current**	**Comparative**	**Result**
MT	14.77	14.85	+ 0.006
Buffer cost	24.44	24.00	- 0.018
Space	1792.62	1643.46	- 0.083
WIP	107.08	98.15	- 0.083

The MT values of production lines 1 and 2 improved by 0.6% and 0.8%, respectively. These improvements might be considered small, but they support the argument that BIW system design engineers should optimise this parameter as a single objective when designing the buffer system of a BIW production line. However,

Table 5.8: Results summary of current and comparative states for production line 2

Objective	**Current**	**Comparative**	**Result**
MT	13.54	13.64	+ 0.008
Buffer cost	22.94	22.32	- 0.027
Space	1123.57	1055.59	- 0.061
WIP	65.12	61.21	- 0.060

the almost 0.1 uph increases in both production lines produce a total of approximately 5,000 extra vehicles over the lifetimes of the production lines. Thus, a small increase has a significant effect. This increase in performance is noted and achieved.

In addition, the cost factors of both production lines are further reduced. Reductions of 1.8% and 2.7% are observed for production lines 1 and 2, respectively. In essence, this means that the relevant OEM could have achieved a greater throughput for less investment.

The main output of this research is the reduction of the space and WIP from the current to the comparative state. For production line 1, both of these objectives are improved by 8.3%; for production line 2, the improvements are 6.1% and 6%, respectively.

Referring back to the South African project, this means that there could have been a small increase in the throughput. However, this increase in throughput would not have relieved the production output pressure that was caused by the various factors during the project realisation. However, the options that would be available if the proposed model were implemented would have made a significant difference. For example, the extra area would allow for a larger production area, and bottleneck processes could have been duplicated and installed in the extra space, which would provide a major relief in areas where the cycle time was high or the OEE was low. The proposed method would also have a major positive impact on the OEM when considering the number of projects that are being executed worldwide, where accumulating all of the small gains of each project would add up to a significant amount that could be reinvested in other projects where funds are required.

5.5 Conclusions

The results confirm that the efficient frontier is useful because it improves the efficiencies of all the objectives. The frontier can be used successfully as a benchmark, as well as a tool for optimising BIW production lines where multiple objectives must be achieved. The efficient frontier delivers a clear line of efficient solutions in terms of buffer configurations for BIW production lines.

During this study, two real production lines were used to test the frontier defined in chapter 4. The research showed that all four objectives could be improved if the efficient buffer configuration was applied to both production lines. The frontier not only improves the objective space parameters defined in the frontier, the MT and cost, but also the physical space and WIP. Finally, it is concluded that the efficient frontier has a positive influence on design objectives such as efficient buffer allocation, and the frontier can be generalised for use with larger problems.

Chapter 6

Conclusions

Some conclusions can be stated about the project in South Africa that was considered to be a victim of misfortune. This thesis examined and ultimately answered the open questions arising from the problems experienced by this project during its launch year.

This research managed to successfully study the case of the South African project by focusing on two key aspects: estimating the Net Ideal Cycle Time (NICT) and studying the buffer allocation in Body-in-White (BIW) production lines. The project in South Africa did not fail because of an incorrect NICT estimation, or as a result of an incorrect buffer allocation. Its failure can be attributed to many factors that each slightly eroded the project until the project ultimately failed. Although the NICT and buffer allocation were not responsible for the failure, they did not have positive effects on the project. If the project had used a more accurate NICT to drive equipment selection, or a more efficient Buffer Allocation Model (BAM), the problems definitely would have been reduced, but not completely avoided.

The failure of the South African project succeeded in creating interesting questions regarding system design for BIW production lines. Although the cost of recovery was high, and the price was paid in full, after five years, there is some compensation in the form of new knowledge gained.

6.1 Contribution to new knowledge and significance of research

It can be concluded with confidence that this research has successfully contributed new knowledge to the fields of cycle time and buffer allocation research. Although both topics discussed in this research are relevant to the BIW domain in the automotive manufacturing industry, the results can also likely be applied to various other manufacturing and production industries.

First, this research successfully managed to critically evaluate the current method used to estimate the NICT for a BIW production line. This is the first time that this has been achieved in research. The evaluation further assisted in the analysis of the real throughput distribution of a BIW production line, and it was found that the throughput most certainly has a Weibull distribution. This is significant because students and BIW system design engineers are now able to better understand the characteristics of production output relating to this type of production system. This knowledge could lead to further research on the process variation and predictive maintenance of production lines. Finally, the finding of a Weibull distribution inspired the development of a new method to estimate the NICT based on the empirical data of a BIW production line. I argue that this new method is more robust and accurate than the current method, and increases the selection of NICT estimators. As shown in one of the papers[1] that resulted from this thesis, the proposed method will also have financial benefits to the Original Equipment Manufacturers (OEMs). This paper is still under review.

The second focal point of this research was the study of a buffer system inside a BIW production line. This research made it clear that there are at least four important objectives that must be considered when designing a buffer system for a BIW production line. The research further demonstrated how these objectives compete with one another, and how certain trade-offs are required. This research

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[1] Grobler, W.C., Kotze, D.J., Joubert, J.W., *Estimating net ideal cycle time for body-in-white production lines*

not only managed to solve the Buffer Allocation Problem (BAP) for BIW production lines, but actually went a step further and defined the efficient frontier for the buffer system. To date, an efficient frontier has not existed for this specific production line. The major advantage of the efficient frontier is that it provides engineers and decision-makers with a clear target of where the buffer system should perform in terms of various objectives, and it is easy to benchmark a proposed solution with the efficient frontier to evaluate the efficiency of the solution.

The contributions of this research are not merely relevant in theory, but also in practice. This research has made a contribution to new knowledge in both disciplines, and even further demonstrates that both contributions would have had a major positive impact on the project in South Africa had it been implemented before the project.

Firstly, during 2012, in the launch year, a couple of thousand units were lost due cycle time non-performance. This tallies to millions of Euro in profit losses. Was the proposed method used instead, then an extra one-time investment would have been required. The extra required investment would have been far less than the loss in profits however. This means for the year 2012 only, already there would have been a return on investment of almost 10%. The losses from 2013–2015 was much smaller but it would have added positively to the return on investment. The South African project is one of the few examples where the production line under performed. The relevant OEM has got several production facility spread across the world. In Leipzig Germany for example, there is a production facility that over performs regularly. This means production of cars outweighs the sales. If the proposed method is now implemented in this facility as well, there will be a decrease in one time investment. Considering then all production facilities worldwide, at least 15 in the case of the specific OEM, this new method will not only improve for example the conditions in South Africa, but the OEM will have a much more balanced investment vs. performance ratio worldwide, resulting in a much more profitable global production network.

The proposed efficient frontier would have further made a major contribution to the project in South Africa. In 2015 it was decided that a new project would again be installed in the current production facility. A brand new BIW facility was decided for the project because of one constraint, physical space. The new facility required a massive structure investment. Was a new facility not required, the structure investment for the project would have been almost 70% lower.

6.2 Limitations of research

Although this research provides a highly comprehensive overview of NICT estimation and buffer allocation, it was limited to two production lines with throughputs of 13.5uph and 15uph. In the automotive manufacturing industry, these are considered to be low-throughput production lines.

Production lines can vary between 5units per hour (uph) and 75uph. The majority of high-throughput lines are in the range of 45–60uph. These high throughput lines were considered when evaluating the usefulness of the frontier. Thus, we feel that our results can be generalised to include high-throughput lines. It is postulated that such lines will deliver similar results.

The second limitation is that this research used configurations of only 20 buffer units to establish the efficient frontier. Increasing this value to 100 (for example) will yield a more detailed solution resolution with many more efficient points, but this has an associated computational price. The goal of this research was never to establish the perfect buffer system for a BIW production line. Rather, it was to study and understand the best Work-in-Process (WIP) placements within a buffer system to yield a more efficient system. Based on this thesis, a new Master's thesis is currently being completed by Mr. Dirk Kotze to bridge the full-enumeration approach by developing a better simulation model that can handle larger size buffers, using an intelligent search algorithm.

6.3 Research implementation

The results of this research were formally presented to the OEM referenced in this study. The OEM acknowledged the results, and good constructive feedback was provided regarding the research. The OEM has further confirmed that the implementation of the NICT estimation method and efficient frontier seem reasonable, and further implementation discussions are currently underway.

6.4 Research beneficiaries

The two topics of this research ensured that it has several beneficiaries.

In the academic world, the main beneficiaries will be industrial engineering students studying production systems. The research provides good insight regarding the reality of the production world through the mini-case study presented in chapter 1. The research takes an in-depth look at the cycle time, types of cycle time, and how to estimate the NICT. The discussions of buffer allocation and the efficient frontier will also give students the opportunity to understand that there are almost always more than one objective to achieve in engineering, and that searching for efficient solutions with trade-offs is more common and realistic than trying to find optimum solutions.

The second main beneficiary is the industry itself. The research focussed on BIW production lines, but the concept could be transferred to other production industries as well. Thus, industry is given a second method to estimate the NICT. The in-depth look at buffer systems in chapters 4 and 5 could also allow OEMs to deliver solutions that are more efficient than the current solutions.

6.5 Further research

As a first step, research into higher throughput lines is recommended to confirm that the theories and concepts discussed in this paper, especially the buffer ratios, will also be applicable to them. More case studies are recommended to help build a knowledge base for the BIW production systems of different countries.

Second, further research is recommended on the application of the Weibull distribution inside a BIW production line. Studying the Weibull distribution can inform quality control and quality assurance practices which, in turn, can aid with topics such as preventative maintenance in the production system. Having an in-depth look into right truncated Weibull distributions to determine Upper Specification Limit (USL) is also proposed to replace the negotiation method with a solid calculation.

Last, it is recommended that the application of the efficient frontier be studied in relation to more specific BIW production line subjects. The efficient frontier delivers excellent benchmarking capabilities that will allow engineers to design and deliver better solutions for their relevant applications.

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Appendices

Appendix A

Throughput distribution graphs

A.1 Throughput distribution reference graphs of the reference BIW 2012

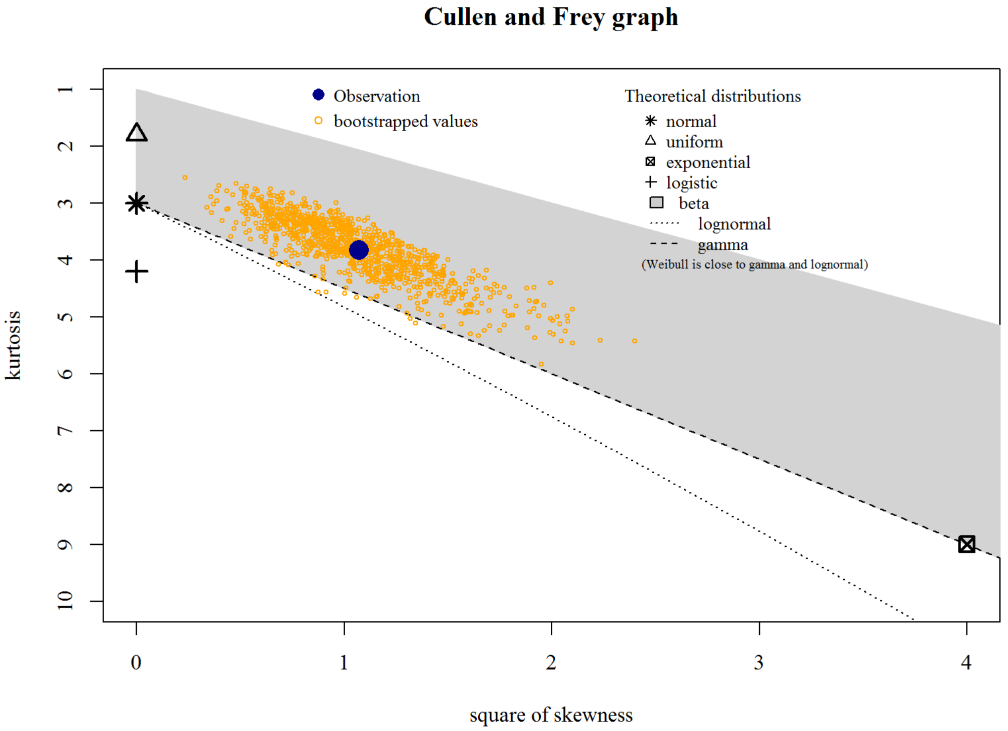
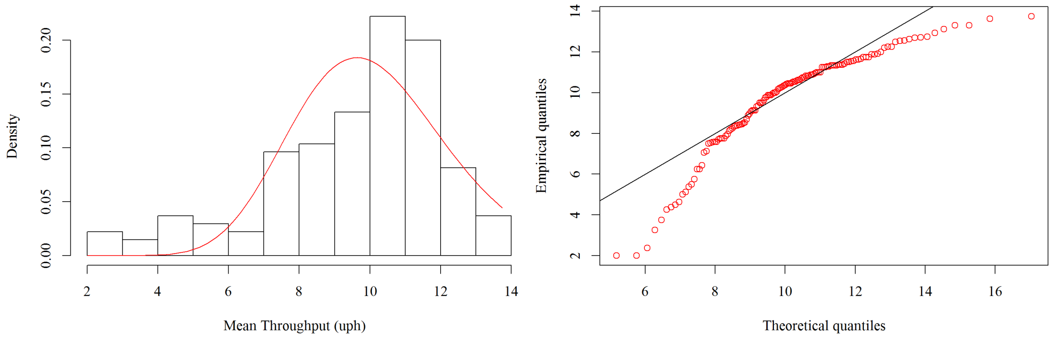
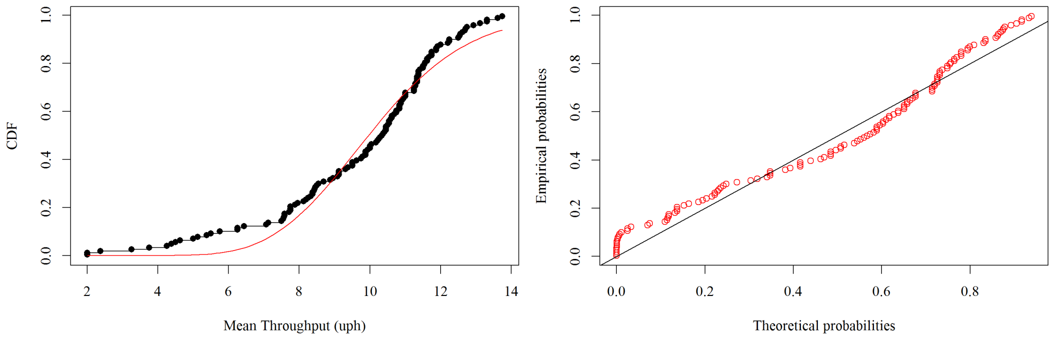


Figure A.1: The 2012 throughput data of the reference BIW plotted on a Cullen and Frey graph.



(a) Histogram and theoretical densities

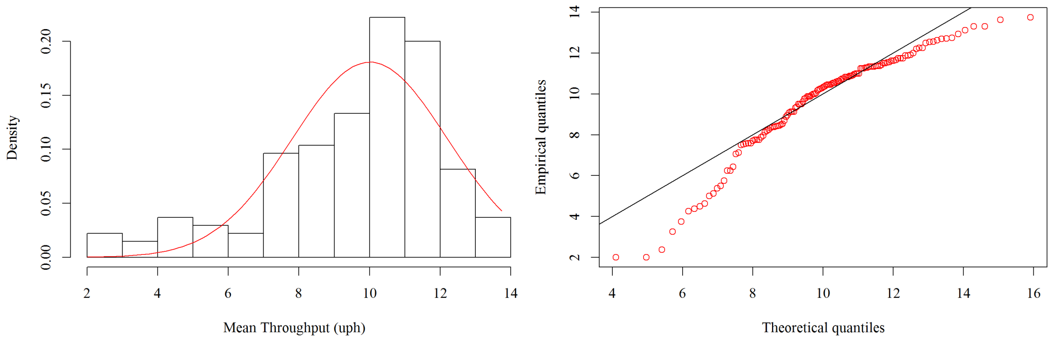
(b) Q-Q plot



(c) Empirical and theoretical CDFs

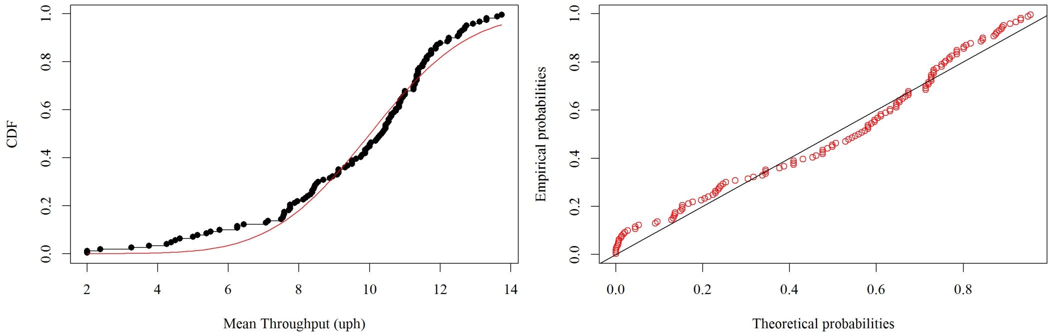
(d) P-P plot

Figure A.2: The 2012 throughput data of the reference BIW compared to a theoretical throughput of a gamma distribution.



(a) Histogram and theoretical densities

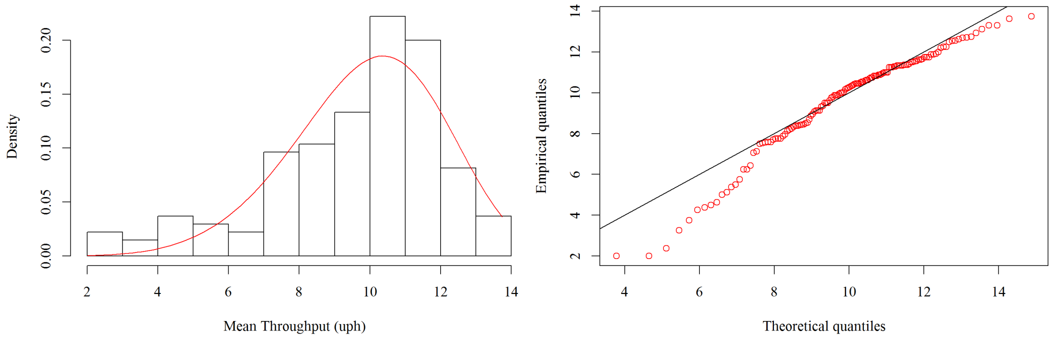
(b) Q-Q plot



(c) Empirical and theoretical CDFs

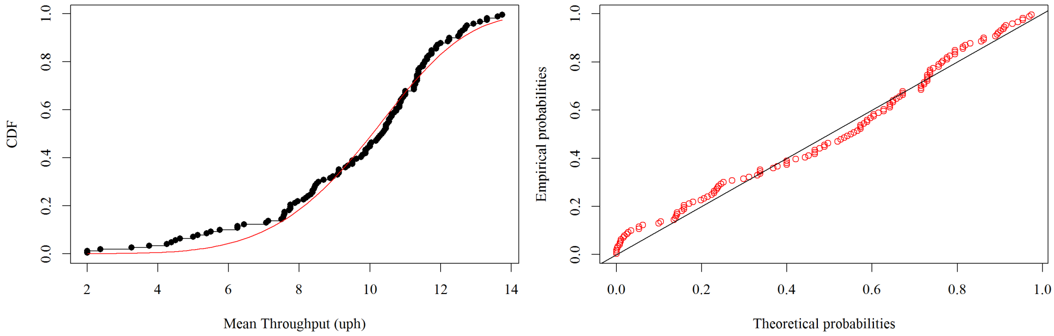
(d) P-P plot

Figure A.3: The 2012 throughput data of the reference BIW compared to a theoretical throughput of a normal distribution.



(a) Histogram and theoretical densities

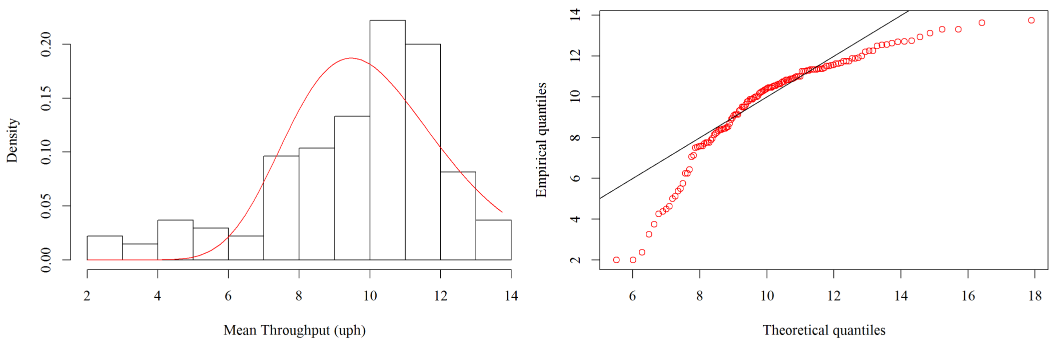
(b) Q-Q plot



(c) Empirical and theoretical CDFs

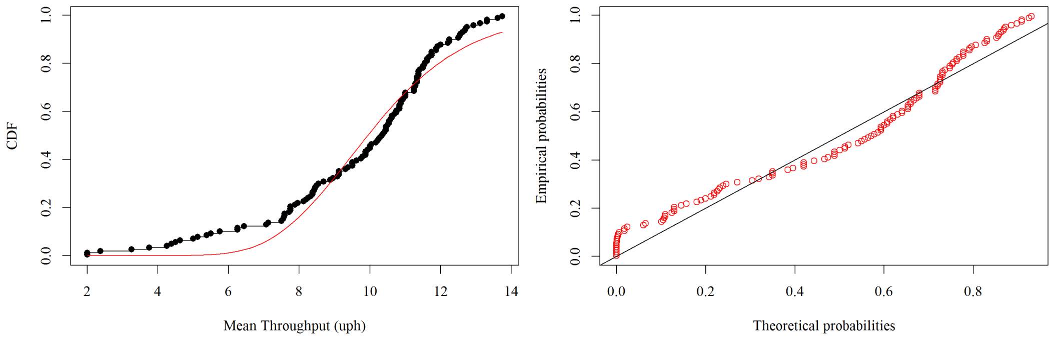
(d) P-P plot

Figure A.4: The 2012 throughput data of the reference BIW compared to a theoretical throughput of a weibull distribution.



(a) Histogram and theoretical densities

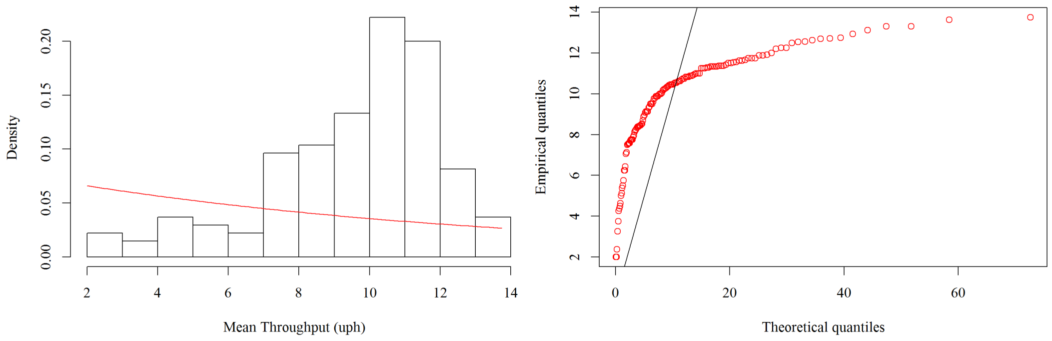
(b) Q-Q plot



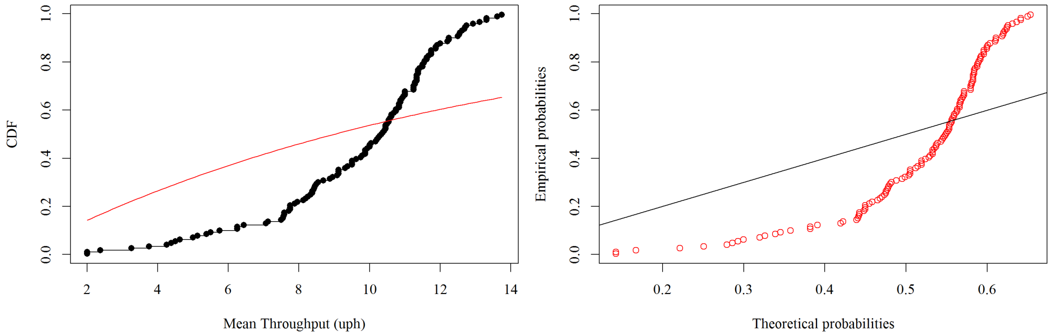
(c) Empirical and theoretical CDFs

(d) P-P plot

Figure A.5: The 2012 throughput data of the reference BIW compared to a theoretical throughput of a log-normal distribution.

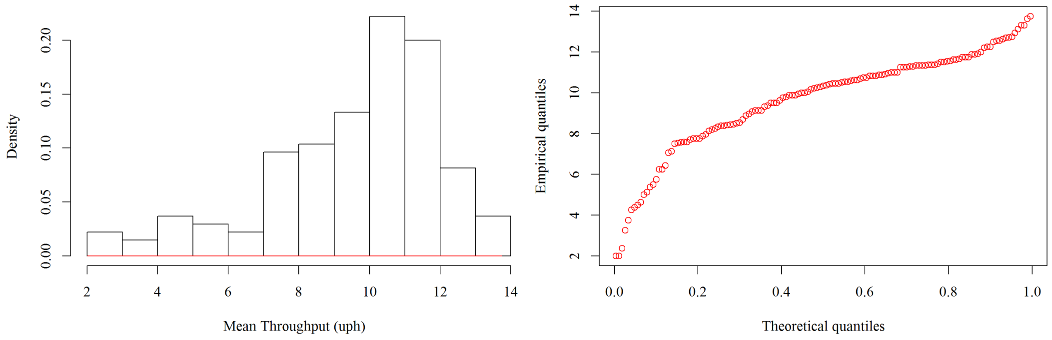


(a) Histogram and theoretical densities (b) Q-Q plot



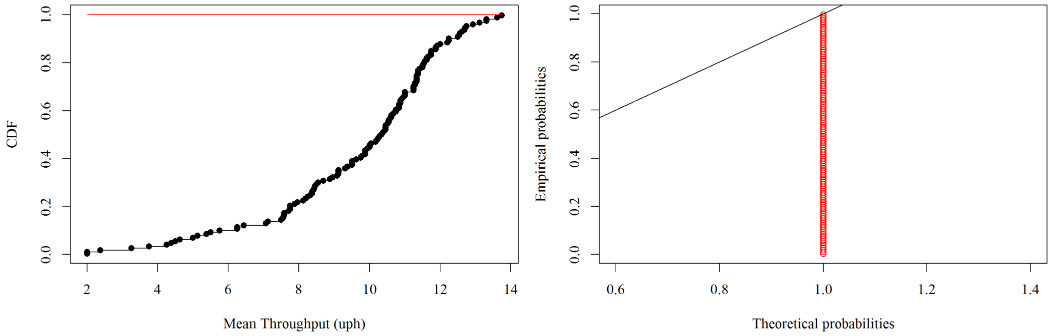
(c) Empirical and theoretical CDFs (d) P-P plot

Figure A.6: The 2012 throughput data of the reference BIW compared to a theoretical throughput of a exponential distribution.



(a) Histogram and theoretical densities

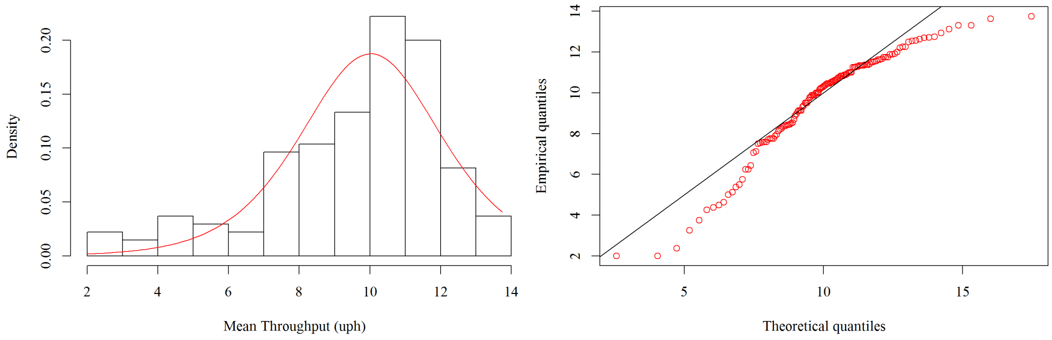
(b) Q-Q plot



(c) Empirical and theoretical CDFs

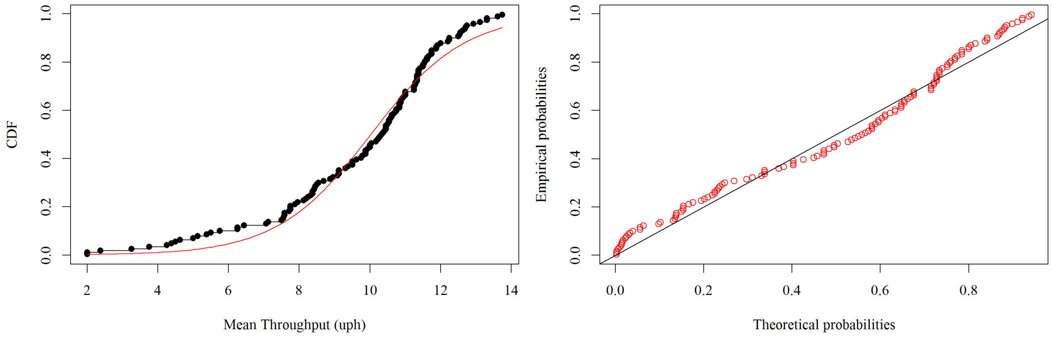
(d) P-P plot

Figure A.7: The 2012 throughput data of the reference BIW compared to a theoretical throughput of a uniformed distribution.



(a) Histogram and theoretical densities

(b) Q-Q plot



(c) Empirical and theoretical CDFs

(d) P-P plot

Figure A.8: The 2012 throughput data of the reference BIW compared to a theoretical throughput of a logistic distribution.

A.2 Throughput distribution reference graphs of the reference BIW 2013

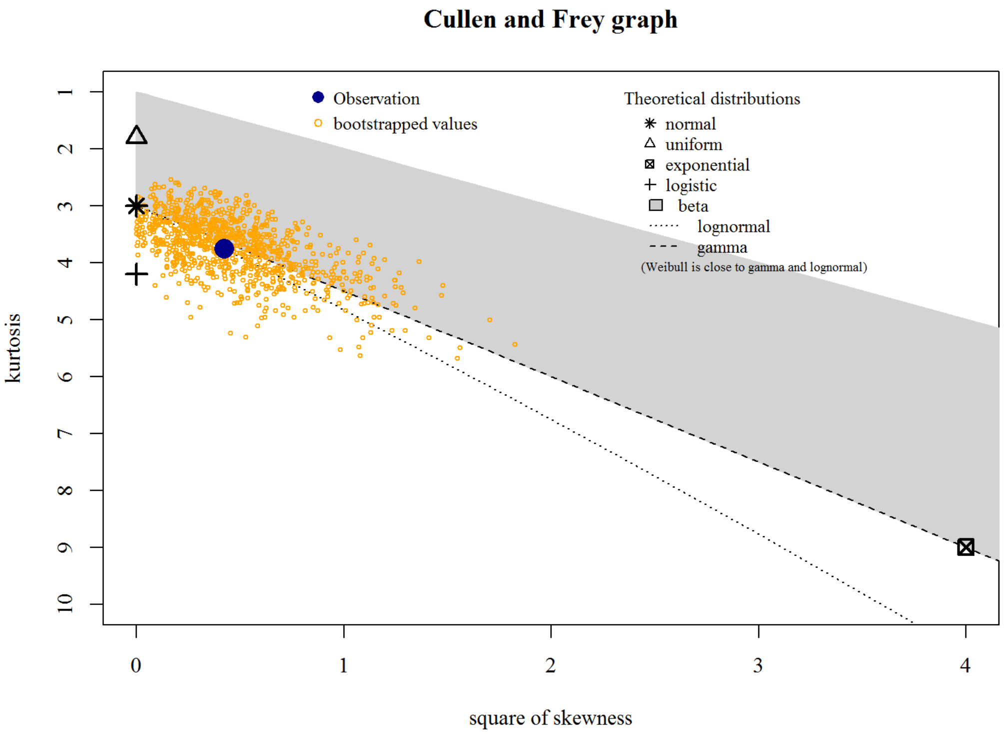
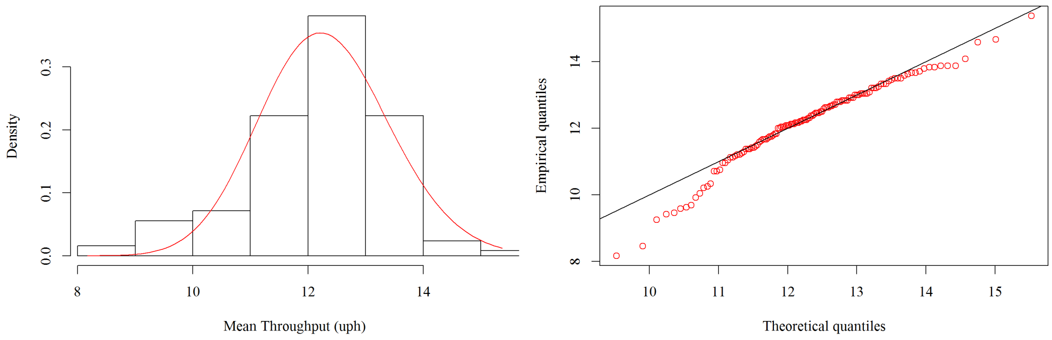
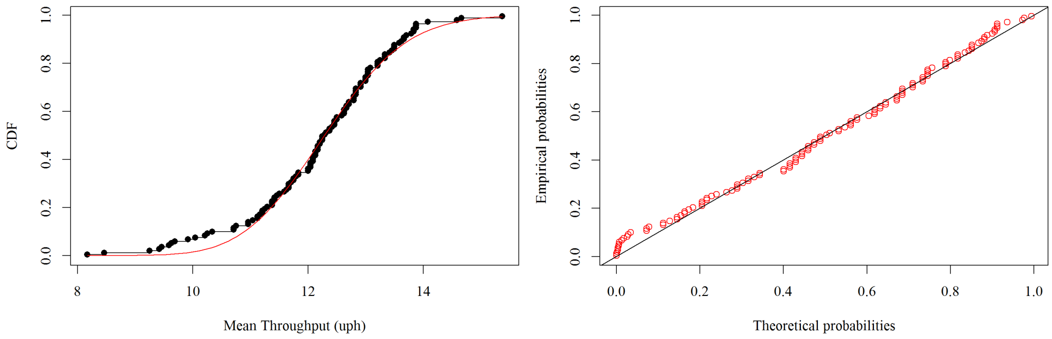


Figure A.9: The 2013 throughput data of the reference BIW plotted on a Cullen and Frey graph.



(a) Histogram and theoretical densities

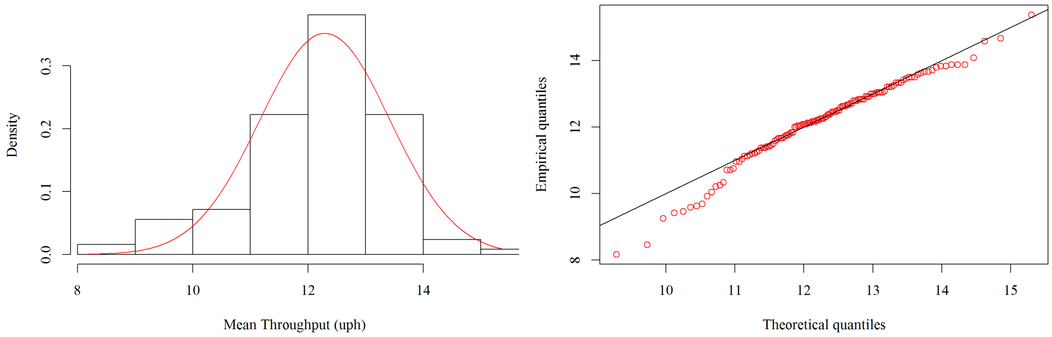
(b) Q-Q plot



(c) Empirical and theoretical CDFs

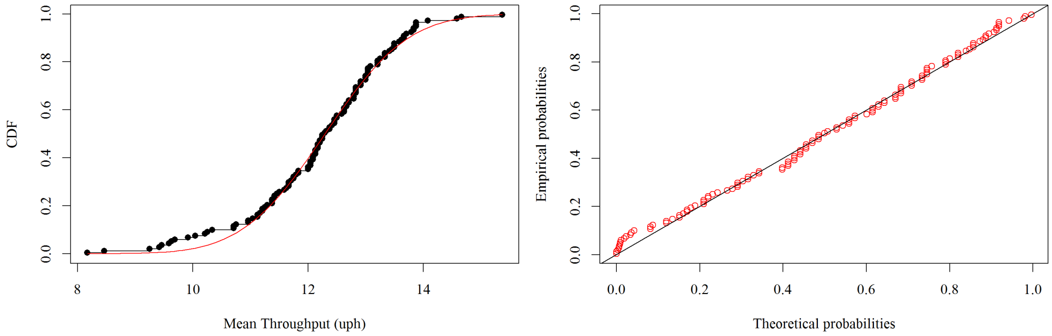
(d) P-P plot

Figure A.10: The 2013 throughput data of the reference BIW compared to a theoretical throughput of a gamma distribution.



(a) Histogram and theoretical densities

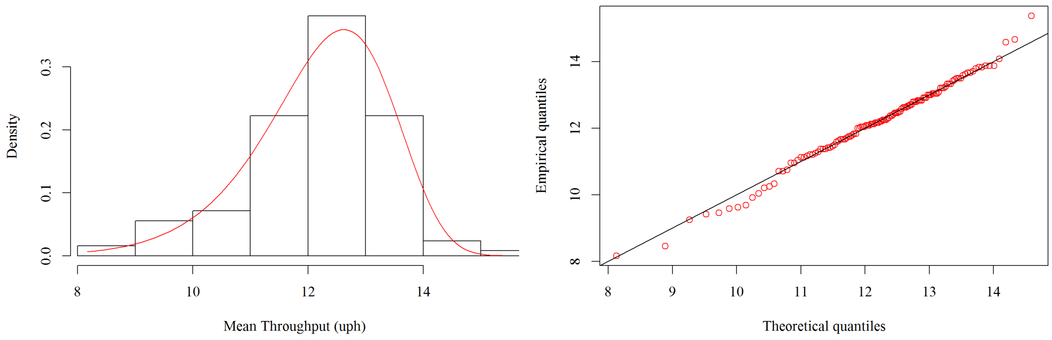
(b) Q-Q plot



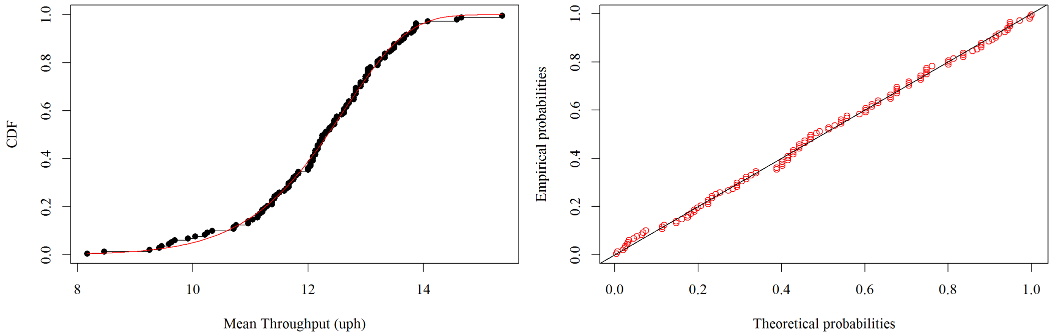
(c) Empirical and theoretical CDFs

(d) P-P plot

Figure A.11: The 2013 throughput data of the reference BIW compared to a theoretical throughput of a normal distribution.

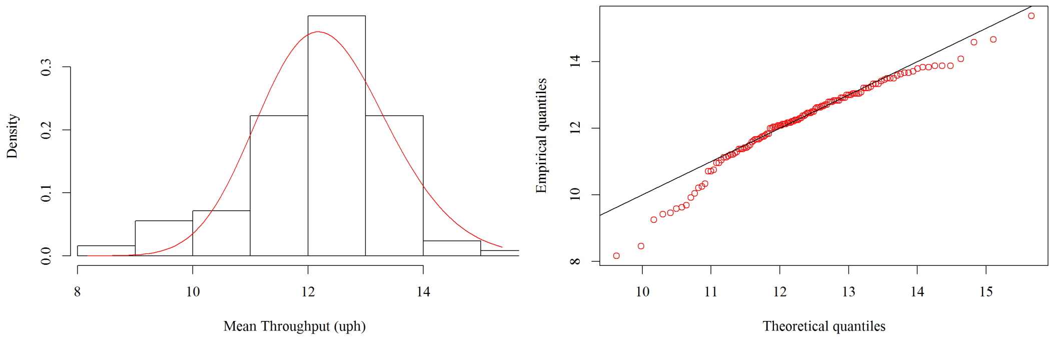


(a) Histogram and theoretical densities (b) Q-Q plot



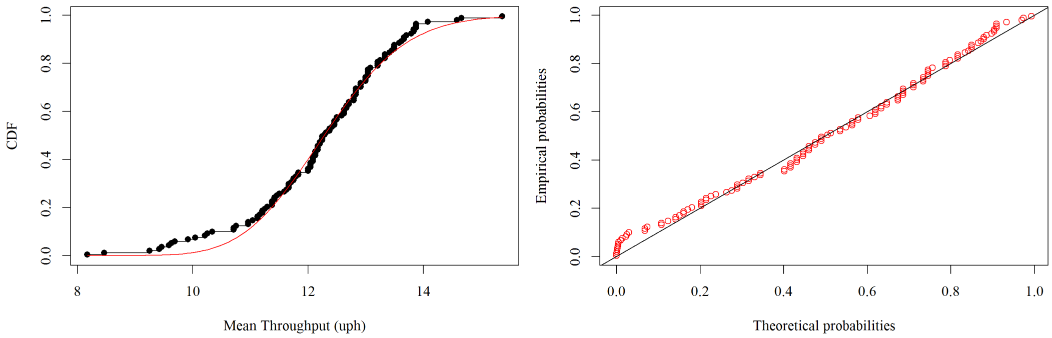
(c) Empirical and theoretical CDFs (d) P-P plot

Figure A.12: The 2013 throughput data of the reference BIW compared to a theoretical throughput of a weibull distribution.



(a) Histogram and theoretical densities

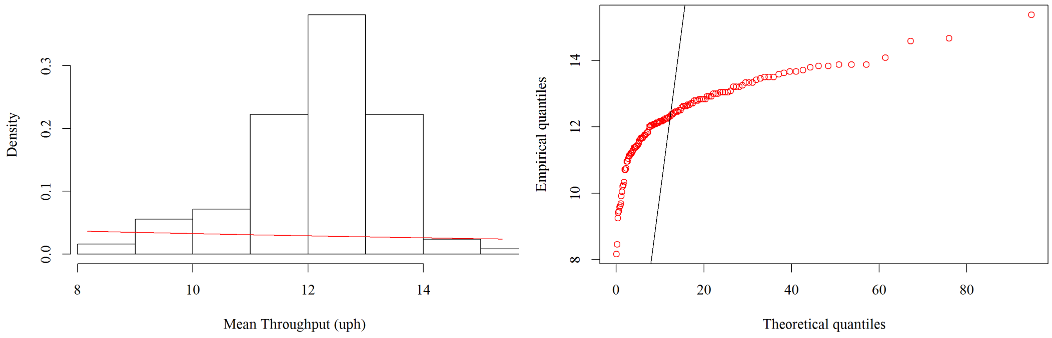
(b) Q-Q plot



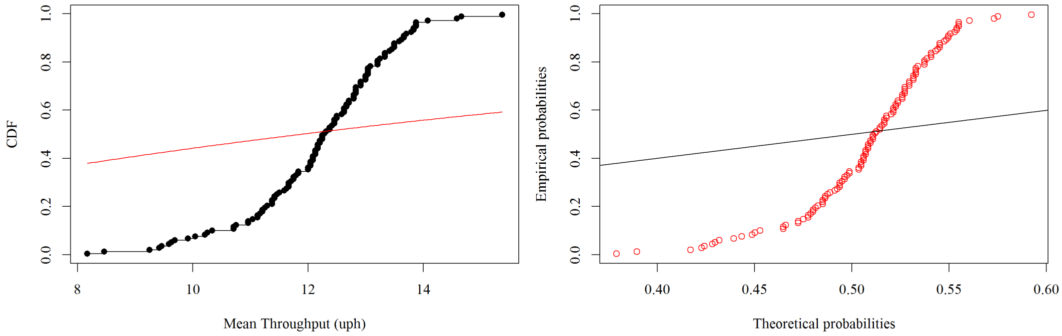
(c) Empirical and theoretical CDFs

(d) P-P plot

Figure A.13: The 2013 throughput data of the reference BIW compared to a theoretical throughput of a log-normal distribution.

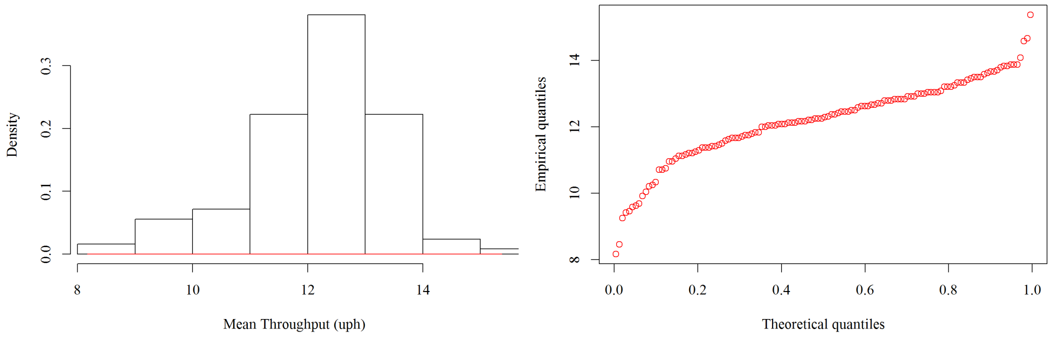


(a) Histogram and theoretical densities (b) Q-Q plot



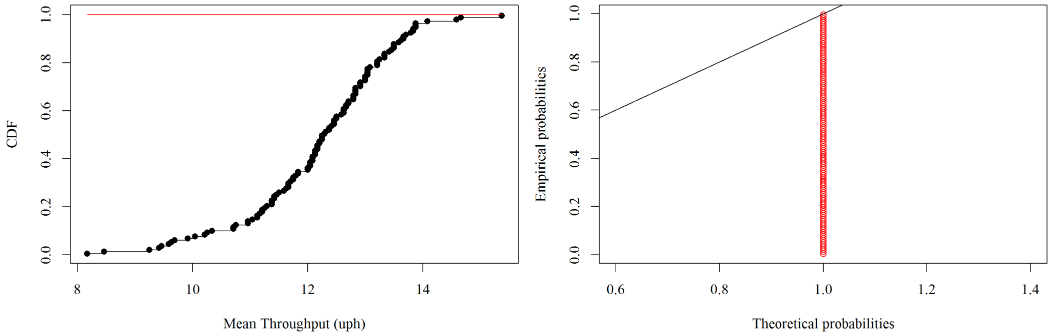
(c) Empirical and theoretical CDFs (d) P-P plot

Figure A.14: The 2013 throughput data of the reference BIW compared to a theoretical throughput of a exponential distribution.



(a) Histogram and theoretical densities

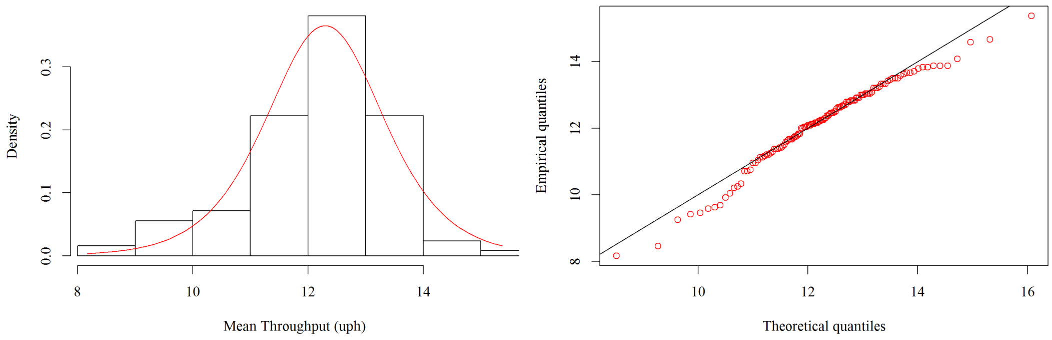
(b) Q-Q plot



(c) Empirical and theoretical CDFs

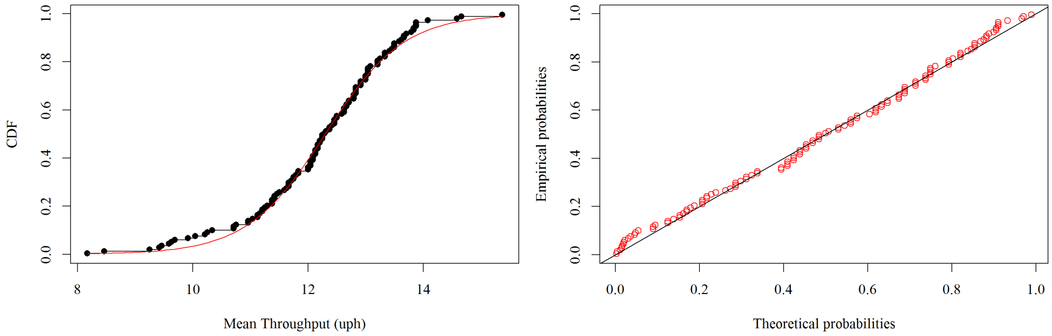
(d) P-P plot

Figure A.15: The 2013 throughput data of the reference BIW compared to a theoretical throughput of a uniformed distribution.



(a) Histogram and theoretical densities

(b) Q-Q plot



(c) Empirical and theoretical CDFs

(d) P-P plot

Figure A.16: The 2013 throughput data of the reference BIW compared to a theoretical throughput of a logistic distribution.

A.3 Throughput distribution reference graphs of the reference BIW 2014

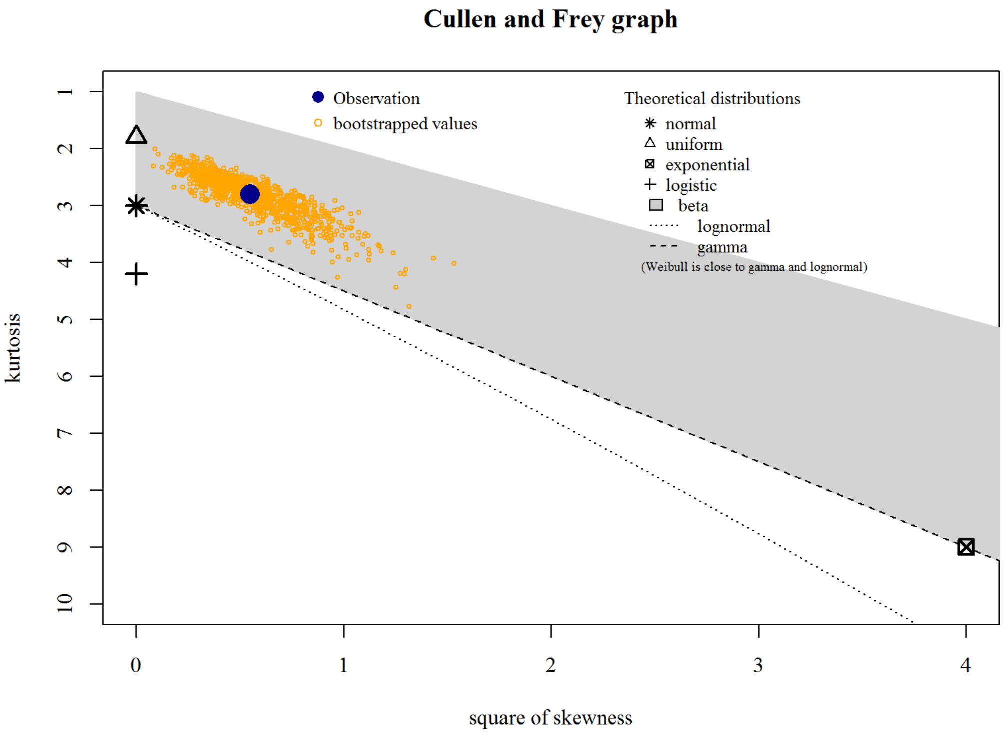
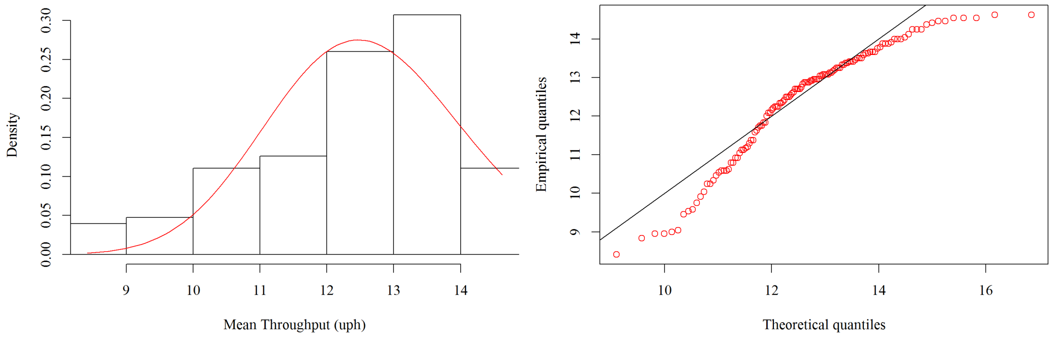
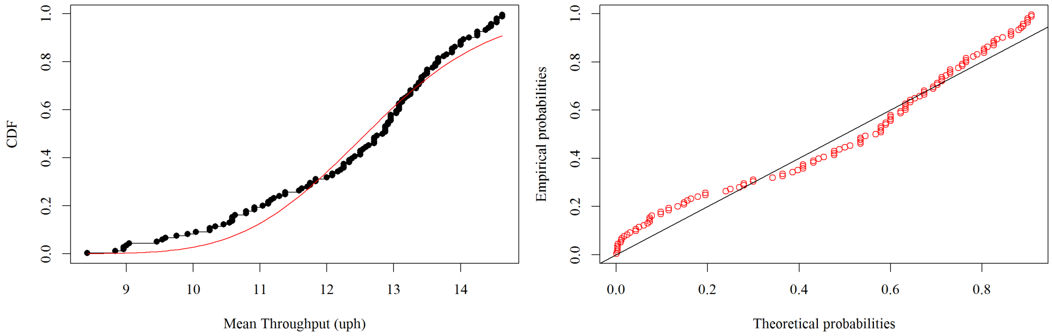


Figure A.17: The 2014 throughput data of the reference BIW plotted on a Cullen and Frey graph.



(a) Histogram and theoretical densities

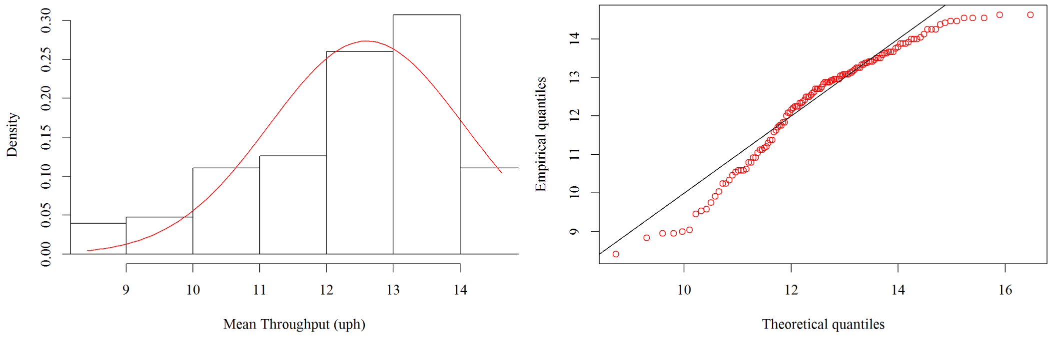
(b) Q-Q plot



(c) Empirical and theoretical CDFs

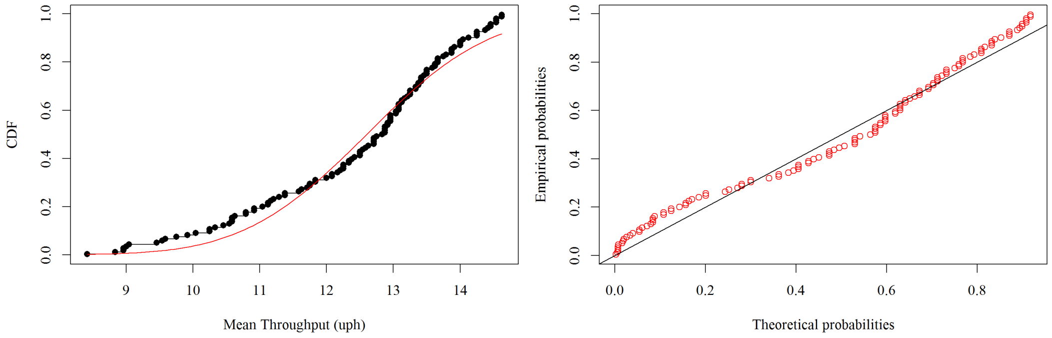
(d) P-P plot

Figure A.18: The 2014 throughput data of the reference BIW compared to a theoretical throughput of a gamma distribution.



(a) Histogram and theoretical densities

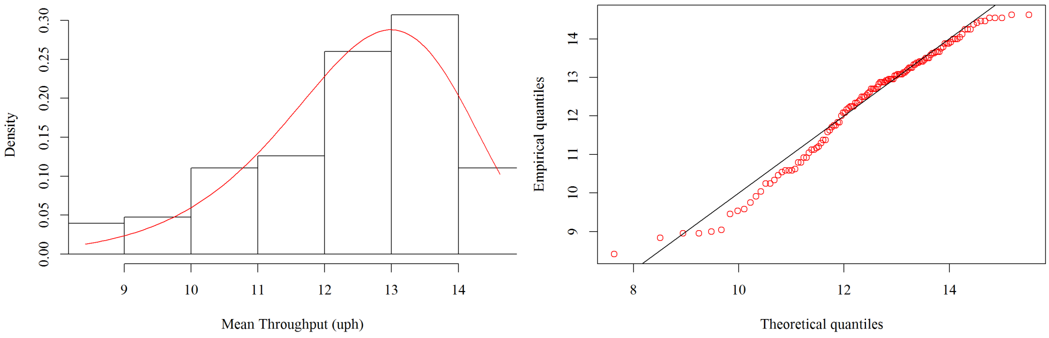
(b) Q-Q plot



(c) Empirical and theoretical CDFs

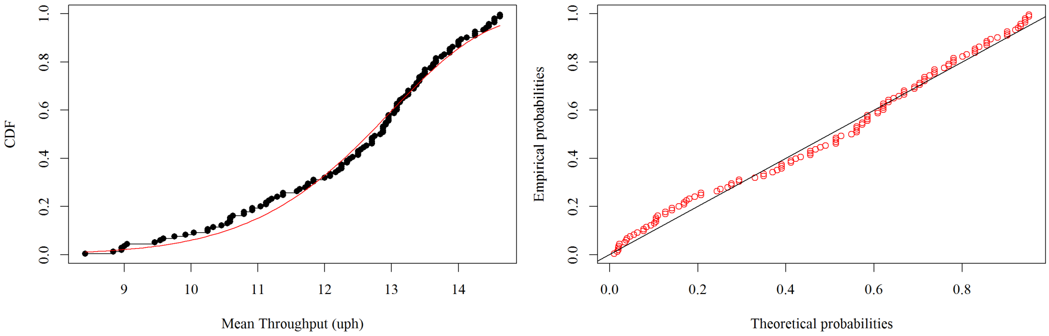
(d) P-P plot

Figure A.19: The 2014 throughput data of the reference BIW compared to a theoretical throughput of a normal distribution.



(a) Histogram and theoretical densities

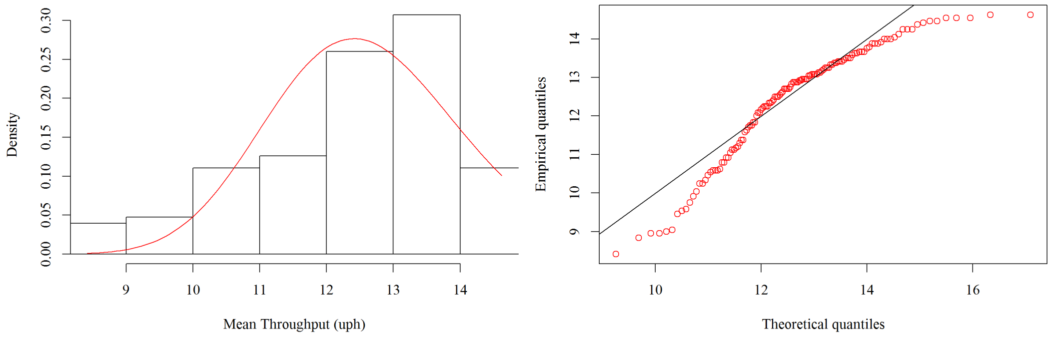
(b) Q-Q plot



(c) Empirical and theoretical CDFs

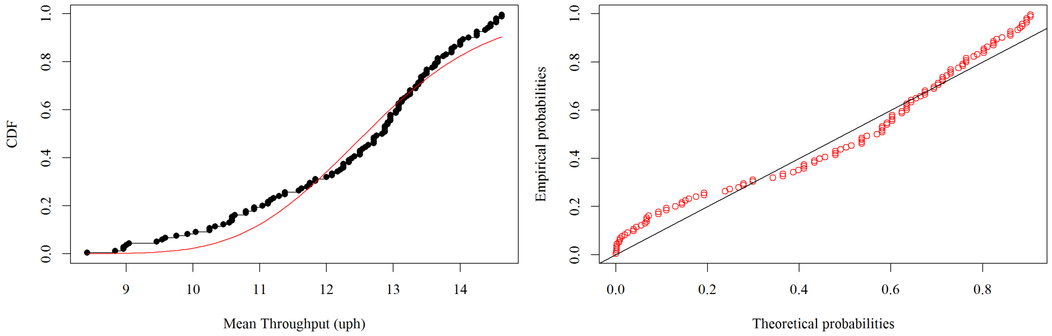
(d) P-P plot

Figure A.20: The 2014 throughput data of the reference BIW compared to a theoretical throughput of a weibull distribution.



(a) Histogram and theoretical densities

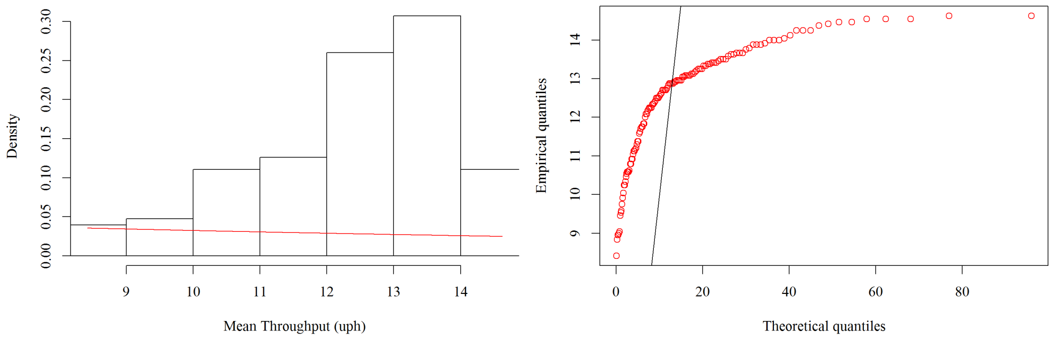
(b) Q-Q plot



(c) Empirical and theoretical CDFs

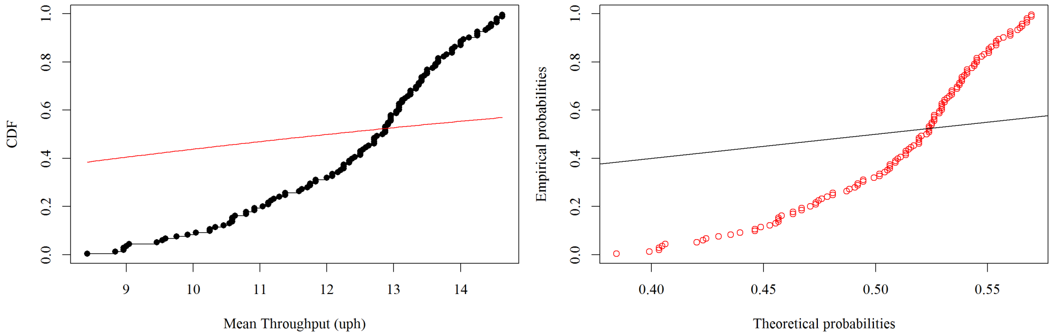
(d) P-P plot

Figure A.21: The 2014 throughput data of the reference BIW compared to a theoretical throughput of a log-normal distribution.



(a) Histogram and theoretical densities

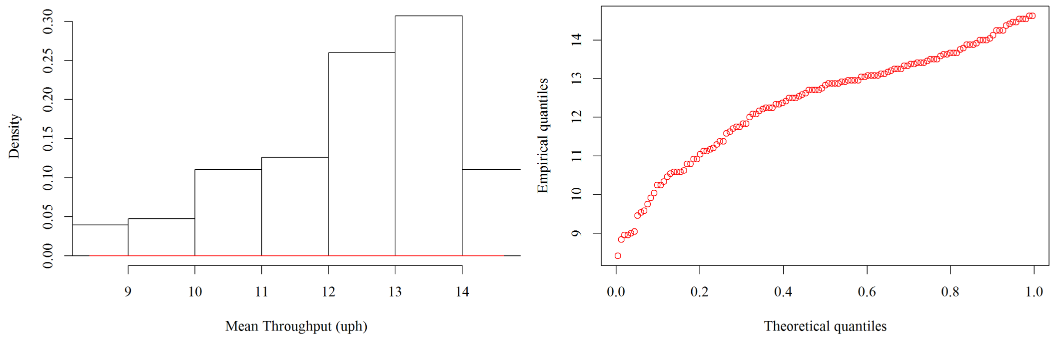
(b) Q-Q plot



(c) Empirical and theoretical CDFs

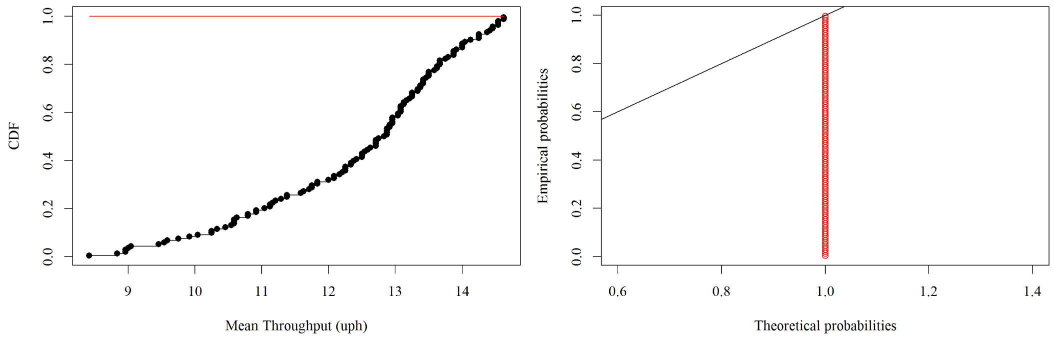
(d) P-P plot

Figure A.22: The 2014 throughput data of the reference BIW compared to a theoretical throughput of a exponential distribution.



(a) Histogram and theoretical densities

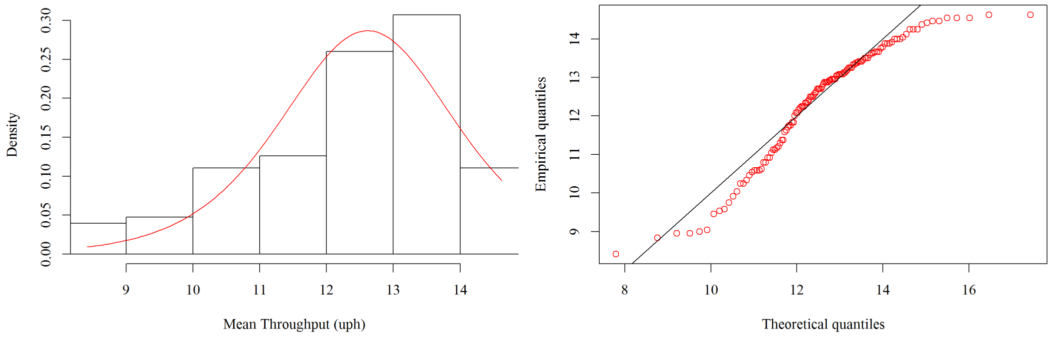
(b) Q-Q plot



(c) Empirical and theoretical CDFs

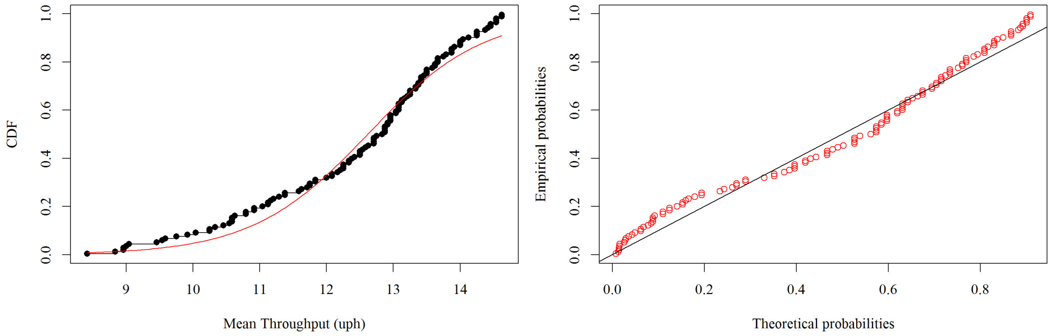
(d) P-P plot

Figure A.23: The 2014 throughput data of the reference BIW compared to a theoretical throughput of a uniformed distribution.



(a) Histogram and theoretical densities

(b) Q-Q plot



(c) Empirical and theoretical CDFs

(d) P-P plot

Figure A.24: The 2014 throughput data of the reference BIW compared to a theoretical throughput of a logistic distribution.

A.4 Throughput distribution reference graphs of the reference BIW 2015

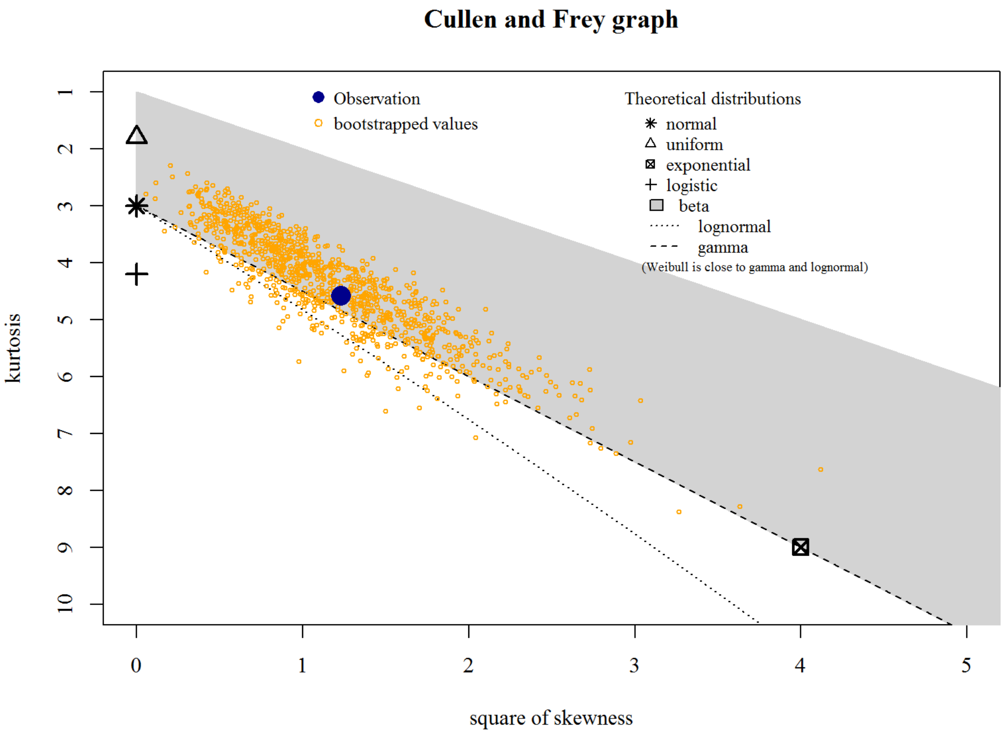
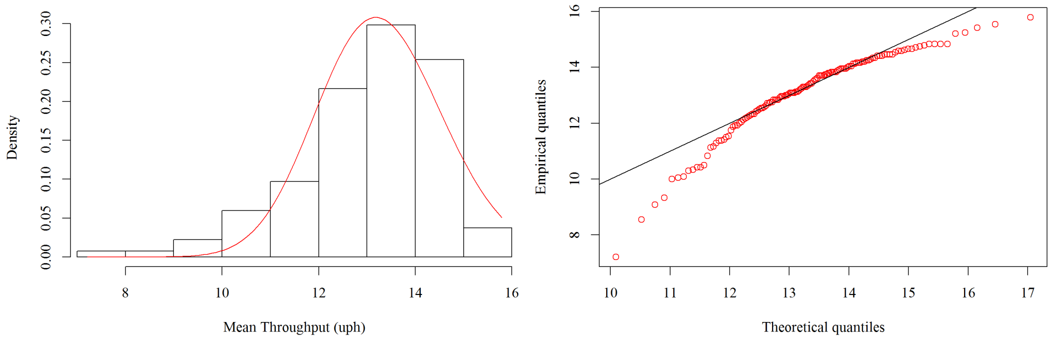
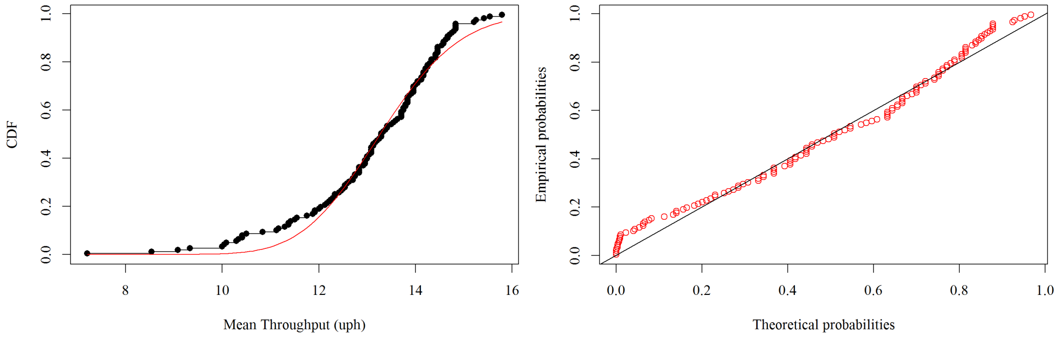


Figure A.25: The 2015 throughput data of the reference BIW plotted on a Cullen and Frey graph.



(a) Histogram and theoretical densities

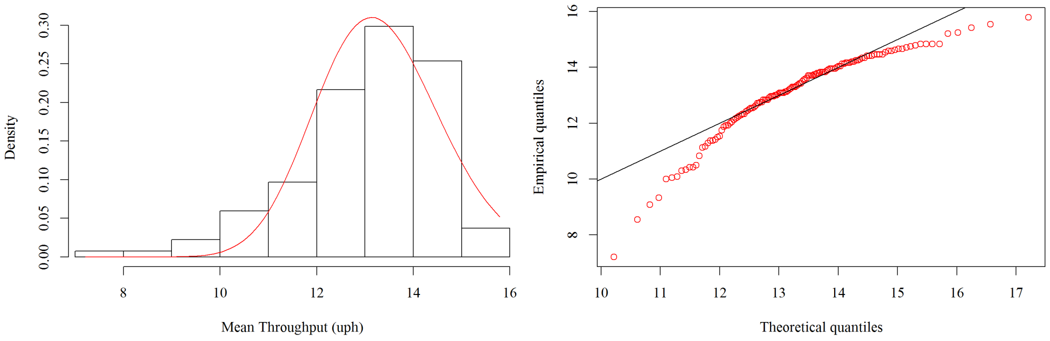
(b) Q-Q plot



(c) Empirical and theoretical CDFs

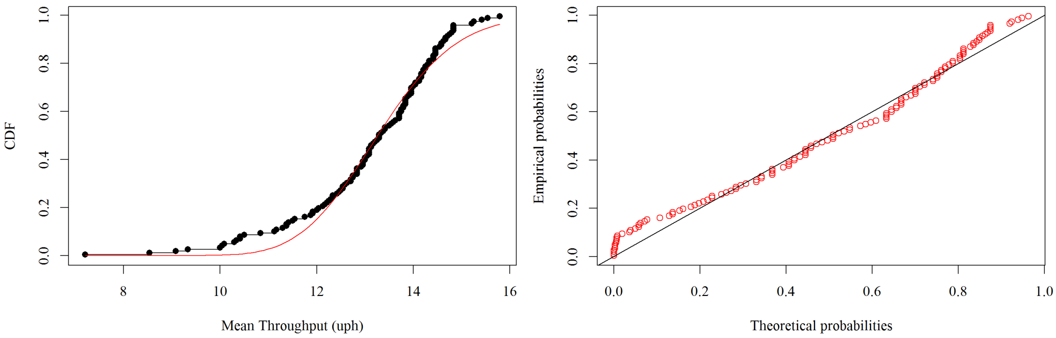
(d) P-P plot

Figure A.26: The 2015 throughput data of the reference BIW compared to a theoretical throughput of a gamma distribution.



(a) Histogram and theoretical densities

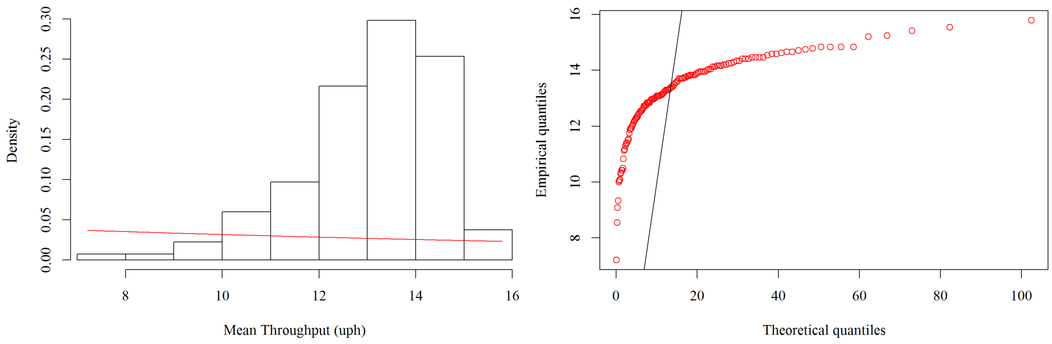
(b) Q-Q plot



(c) Empirical and theoretical CDFs

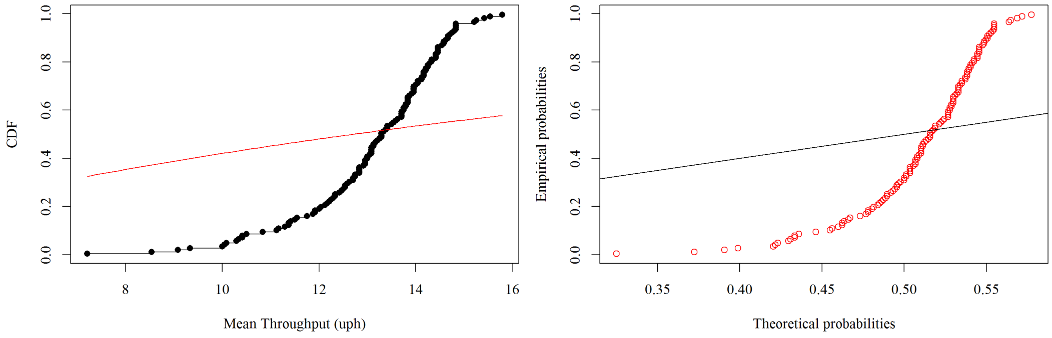
(d) P-P plot

Figure A.27: The 2015 throughput data of the reference BIW compared to a theoretical throughput of a log-normal distribution.



(a) Histogram and theoretical densities

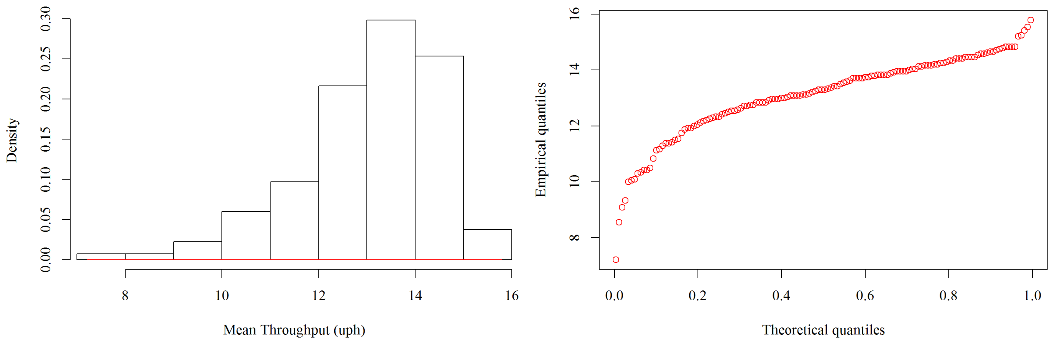
(b) Q-Q plot



(c) Empirical and theoretical CDFs

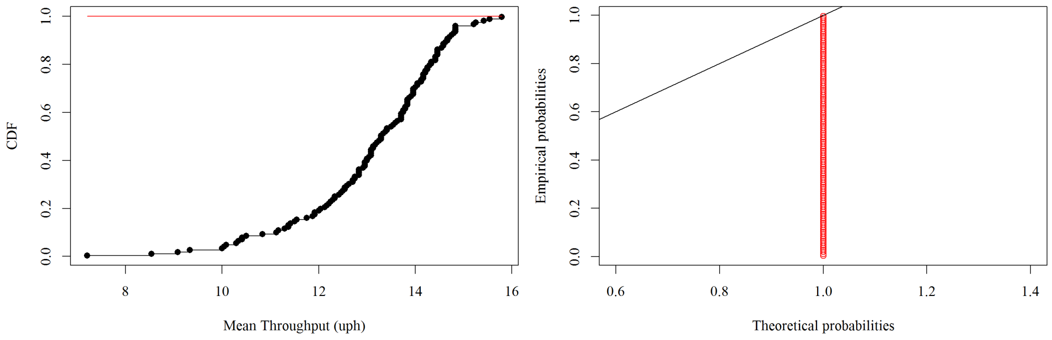
(d) P-P plot

Figure A.28: The 2015 throughput data of the reference BIW compared to a theoretical throughput of a exponential distribution.



(a) Histogram and theoretical densities

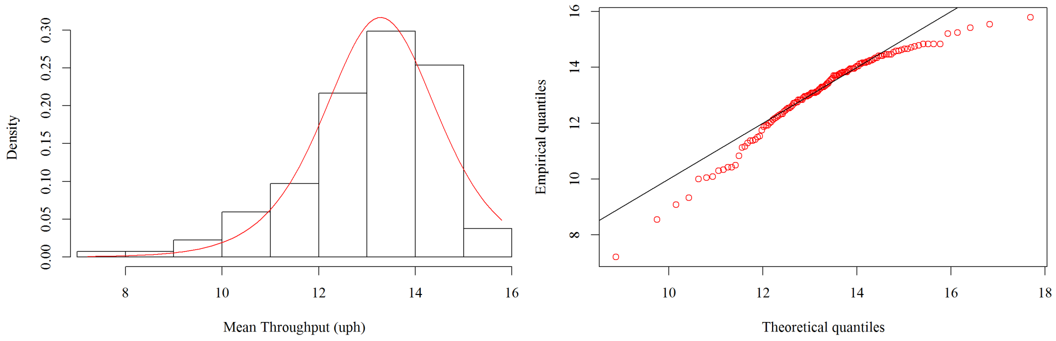
(b) Q-Q plot



(c) Empirical and theoretical CDFs

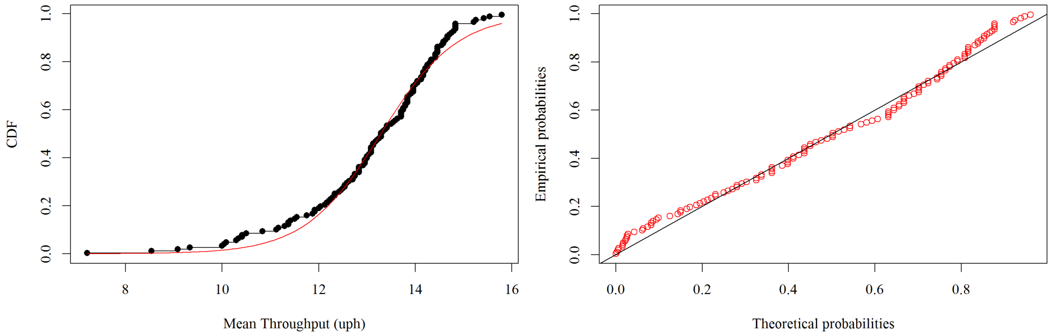
(d) P-P plot

Figure A.29: The 2015 throughput data of the reference BIW compared to a theoretical throughput of a uniformed distribution.



(a) Histogram and theoretical densities

(b) Q-Q plot



(c) Empirical and theoretical CDFs

(d) P-P plot

Figure A.30: The 2015 throughput data of the reference BIW compared to a theoretical throughput of a logistic distribution.

Appendix B

Simulation data

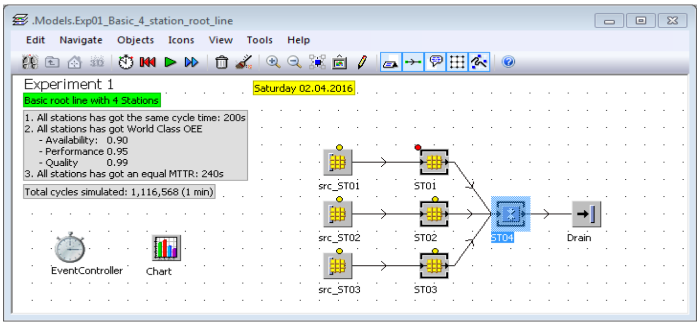
Experiment 1

Basic 4 station root line

1. Experiment description

The purpose of this experiment is to create a base comparison between serial lines and root lines. Experiment 1 and Experiment 2 are used as the input basis for serial lines. All station parameters are equal (Cycle time, availability, performance, quality, OEE and MTTR). The production line is based on a 15uph line with world class OEE. No buffers are used.

2. Simulation model in Siemens Plant Simulation



Experiment 1

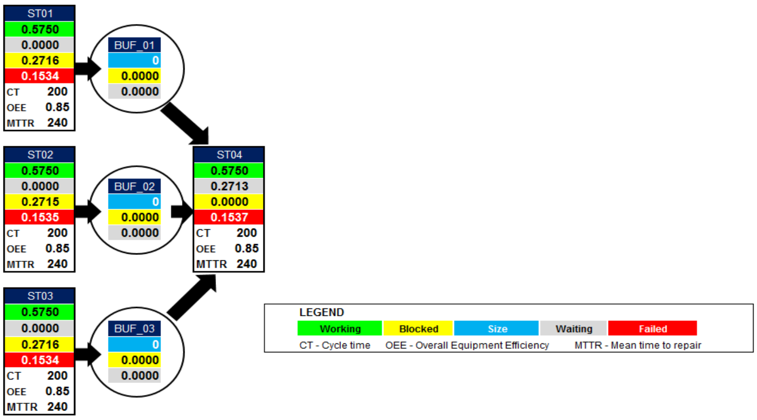
Basic root line with 4 Stations

Saturday 02.04.2016

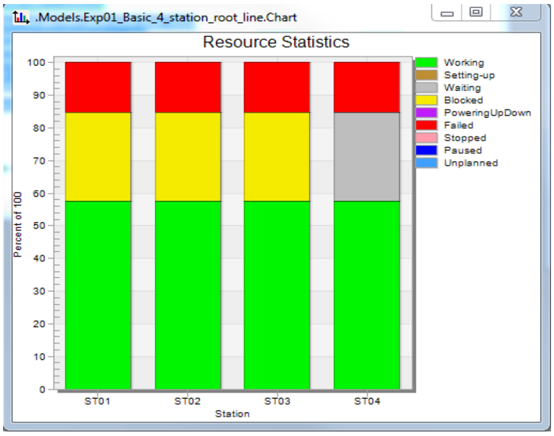
1. All stations has got the same cycle time: 200s
2. All stations has got World Class OEE
   - Availability: 0.90
   - Performance 0.95
   - Quality 0.99
3. All stations has got an equal MTTR: 240s

Total cycles simulated: 1,116,568 (1 min)

3. Simulation results



4. Summary graph of the results



5. Observations and conclusions

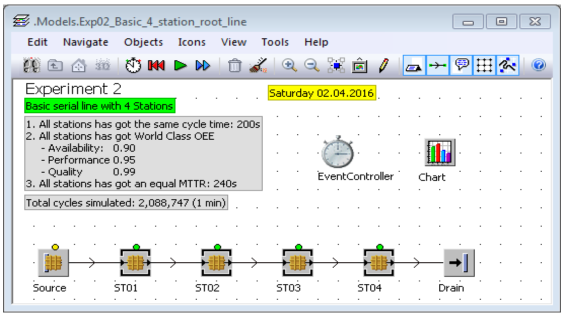
1. The overall OEE for all stations are the same at 0.5740.
2. The expected OEE was 0.5220 (0.85^4). This is similar to the simulated results.
3. The blocked time of Station 01, 02 and 03 are equal and the same as the waiting times of Station 04, and vice versa.
4. The model performed as expected and can be used as a base reference for further experiments.

Experiment 2
Basic 4 station serial line

1. Experiment description

The purpose of this experiment is to create a base comparison between serial lines and root lines. Experiment 1 and Experiment 2 are used as the input basis for serial lines. All station parameters are equal (Cycle time, availability, peroformance, quality, OEE and MTTR). The production line is based on a 15uph line with world class OEE. No buffers are used.

2. Simulation model in Siemens Plant Simulation



Experiment 2

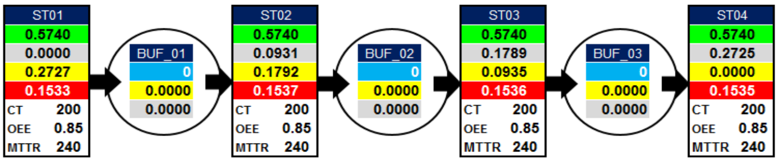
Basic serial line with 4 Stations

Saturday 02.04.2016

1. All stations has got the same cycle time: 200s
2. All stations has got World Class OEE
   - Availability: 0.90
   - Performance 0.95
   - Quality 0.99
3. All stations has got an equal MTTR: 240s

Total cycles simulated: 2,088,747 (1 min)

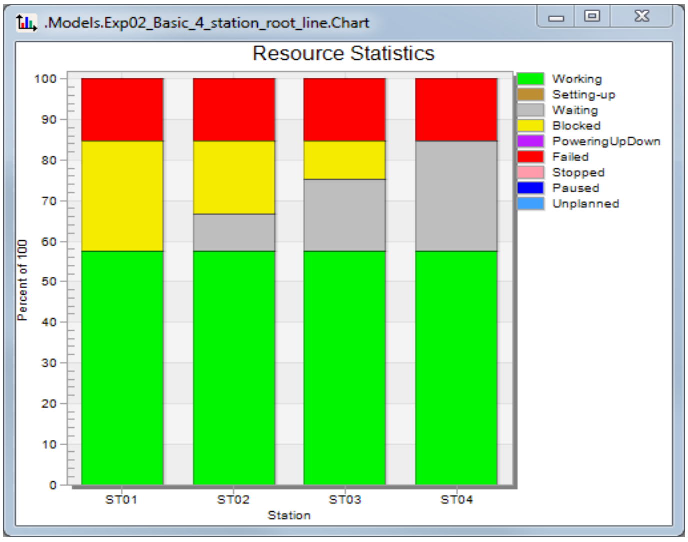
3. Simulation results



ST01	BUF_01	ST02	BUF_02	ST03	BUF_03	ST04
0.5740		0.5740		0.5740		0.5740
0.0000		0.0931		0.1789		0.2725
0.2727	0	0.1792	0	0.0935	0	0.0000
0.1533	0.0000	0.1537	0.0000	0.1536	0.0000	0.1535
CT 200	0.0000	CT 200	0.0000	CT 200	0.0000	CT 200
OEE 0.85		OEE 0.85		OEE 0.85		OEE 0.85
MTTR 240		MTTR 240		MTTR 240		MTTR 240

LEGEND
🟩 Working 🟨 Blocked 🟦 Size ⬜ Waiting 🟥 Failed
CT - Cycle time OEE - Overall Equipment Efficiency MTTR - Mean time to repair

4. Summary graph of the results



5. Observations and conclusions

1. The overall OEE for all stations are the same at 0.5740.
2. The expected OEE was 0.5220 (0.85^4). This is similar to the simulated results.
3. The blocked time of Station 01 and 02 are the same as the waiting times of Station 03 and 04, and vice versa.
4. The model performed as expected and can be used as a base reference for further experiments.

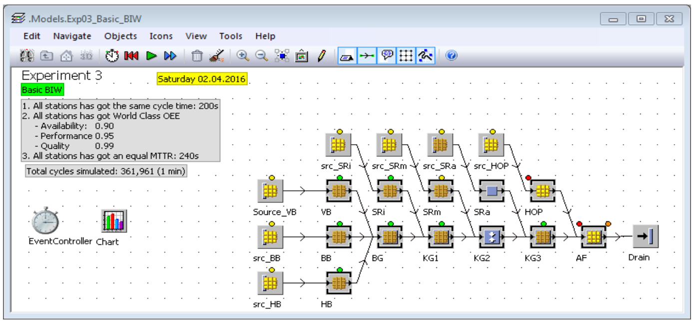
Experiment 3

Basic BIW line

1. Experiment description

The purpose of this experiment is to create a base comparison between a basic BIW and a serial line. Experiment 3 and Experiment 4 are used as the input basis for serial lines. All station parameters are equal (Cycle time, availability, peroformance, quality, OEE and MTTR). The production line is based on a 15uph line with world class OEE. No buffers are used.

2. Simulation model in Siemens Plant Simulation



Experiment 3

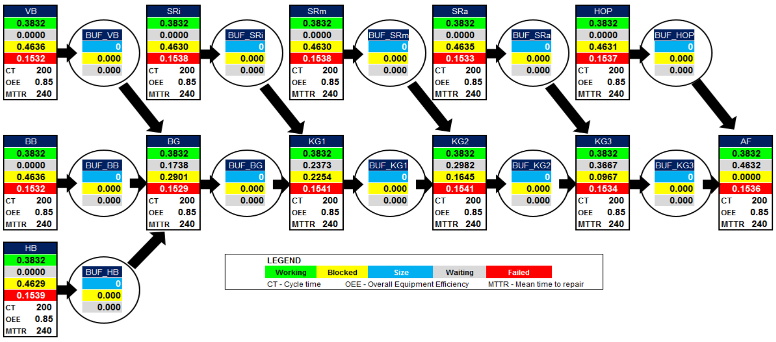
Saturday 02.04.2016

Basic BIW

1. All stations has got the same cycle time: 200s
2. All stations has got World Class OEE
   - Availability: 0.90
   - Performance 0.95
   - Quality 0.99
3. All stations has got an equal MTTR: 240s

Total cycles simulated: 361,961 (1 min)

3. Simulation results



	VB	SRi	SRm	SRa	HOP	BB	BG	KG1	KG2	KG3	AF	HB
🟩	0.3832	0.3832	0.3832	0.3832	0.3832	0.3832	0.3832	0.3832	0.3832	0.3832	0.3832	0.3832
⬜	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1738	0.2373	0.2982	0.3667	0.4632	0.0000
🟨	0.4636	0.4630	0.4630	0.4635	0.4631	0.4636	0.2901	0.2254	0.1645	0.0967	0.0000	0.4629
🟥	0.1532	0.1538	0.1538	0.1533	0.1537	0.1532	0.1529	0.1541	0.1541	0.1534	0.1536	0.1539
CT	200	200	200	200	200	200	200	200	200	200	200	200
OEE	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
MTTR	240	240	240	240	240	240	240	240	240	240	240	240

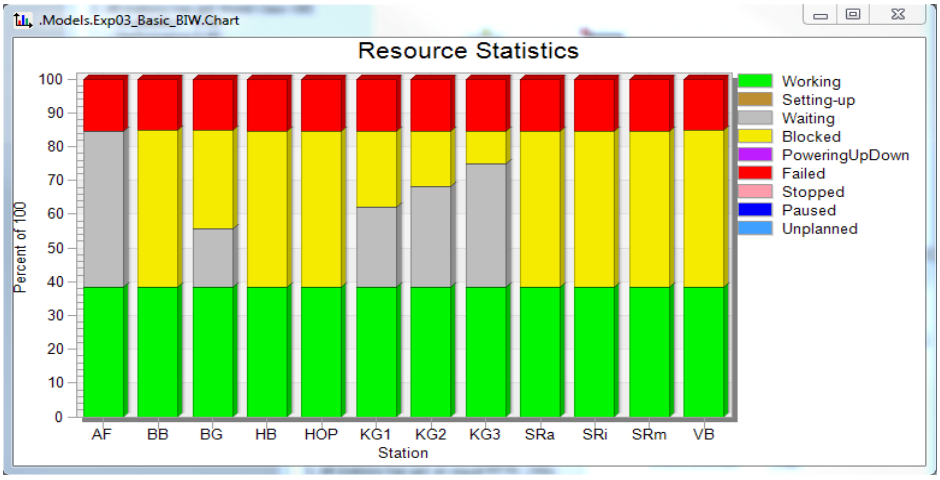
	BUF_VB	BUF_SRi	BUF_SRm	BUF_SRa	BUF_HOP	BUF_BB	BUF_BG	BUF_KG1	BUF_KG2	BUF_KG3	BUF_HB
🟦	0	0	0	0	0	0	0	0	0	0	0
🟨	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
⬜	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

LEGEND

🟩 Working 🟨 Blocked 🟦 Size ⬜ Waiting 🟥 Failed

CT - Cycle time OEE - Overall Equipment Efficiency MTTR - Mean time to repair

4. Summary graph of the results



5. Observations and conclusions

1. The overall OEE for all stations are the same at 0.3832.
2. The expected OEE was 0.1422 (0.85^{12}). This is not close to the simulated results.
3. The blocked time decreases from Subs stations to the main lines while to waiting time increases.
4. The model performed as expected and can be used as a base reference for further experiments.

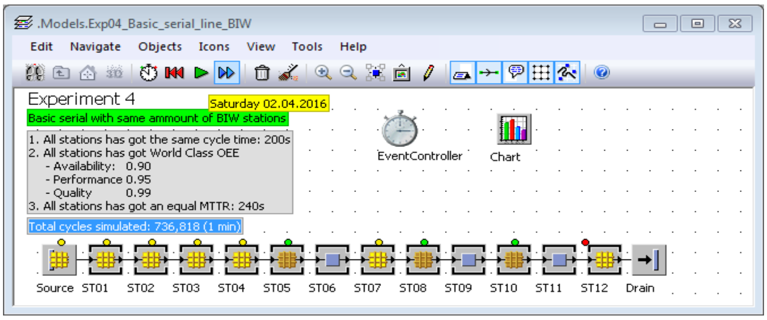
Experiment 4

Basic serial line with the same ammount of BIW stations

1. Experiment description

The purpose of this experiment is to create a base comparison between a basic BIW and a serial line. Experiment 3 and Experiment 4 are used as the input basis for serial lines. All station parameters are equal (Cycle time, availability, peroformance, quality, OEE and MTTR). The production line is based on a 15uph line with world class OEE. No buffers are used.

2. Simulation model in Siemens Plant Simulation



Experiment 4

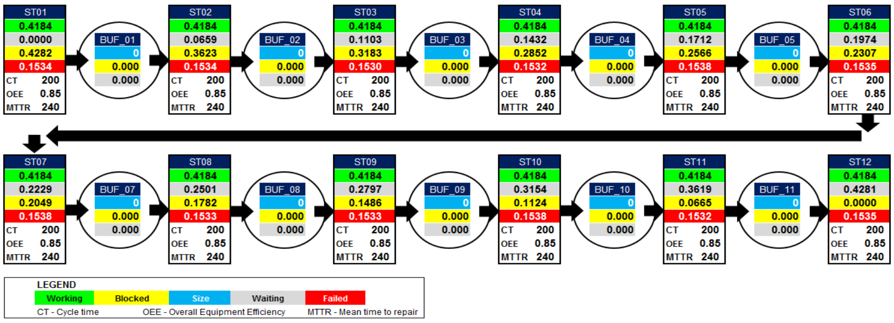
Saturday 02.04.2016

Basic serial with same ammount of BIW stations

1. All stations has got the same cycle time: 200s
2. All stations has got World Class OEE
   - Availability: 0.90
   - Performance 0.95
   - Quality 0.99
3. All stations has got an equal MTTR: 240s

Total cycles simulated: 736,818 (1 min)

3. Simulation results



	ST01	ST02	ST03	ST04	ST05	ST06
🟩	0.4184	0.4184	0.4184	0.4184	0.4184	0.4184
⬜	0.0000	0.0659	0.1103	0.1432	0.1712	0.1974
🟨	0.4282	0.3623	0.3183	0.2852	0.2566	0.2307
🟥	0.1534	0.1534	0.1530	0.1532	0.1538	0.1535
CT	200	200	200	200	200	200
OEE	0.85	0.85	0.85	0.85	0.85	0.85
MTTR	240	240	240	240	240	240

	BUF_01	BUF_02	BUF_03	BUF_04	BUF_05
🟦	0	0	0	0	0
🟨	0.000	0.000	0.000	0.000	0.000
⬜	0.000	0.000	0.000	0.000	0.000

	ST07	ST08	ST09	ST10	ST11	ST12
🟩	0.4184	0.4184	0.4184	0.4184	0.4184	0.4184
⬜	0.2229	0.2501	0.2797	0.3154	0.3619	0.4281
🟨	0.2049	0.1782	0.1486	0.1124	0.0665	0.0000
🟥	0.1538	0.1533	0.1533	0.1538	0.1532	0.1535
CT	200	200	200	200	200	200
OEE	0.85	0.85	0.85	0.85	0.85	0.85
MTTR	240	240	240	240	240	240

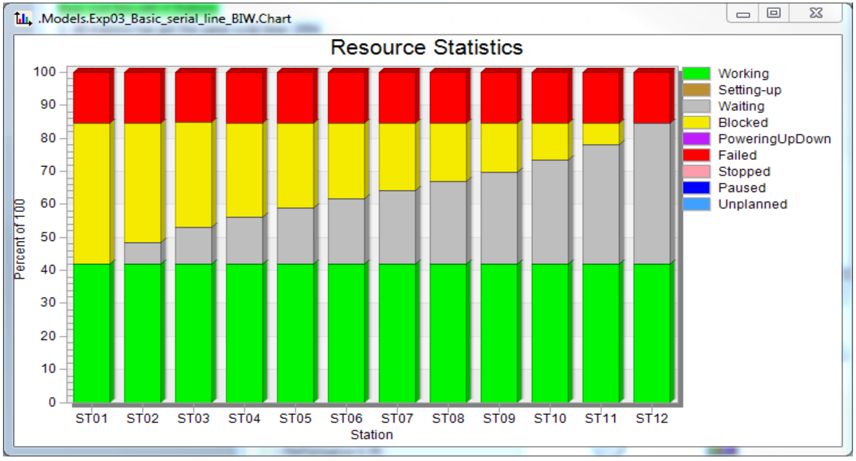
	BUF_07	BUF_08	BUF_09	BUF_10	BUF_11
🟦	0	0	0	0	0
🟨	0.000	0.000	0.000	0.000	0.000
⬜	0.000	0.000	0.000	0.000	0.000

LEGEND

🟩 Working 🟨 Blocked 🟦 Size ⬜ Waiting 🟥 Failed

CT - Cycle time
OEE - Overall Equipment Efficiency
MTTR - Mean time to repair

4. Summary graph of the results



5. Observations and conclusions

1. The overall OEE for all stations are the same at 0.4184.
2. The expected OEE was 0.1422 (0.85^{12}). This is not close to the simulated results.
3. The blocked time dencreases from ST01 to ST12 while to waiting time increases.
4. The model performed as expected and can be used as a base reference for further experiments.

Experiment 5

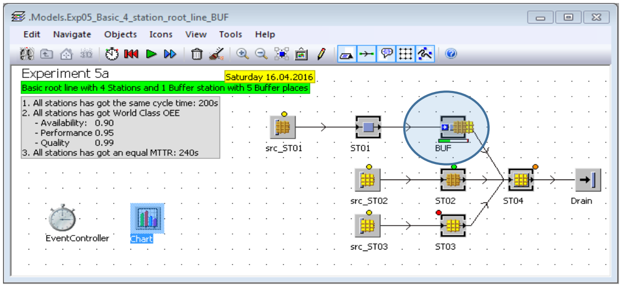
Basic 4 station root line with 1 buffer place and 5 buffers

1. Experiment description

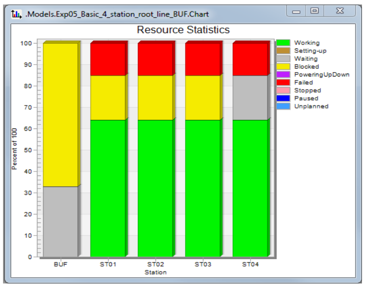
The purpose of this experiment is to test whether the location of the buffer place influence the overall output.. All station parameters are equal (Cycle time, availability, performance, quality, OEE and MTTR). The production line is based on a 15uph line with world class OEE. The buffer is moved to 4 different locations.

2. Simulation model in Siemens Plant Simulation and summary graph of the results

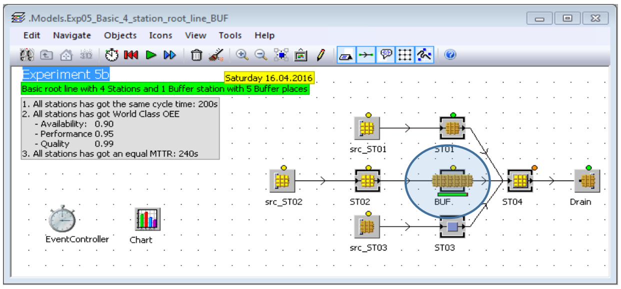
EXP05a



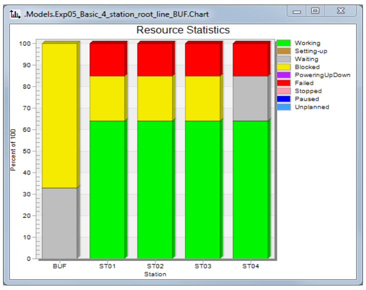
Experiment 5a
Saturday 16.04.2016
Basic root line with 4 Stations and 1 Buffer station with 5 Buffer places
1. All stations has got the same cycle time: 200s
2. All stations has got World Class OEE
- Availability: 0.90
- Performance 0.95
- Quality 0.99
3. All stations has got an equal MTTR: 240s



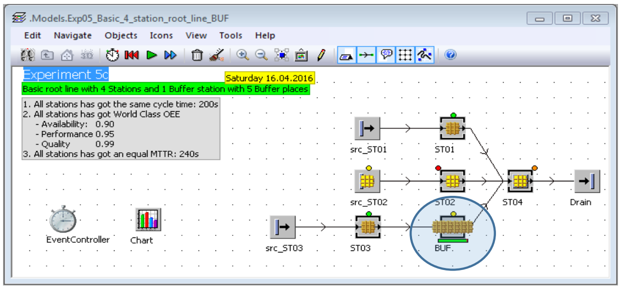
EXP05b



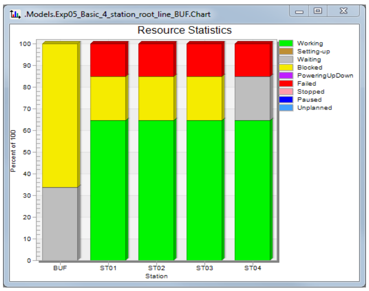
Experiment 5b
Saturday 16.04.2016
Basic root line with 4 Stations and 1 Buffer station with 5 Buffer places
1. All stations has got the same cycle time: 200s
2. All stations has got World Class OEE
- Availability: 0.90
- Performance 0.95
- Quality 0.99
3. All stations has got an equal MTTR: 240s



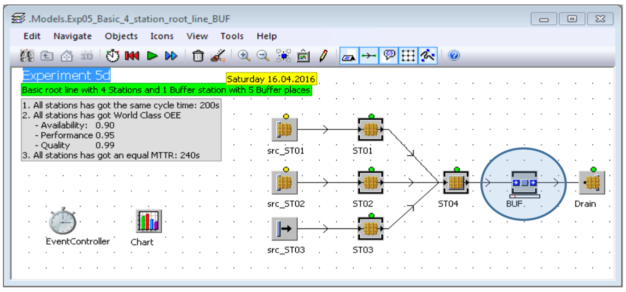
EXP05c



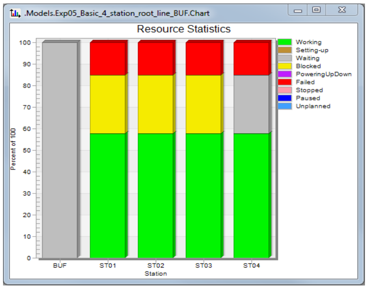
Experiment 5c
Saturday 16.04.2016
Basic root line with 4 Stations and 1 Buffer station with 5 Buffer places
1. All stations has got the same cycle time: 200s
2. All stations has got World Class OEE
- Availability: 0.90
- Performance 0.95
- Quality 0.99
3. All stations has got an equal MTTR: 240s



EXP05d



Experiment 5d
Saturday 16.04.2016
Basic root line with 4 Stations and 1 Buffer station with 5 Buffer places
1. All stations has got the same cycle time: 200s
2. All stations has got World Class OEE
- Availability: 0.90
- Performance 0.95
- Quality 0.99
3. All stations has got an equal MTTR: 240s



3. Observations and conclusions

1. The overall OEE for all stations in EXP05a - EXP05c are the same at 0.6370.

2. The expected OEE was 0.6141 (0.85^3). This is similar to the simulated results.

3. The overall OEE for all stations in EXP05d is 0.6141. This is not similar to th expected result. The delta is caused because it is assumbed that the drain never fails. This is not the case in real BIW systems as the drain can fail.

4. The expected OEE was 0.5220 (0.85^3). This is similar to the simulated results.

5. The OEE of EXP05a - EXP05c is 6% higher than the OEE of EXP01 & EXP05d, showing the positive effect of buffers.

Experiment 6

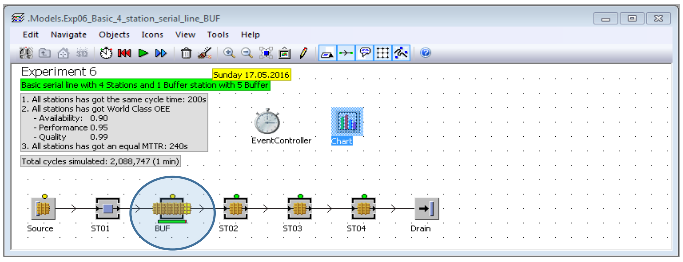
Basic 4 station serial line with 1 buffer place and 5 buffers

1. Experiment description

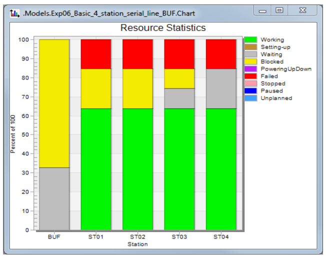
The purpose of this experiment is to test whether the location of the buffer place influence the overall output. All station parameters are equal (Cycle time, availability, performance, quality, OEE and MTTR). The production line is based on a 15uph line with world class OEE. The buffer is moved to 4 different locations.

2. Simulation model in Siemens Plant Simulation and summary graph of the results

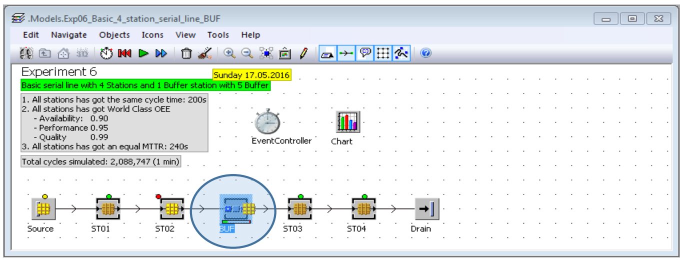
EXP06a



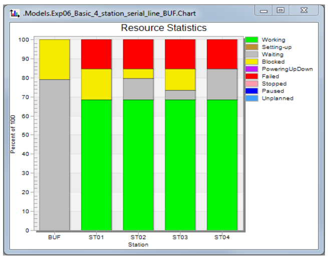
Experiment 6
Sunday 17.05.2016
Basic serial line with 4 Stations and 1 Buffer station with 5 Buffer
1. All stations has got the same cycle time: 200s
2. All stations has got World Class OEE
- Availability: 0.90
- Performance 0.95
- Quality 0.99
3. All stations has got an equal MTTR: 240s
Total cycles simulated: 2,088,747 (1 min)



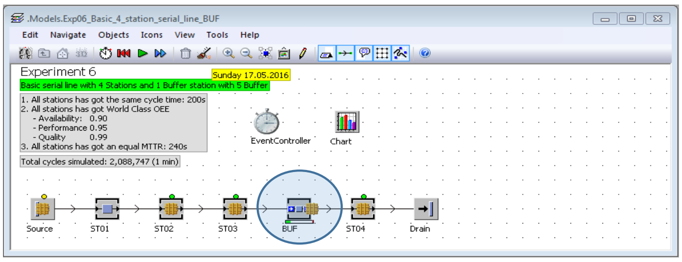
EXP06b



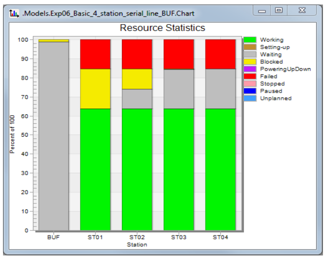
Experiment 6
Sunday 17.05.2016
Basic serial line with 4 Stations and 1 Buffer station with 5 Buffer
1. All stations has got the same cycle time: 200s
2. All stations has got World Class OEE
- Availability: 0.90
- Performance 0.95
- Quality 0.99
3. All stations has got an equal MTTR: 240s
Total cycles simulated: 2,088,747 (1 min)



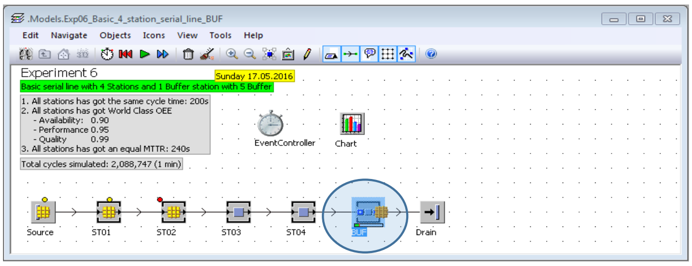
EXP06c



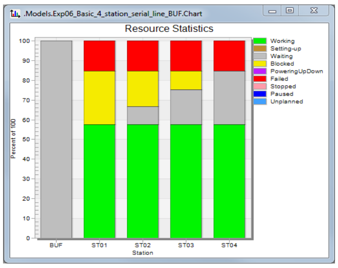
Experiment 6
Sunday 17.05.2016
Basic serial line with 4 Stations and 1 Buffer station with 5 Buffer
1. All stations has got the same cycle time: 200s
2. All stations has got World Class OEE
- Availability: 0.90
- Performance 0.95
- Quality 0.99
3. All stations has got an equal MTTR: 240s
Total cycles simulated: 2,088,747 (1 min)



EXP06d



Experiment 6
Sunday 17.05.2016
Basic serial line with 4 Stations and 1 Buffer station with 5 Buffer
1. All stations has got the same cycle time: 200s
2. All stations has got World Class OEE
- Availability: 0.90
- Performance 0.95
- Quality 0.99
3. All stations has got an equal MTTR: 240s
Total cycles simulated: 2,088,747 (1 min)



3. Observations and conclusions

1. The overall OEE for only stations in EXP06a and EXP06c are the same at ~0.6360.
2. The expected OEE was 0.6141 (0.85^3). This is similar to the simulated results.

3. The overall OEE for all stations in EXP06b is 0.6842. This is an increase compared to EXP06a,c,&d.
4. The expected OEE was 0.6141 (0.85^3). This is similar to the simulated results.

5. The overall OEE for all stations in EXP06d is 0.5743. This is a decrease compared to EXP06a,c,&d. Drain situation.
6. The expected OEE was 0.5220 (0.85^3). This is similar to the simulated results.

7. The OEE of EXP06a - EXP06c is 6-11% higher than the OEE of EXP02 & EXP06d, showing the positive effect of buffers.

Experiment 7

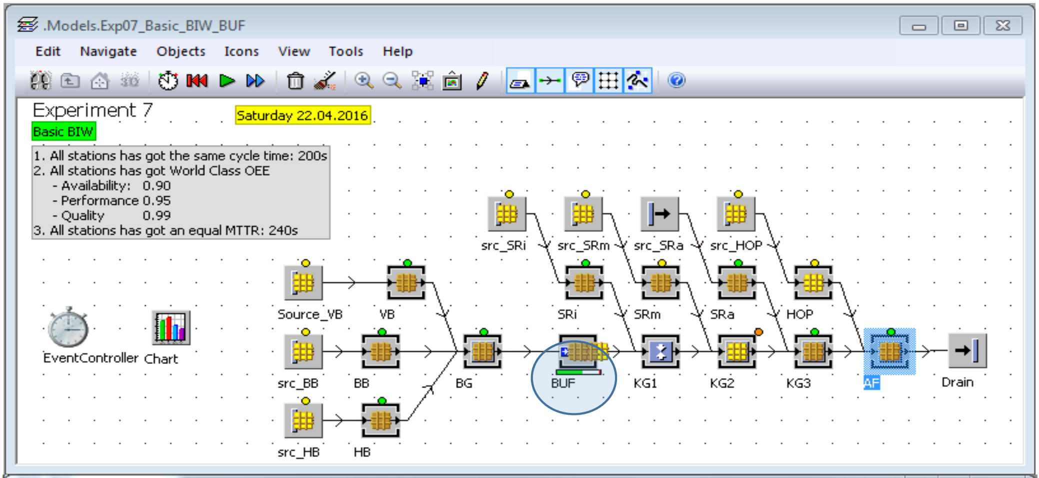
Basic BIW line with 1 buffer place and 5 buffers

1. Experiment description

The purpose of this experiment is to test whether the location of the buffer place influence the overall output. All station parameters are equal (Cycle time, availability, performance, quality, OEE and MTTR). The production line is based on a 15uph line with world class OEE. The buffer is moved to 7 different locations.

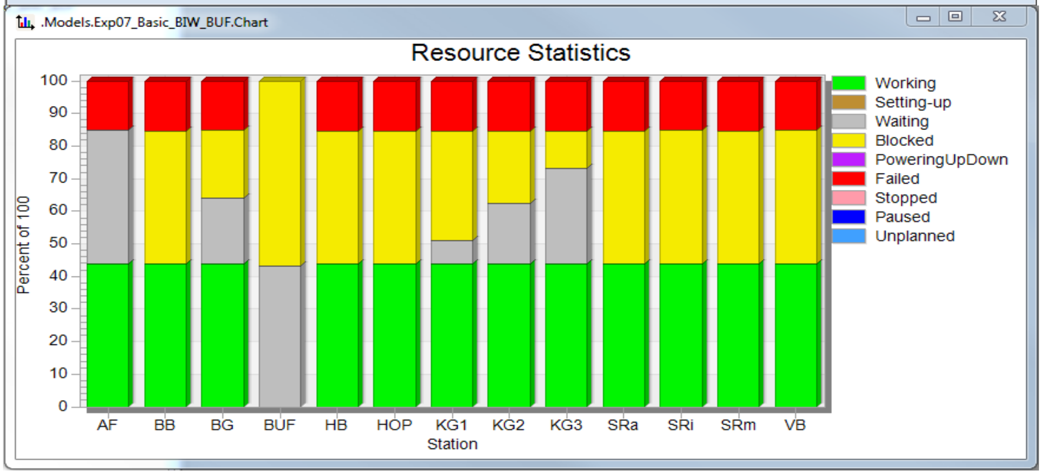
2. Simulation model in Siemens Plant Simulation and summary graph of the results

EXP07.8



1. All stations has got the same cycle time: 200s
2. All stations has got World Class OEE
   - Availability: 0.90
   - Performance 0.95
   - Quality 0.99
3. All stations has got an equal MTTR: 240s

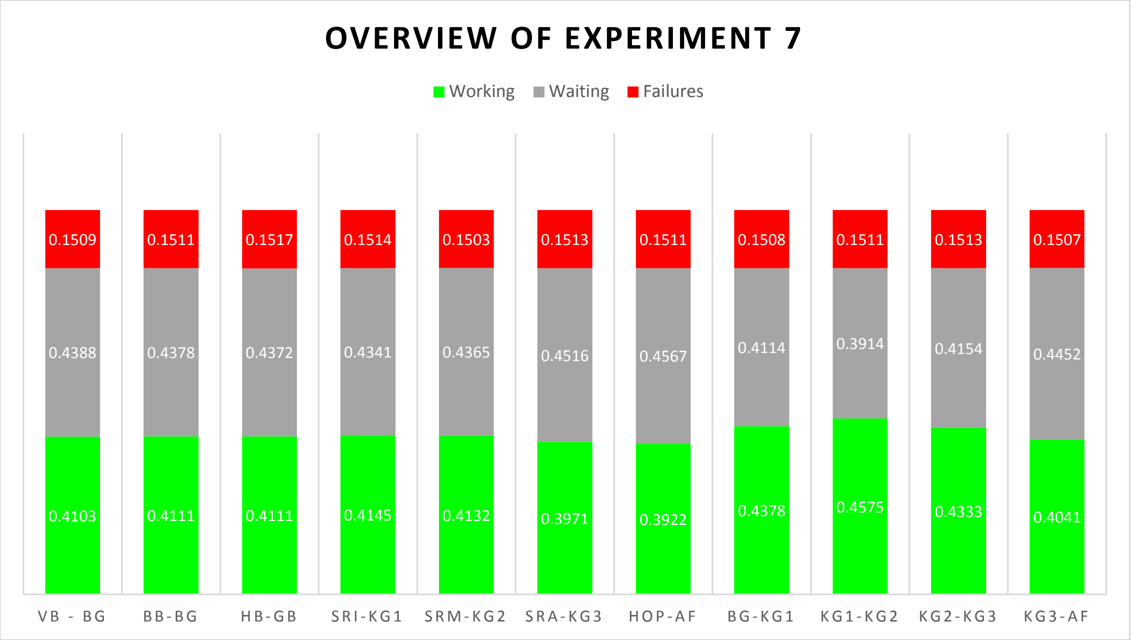
EXP07.8



3. Results from BUFFER locations

Exp No.	Location	Cycles	Working	Blocked	Waiting	Failures
Exp07.1	VB - BG	55279	0.4103	0	0.4388	0.1509
Exp07.2	BB-BG	51548	0.4111	0	0.4378	0.1511
Exp07.3	HB-GB	57498	0.4111	0	0.4372	0.1517
Exp07.4	SRi-KG1	56509	0.4145	0	0.4341	0.1514
Exp07.5	SRm-KG2	53908	0.4132	0	0.4365	0.1503
Exp07.6	SRa-KG3	53857	0.3971	0	0.4516	0.1513
Exp07.7	HOP-AF	51456	0.3922	0	0.4567	0.1511
Exp07.8	BG-KG1	54194	0.4378	0	0.4114	0.1508
Exp07.9	KG1-KG2	53508	0.4575	0	0.3914	0.1511
Exp07.10	KG2-KG3	58855	0.4333	0	0.4154	0.1513
Exp07.11	KG3-AF	50741	0.4041	0	0.4452	0.1507

4. Results comparison chart



5. Observations and conclusions

1. The Buffer had the best positive effect at postition KG1-KG2 with 0.4575 working time.
2. The Buffer had the the 2nd best effect at positions BG-KG1 and KG2-KG3.
3. The Buffer had the least effect at positions SRa-KG3 and HOP-AF.
4. The buffer had the same effect for positions VB-BG, BB-BG, HB-BG, SRi-KG1, SRm-KG2 and KG3-AF.

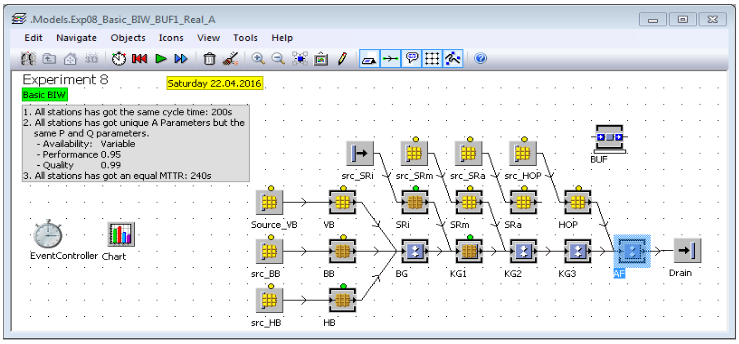
Experiment 8

Basic BIW line with unique Availability parameters

1. Experiment description

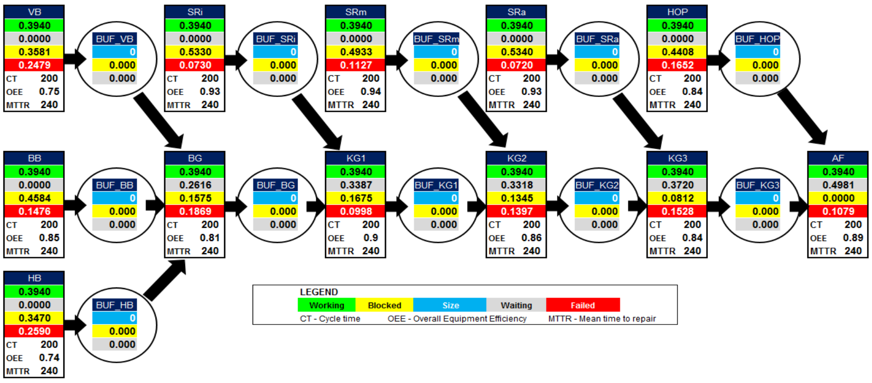
The purpose of this experiment is to comparison the ouput of real availability parameters to the output of experiment 3. All station parameters are equal (Cycle time, peroformance, quality, and MTTR). The production line is based on a 15uph line with world class OEE was not considered.

2. Simulation model in Siemens Plant Simulation



1. All stations has got the same cycle time: 200s
2. All stations has got unique A Parameters but the same P and Q parameters.
   - Availability: Variable
   - Performance 0.95
   - Quality 0.99
3. All stations has got an equal MTTR: 240s

3. Simulation results

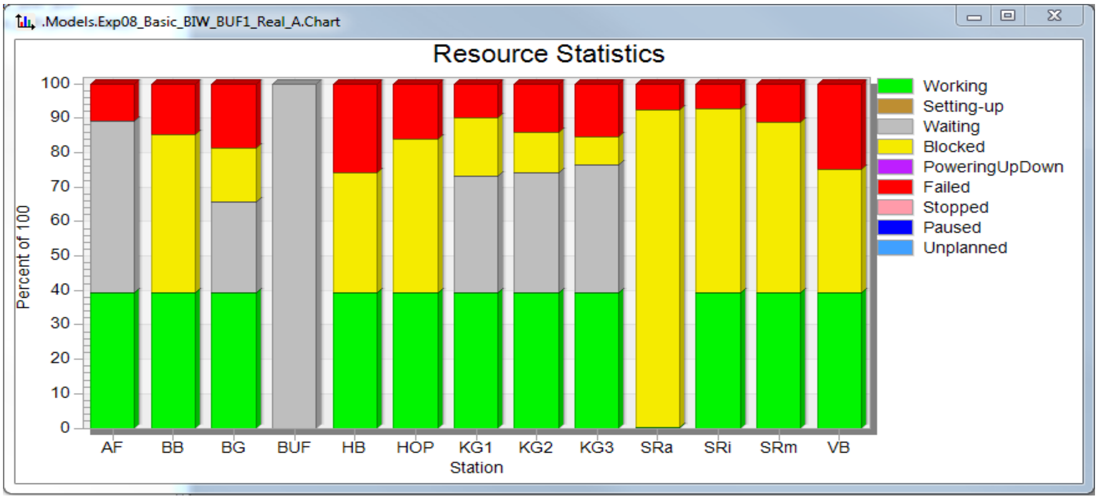


	VB	SRi	SRm	SRa	HOP	BB	BG	KG1	KG2	KG3	AF	HB
Working	0.3940	0.3940	0.3940	0.3940	0.3940	0.3940	0.3940	0.3940	0.3940	0.3940	0.3940	0.3940
Waiting	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2616	0.3387	0.3318	0.3720	0.4981	0.0000
Blocked	0.3581	0.5330	0.4933	0.5340	0.4408	0.4584	0.1575	0.1675	0.1345	0.0812	0.0000	0.3470
Failed	0.2479	0.0730	0.1127	0.0720	0.1652	0.1476	0.1869	0.0998	0.1397	0.1528	0.1079	0.2590
CT	200	200	200	200	200	200	200	200	200	200	200	200
OEE	0.75	0.93	0.94	0.93	0.84	0.85	0.81	0.9	0.86	0.84	0.89	0.74
MTTR	240	240	240	240	240	240	240	240	240	240	240	240

	BUF_VB	BUF_SRi	BUF_SRm	BUF_SRa	BUF_HOP	BUF_BB	BUF_BG	BUF_KG1	BUF_KG2	BUF_KG3	BUF_HB
Size	0	0	0	0	0	0	0	0	0	0	0
Blocked	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Waiting	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

CT - Cycle time OEE - Overall Equipment Efficiency MTTR - Mean time to repair

4. Summary graph of the results



5. Observations and conclusions

1. The overall OEE for all stations are the same at 0.3940.
2. The overall OEE is 1% higher as the OEE of experiment 3.
3. The faillure block is completely different for Exp 8 compated to Exp 3. Varations is visible.
4. Area VB and HB have the highest failure rate. This is due to the A parameter.

Experiment 9

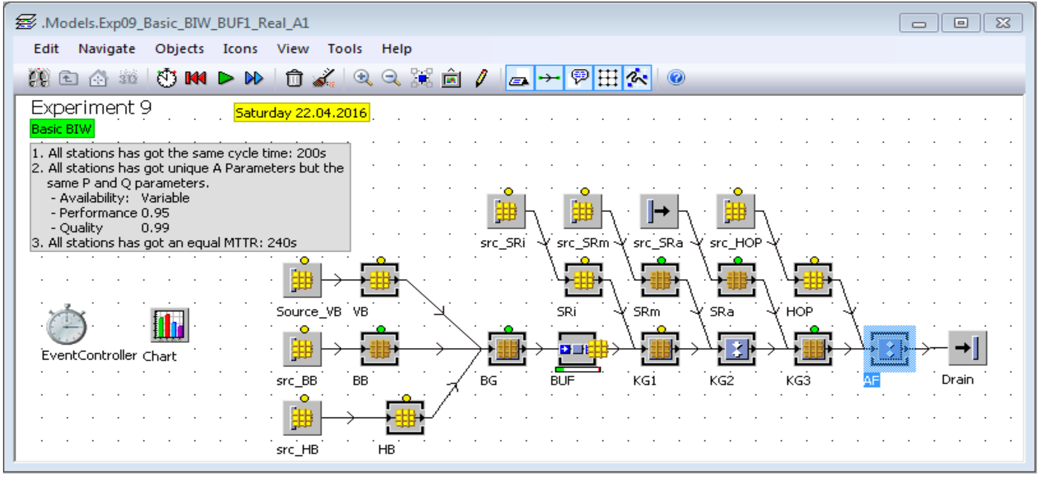
Basic BIW line with 1 buffer place and 5 buffers

1. Experiment description

The purpose of this experiment is to test whether the location of the buffer place influence the overall output. All station parameters are equal (Cycle time, performance, quality, and MTTR). The production line is based on a 15uph line with world class OEE. The buffer is moved to 11 different locations.

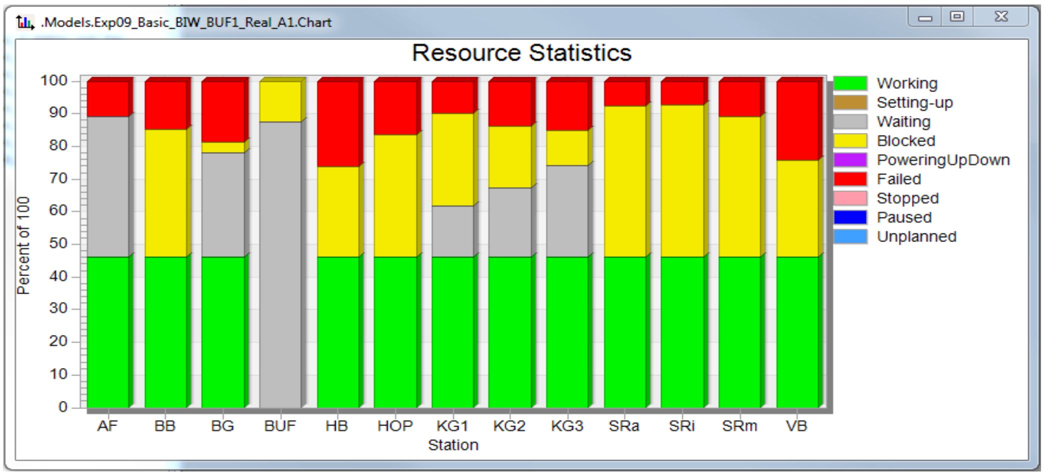
2. Simulation model in Siemens Plant Simulation and summary graph of the results

EXP09.8



1. All stations has got the same cycle time: 200s
2. All stations has got unique A Parameters but the same P and Q parameters.
   - Availability: Variable
   - Performance 0.95
   - Quality 0.99
3. All stations has got an equal MTTR: 240s

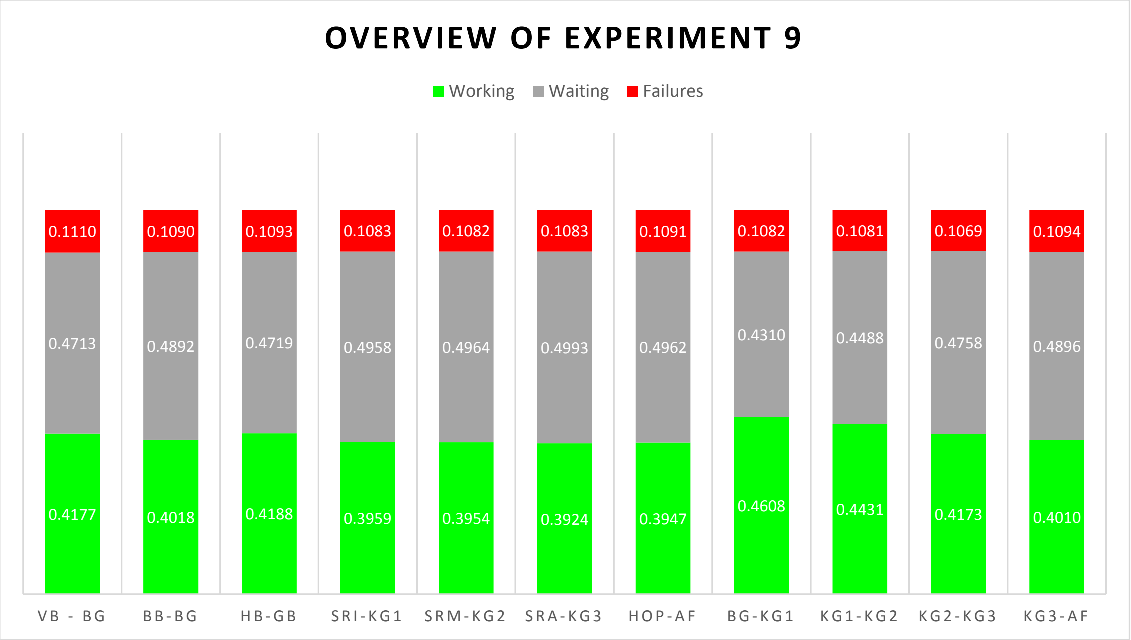
EXP09.8



3. Results from BUFFER locations

Exp No.	Location	Cycles	Working	Blocked	Waiting	Failures
Exp09.1	VB - BG	50789	0.4177	0	0.4713	0.1110
Exp09.2	BB-BG	54122	0.4018	0	0.4892	0.1090
Exp09.3	HB-GB	54285	0.4188	0	0.4719	0.1093
Exp09.4	SRi-KG1	55133	0.3959	0	0.4958	0.1083
Exp09.5	SRm-KG2	58756	0.3954	0	0.4964	0.1082
Exp09.6	SRa-KG3	53672	0.3924	0	0.4993	0.1083
Exp09.7	HOP-AF	52650	0.3947	0	0.4962	0.1091
Exp09.8	BG-KG1	55095	0.4608	0	0.4310	0.1082
Exp09.9	KG1-KG2	52987	0.4431	0	0.4488	0.1081
Exp09.10	KG2-KG3	50817	0.4173	0	0.4758	0.1069
Exp09.11	KG3-AF	57918	0.4010	0	0.4896	0.1094

4. Results comparison chart



5. Observations and conclusions

1. The Buffer had the best positive effect at postition BG-KG1 with 0.4608 working time.
2. The Buffer had the the 2nd best effect at position KG1-BG.
3. The Buffer had the least effect at positions SRi-KG1, SRm-KG2, SRa-KG3 and HOP-AF.
4. The buffer had the same effect for positions VB-BG, BB-BG, HB-BG, and KG3-AF.

Appendix C

Efficient frontier

Table C.1: The efficient frontier results

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
001	3	2	2	2	11	114370.2	166.32	13.056	13.106
002	3	2	2	3	10	114655.3	173.57	13.089	13.338
003	3	2	2	4	9	114669.3	173.671	13.09	13.57
004	3	2	2	5	8	114766.6	173.062	13.101	13.802
005	3	2	2	6	7	114766.3	173.347	13.101	14.034
006	3	2	2	7	6	114799.1	173.692	13.105	14.266
007	3	2	2	8	5	114792.5	173.074	13.104	14.498
008	3	2	2	9	4	114801.1	174.576	13.105	14.73
009	3	2	2	10	3	114778.8	173.566	13.103	14.962
010	3	2	2	11	2	114756.8	172.212	13.1	15.194
011	3	2	3	2	10	114849.8	184.894	13.111	13.538
012	3	2	3	3	9	115004.1	186.566	13.128	13.77
013	3	2	3	4	8	115003.5	186.814	13.128	14.002
014	3	2	3	5	7	115060.6	188	13.135	14.234
015	3	2	3	6	6	115050	186.991	13.134	14.466
016	3	2	3	7	5	115073.4	188.272	13.136	14.698

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
017	3	2	3	8	4	115054.8	186.974	13.134	14.93
018	3	2	3	9	3	115061.9	188.468	13.135	15.162
019	3	2	3	10	2	115003.3	186.796	13.128	15.394
020	3	2	4	2	9	114898	187.449	13.116	13.97
021	3	2	4	3	8	115031.7	187.094	13.131	14.202
022	3	2	4	4	7	115036.9	187.528	13.132	14.434
023	3	2	4	5	6	115080.8	189.303	13.137	14.666
024	3	2	4	6	5	115073.9	189.078	13.136	14.898
025	3	2	4	7	4	115084.7	190.333	13.138	15.13
026	3	2	4	8	3	115058.3	190.781	13.135	15.362
027	3	2	4	9	2	115034.5	189.909	13.132	15.594
028	3	2	5	2	8	115074.2	186.953	13.136	14.402
029	3	2	5	3	7	115150	191.219	13.145	14.634
030	3	2	5	4	6	115141.9	190.295	13.144	14.866
031	3	2	5	5	5	115170.3	191.622	13.147	15.098
032	3	2	5	6	4	115150.2	190.25	13.145	15.33
033	3	2	5	7	3	115157.9	192.316	13.146	15.562
034	3	2	5	8	2	115097.7	189.69	13.139	15.794
035	3	2	6	2	7	115079.6	186.613	13.137	14.834
036	3	2	6	3	6	115141.4	189.583	13.144	15.066
037	3	2	6	4	5	115139	189.136	13.144	15.298
038	3	2	6	5	4	115153.4	189.367	13.145	15.53
039	3	2	6	6	3	115125.4	189.74	13.142	15.762
040	3	2	6	7	2	115101.8	189.04	13.139	15.994
041	3	2	7	2	6	115148.1	187.858	13.145	15.266
042	3	2	7	3	5	115187.6	190.868	13.149	15.498

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
043	3	2	7	4	4	115168	189.211	13.147	15.73
044	3	2	7	5	3	115177.6	191.018	13.148	15.962
045	3	2	7	6	2	115116.3	188.544	13.141	16.194
046	3	2	8	2	5	115141.6	186.358	13.144	15.698
047	3	2	8	3	4	115164.7	188.999	13.147	15.93
048	3	2	8	4	3	115138.7	190.211	13.144	16.162
049	3	2	8	5	2	115115.9	188.436	13.141	16.394
050	3	2	9	2	4	115161.8	186.81	13.146	16.13
051	3	2	9	3	3	115178.9	191.571	13.148	16.362
052	3	2	9	4	2	115115.7	187.149	13.141	16.594
053	3	2	10	2	3	115128	187.283	13.142	16.562
054	3	2	10	3	2	115109.4	187.017	13.14	16.794
055	3	2	11	2	2	115092.8	184.947	13.138	16.994
056	3	3	2	2	10	115248.9	193.082	13.156	13.277
057	3	3	2	3	9	115431.9	195.545	13.177	13.509
058	3	3	2	4	8	115431.1	194.714	13.177	13.741
059	3	3	2	5	7	115498.3	195.483	13.185	13.973
060	3	3	2	6	6	115485.6	194.326	13.183	14.205
061	3	3	2	7	5	115514.2	194.905	13.187	14.437
062	3	3	2	8	4	115491	193.747	13.184	14.669
063	3	3	2	9	3	115499.9	195.435	13.185	14.901
064	3	3	2	10	2	115432	193.399	13.177	15.133
065	3	3	3	2	9	115515.9	196.706	13.187	13.709
066	3	3	3	3	8	115605	199.337	13.197	13.941
067	3	3	3	4	7	115609.3	199.862	13.197	14.173
068	3	3	3	5	6	115637.9	199.282	13.201	14.405

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
069	3	3	3	6	5	115632.5	199.422	13.2	14.637
070	3	3	3	7	4	115639.3	199.092	13.201	14.869
071	3	3	3	8	3	115617.7	200.265	13.198	15.101
072	3	3	3	9	2	115595.3	199.032	13.196	15.333
073	3	3	4	2	8	115535.3	197.672	13.189	14.141
074	3	3	4	3	7	115625.4	200.431	13.199	14.373
075	3	3	4	4	6	115615.8	199.892	13.198	14.605
076	3	3	4	5	5	115651	200.989	13.202	14.837
077	3	3	4	6	4	115626.5	199.527	13.199	15.069
078	3	3	4	7	3	115636.2	201.738	13.2	15.301
079	3	3	4	8	2	115564.9	199.155	13.192	15.533
080	3	3	5	2	7	115641.3	198.562	13.201	14.573
081	3	3	5	3	6	115679.8	199.405	13.205	14.805
082	3	3	5	4	5	115677.3	200.466	13.205	15.037
083	3	3	5	5	4	115684.7	199.9	13.206	15.269
084	3	3	5	6	3	115663	200.331	13.204	15.501
085	3	3	5	7	2	115640.8	198.767	13.201	15.733
086	3	3	6	2	6	115628.5	196.541	13.2	15.005
087	3	3	6	3	5	115676.3	199.227	13.205	15.237
088	3	3	6	4	4	115652.8	197.746	13.202	15.469
089	3	3	6	5	3	115664.7	200.218	13.204	15.701
090	3	3	6	6	2	115593.1	197.223	13.196	15.933
091	3	3	7	2	5	115678	197.542	13.205	15.437
092	3	3	7	3	4	115690.9	198.869	13.207	15.669
093	3	3	7	4	3	115670.3	200.284	13.204	15.901
094	3	3	7	5	2	115649.6	198.08	13.202	16.133

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
095	3	3	8	2	4	115646.6	194.028	13.202	15.869
096	3	3	8	3	3	115667.7	200.688	13.204	16.101
097	3	3	8	4	2	115594.6	195.249	13.196	16.333
098	3	3	9	2	3	115661.2	198.62	13.203	16.301
099	3	3	9	3	2	115642.9	197.289	13.201	16.533
100	3	3	10	2	2	115568	193.354	13.193	16.733
101	3	4	2	2	9	115277.5	192.739	13.16	13.448
102	3	4	2	3	8	115449.4	194.778	13.179	13.68
103	3	4	2	4	7	115456.1	194.129	13.18	13.912
104	3	4	2	5	6	115510.5	195.064	13.186	14.144
105	3	4	2	6	5	115502.5	194.764	13.185	14.376
106	3	4	2	7	4	115517	194.447	13.187	14.608
107	3	4	2	8	3	115486	196.899	13.183	14.84
108	3	4	2	9	2	115458.3	194.199	13.18	15.072
109	3	4	3	2	8	115527.6	194.772	13.188	13.88
110	3	4	3	3	7	115625.9	198.378	13.199	14.112
111	3	4	3	4	6	115615.8	197.618	13.198	14.344
112	3	4	3	5	5	115654.3	199.409	13.203	14.576
113	3	4	3	6	4	115629.3	197.619	13.2	14.808
114	3	4	3	7	3	115640	200.129	13.201	15.04
115	3	4	3	8	2	115566.8	197.629	13.193	15.272
116	3	4	4	2	7	115556	195.675	13.191	14.312
117	3	4	4	3	6	115631.4	198.394	13.2	14.544
118	3	4	4	4	5	115628.4	199.162	13.2	14.776
119	3	4	4	5	4	115647.1	199.055	13.202	15.008
120	3	4	4	6	3	115614.1	201.895	13.198	15.24

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
121	3	4	4	7	2	115586.6	199.243	13.195	15.472
122	3	4	5	2	6	115644.5	196.811	13.201	14.744
123	3	4	5	3	5	115694.7	199.507	13.207	14.976
124	3	4	5	4	4	115671.1	198.176	13.204	15.208
125	3	4	5	5	3	115683	200.887	13.206	15.44
126	3	4	5	6	2	115611.2	197.889	13.198	15.672
127	3	4	6	2	5	115639.9	195.187	13.201	15.176
128	3	4	6	3	4	115668.7	196.276	13.204	15.408
129	3	4	6	4	3	115638.9	200.053	13.201	15.64
130	3	4	6	5	2	115613.1	197.069	13.198	15.872
131	3	4	7	2	4	115666.5	193.819	13.204	15.608
132	3	4	7	3	3	115687.9	200.765	13.206	15.84
133	3	4	7	4	2	115614.9	195.622	13.198	16.072
134	3	4	8	2	3	115628.9	197.091	13.2	16.04
135	3	4	8	3	2	115608.6	195.775	13.197	16.272
136	3	4	9	2	2	115589	193.728	13.195	16.472
137	3	5	2	2	8	115630	196.019	13.2	13.619
138	3	5	2	3	7	115738.7	200.826	13.212	13.851
139	3	5	2	4	6	115728.6	199.684	13.211	14.083
140	3	5	2	5	5	115770.3	201.675	13.216	14.315
141	3	5	2	6	4	115743.7	199.366	13.213	14.547
142	3	5	2	7	3	115755.8	202.721	13.214	14.779
143	3	5	2	8	2	115677.3	199.333	13.205	15.011
144	3	5	3	2	7	115768.8	198.834	13.216	14.051
145	3	5	3	3	6	115818.2	201.022	13.221	14.283
146	3	5	3	4	5	115815.8	202.232	13.221	14.515

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
147	3	5	3	5	4	115826.6	202.146	13.222	14.747
148	3	5	3	6	3	115802.8	203.73	13.219	14.979
149	3	5	3	7	2	115779.7	202.085	13.217	15.211
150	3	5	4	2	6	115770.3	199.155	13.216	14.483
151	3	5	4	3	5	115825.1	202.078	13.222	14.715
152	3	5	4	4	4	115799.6	200.487	13.219	14.947
153	3	5	4	5	3	115813.2	204.171	13.221	15.179
154	3	5	4	6	2	115736.5	200.669	13.212	15.411
155	3	5	5	2	5	115827.2	200.789	13.222	14.915
156	3	5	5	3	4	115843.1	202.009	13.224	15.147
157	3	5	5	4	3	115821.4	204.062	13.222	15.379
158	3	5	5	5	2	115800	201.749	13.219	15.611
159	3	5	6	2	4	115796	196.645	13.219	15.347
160	3	5	6	3	3	115819.9	204.232	13.221	15.579
161	3	5	6	4	2	115742.3	198.211	13.213	15.811
162	3	5	7	2	3	115813.5	202.993	13.221	15.779
163	3	5	7	3	2	115795	200.96	13.219	16.011
164	3	5	8	2	2	115714.2	197.273	13.209	16.211
165	3	6	2	2	7	115629.9	194.442	13.2	13.79
166	3	6	2	3	6	115723.5	198.282	13.21	14.022
167	3	6	2	4	5	115720.9	198.662	13.21	14.254
168	3	6	2	5	4	115745.1	198.964	13.213	14.486
169	3	6	2	6	3	115708.6	201.438	13.209	14.718
170	3	6	2	7	2	115679.6	198.774	13.205	14.95
171	3	6	3	2	6	115751.3	195.884	13.214	14.222
172	3	6	3	3	5	115813.3	201.034	13.221	14.454

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
173	3	6	3	4	4	115787.5	199.088	13.218	14.686
174	3	6	3	5	3	115803.8	203.5	13.22	14.918
175	3	6	3	6	2	115724.2	199.848	13.211	15.15
176	3	6	4	2	5	115761.7	197.455	13.215	14.654
177	3	6	4	3	4	115795.8	198.988	13.219	14.886
178	3	6	4	4	3	115763.6	202.422	13.215	15.118
179	3	6	4	5	2	115737.4	199.716	13.212	15.35
180	3	6	5	2	4	115794.1	196.524	13.219	15.086
181	3	6	5	3	3	115819.4	204.088	13.221	15.318
182	3	6	5	4	2	115741.4	198.361	13.212	15.55
183	3	6	6	2	3	115756.5	199.326	13.214	15.518
184	3	6	6	3	2	115736.4	198.939	13.212	15.75
185	3	6	7	2	2	115715.4	196.954	13.21	15.95
186	3	7	2	2	6	115774	200.058	13.216	13.961
187	3	7	2	3	5	115841.4	204.61	13.224	14.193
188	3	7	2	4	4	115814.9	202.963	13.221	14.425
189	3	7	2	5	3	115833.7	206.572	13.223	14.657
190	3	7	2	6	2	115750.6	202.804	13.214	14.889
191	3	7	3	2	5	115850.6	202.985	13.225	14.393
192	3	7	3	3	4	115872.7	205.025	13.227	14.625
193	3	7	3	4	3	115850	207.599	13.225	14.857
194	3	7	3	5	2	115828.9	205.245	13.222	15.089
195	3	7	4	2	4	115827.6	200.113	13.222	14.825
196	3	7	4	3	3	115855.2	207.542	13.225	15.057
197	3	7	4	4	2	115774.8	201.044	13.216	15.289
198	3	7	5	2	3	115847.9	206.29	13.225	15.257

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
199	3	7	5	3	2	115830.4	204.81	13.223	15.489
200	3	7	6	2	2	115748.8	200.463	13.213	15.689
201	3	8	2	2	5	115762.9	199	13.215	14.132
202	3	8	2	3	4	115807.6	202.029	13.22	14.364
203	3	8	2	4	3	115774.1	205.343	13.216	14.596
204	3	8	2	5	2	115749.2	202.767	13.213	14.828
205	3	8	3	2	4	115811.7	199.213	13.221	14.564
206	3	8	3	3	3	115845.6	207.938	13.224	14.796
207	3	8	3	4	2	115760.8	201.166	13.215	15.028
208	3	8	4	2	3	115784.6	203.012	13.217	14.996
209	3	8	4	3	2	115766.2	202.336	13.215	15.228
210	3	8	5	2	2	115743.8	201.249	13.213	15.428
211	3	9	2	2	4	115812.9	199.574	13.221	14.303
212	3	9	2	3	3	115851.8	207.237	13.225	14.535
213	3	9	2	4	2	115763.4	201.399	13.215	14.767
214	3	9	3	2	3	115846.5	205.471	13.224	14.735
215	3	9	3	3	2	115831.1	204.457	13.223	14.967
216	3	9	4	2	2	115750.8	200.851	13.214	15.167
217	3	10	2	2	3	115766.4	201.364	13.215	14.474
218	3	10	2	3	2	115753.6	202.317	13.214	14.706
219	3	10	3	2	2	115732.6	199.126	13.211	14.906
220	3	11	2	2	2	115722.5	198.918	13.21	14.645
221	4	2	2	2	10	116694.3	170.43	13.321	13.258
222	4	2	2	3	9	117024.6	180.374	13.359	13.49
223	4	2	2	4	8	117025.8	179.614	13.359	13.722
224	4	2	2	5	7	117154.8	176.569	13.374	13.954

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
225	4	2	2	6	6	117131.6	176.2	13.371	14.186
226	4	2	2	7	5	117187	177.843	13.378	14.418
227	4	2	2	8	4	117144.3	175.689	13.373	14.65
228	4	2	2	9	3	117158.4	175.642	13.374	14.882
229	4	2	2	10	2	117038.4	166.467	13.361	15.114
230	4	2	3	2	9	117221.8	184.968	13.381	13.69
231	4	2	3	3	8	117396.9	190.073	13.401	13.922
232	4	2	3	4	7	117404.6	188.681	13.402	14.154
233	4	2	3	5	6	117462.8	189.727	13.409	14.386
234	4	2	3	6	5	117452.5	190.578	13.408	14.618
235	4	2	3	7	4	117466.3	190.113	13.409	14.85
236	4	2	3	8	3	117421.9	188.647	13.404	15.082
237	4	2	3	9	2	117379.2	184.33	13.399	15.314
238	4	2	4	2	8	117260	185.216	13.386	14.122
239	4	2	4	3	7	117438.7	189.417	13.406	14.354
240	4	2	4	4	6	117419.4	187.298	13.404	14.586
241	4	2	4	5	5	117490.4	190.619	13.412	14.818
242	4	2	4	6	4	117442.5	189.265	13.407	15.05
243	4	2	4	7	3	117459.5	190.038	13.409	15.282
244	4	2	4	8	2	117324.8	180.396	13.393	15.514
245	4	2	5	2	7	117478	184.139	13.411	14.554
246	4	2	5	3	6	117558	188.721	13.42	14.786
247	4	2	5	4	5	117553.1	189.171	13.419	15.018
248	4	2	5	5	4	117569.6	188.561	13.421	15.25
249	4	2	5	6	3	117524.1	187.774	13.416	15.482
250	4	2	5	7	2	117480.4	182.788	13.411	15.714

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
251	4	2	6	2	6	117454.4	183.8	13.408	14.986
252	4	2	6	3	5	117551.8	189.469	13.419	15.218
253	4	2	6	4	4	117505.7	186.732	13.414	15.45
254	4	2	6	5	3	117528.3	187.311	13.416	15.682
255	4	2	6	6	2	117389.1	178.336	13.401	15.914
256	4	2	7	2	5	117555.8	186.657	13.42	15.418
257	4	2	7	3	4	117583.4	188.204	13.423	15.65
258	4	2	7	4	3	117542	187.464	13.418	15.882
259	4	2	7	5	2	117499.4	182.897	13.413	16.114
260	4	2	8	2	4	117495.5	183.493	13.413	15.85
261	4	2	8	3	3	117535	187.394	13.417	16.082
262	4	2	8	4	2	117393.6	176.686	13.401	16.314
263	4	2	9	2	3	117522.9	184.526	13.416	16.282
264	4	2	9	3	2	117486.3	181.285	13.412	16.514
265	4	2	10	2	2	117343.9	176.062	13.395	16.714
266	4	3	2	2	9	117592	191.657	13.424	13.429
267	4	3	2	3	8	117797.4	196.736	13.447	13.661
268	4	3	2	4	7	117805.5	195.39	13.448	13.893
269	4	3	2	5	6	117873.6	194.279	13.456	14.125
270	4	3	2	6	5	117861.7	194.918	13.455	14.357
271	4	3	2	7	4	117877.5	194.642	13.456	14.589
272	4	3	2	8	3	117825.1	194.11	13.45	14.821
273	4	3	2	9	2	117777.7	189.567	13.445	15.053
274	4	3	3	2	8	117883.9	192.041	13.457	13.861
275	4	3	3	3	7	118008.3	196.996	13.471	14.093
276	4	3	3	4	6	117993.3	194.48	13.47	14.325

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
277	4	3	3	5	5	118042	197.746	13.475	14.557
278	4	3	3	6	4	118004.5	195.861	13.471	14.789
279	4	3	3	7	3	118013.5	198.928	13.472	15.021
280	4	3	3	8	2	117898.3	190.244	13.459	15.253
281	4	3	4	2	7	117919	193.609	13.461	14.293
282	4	3	4	3	6	118012.3	195.447	13.472	14.525
283	4	3	4	4	5	118005.7	196.784	13.471	14.757
284	4	3	4	5	4	118026.9	196.5	13.473	14.989
285	4	3	4	6	3	117972.3	197.199	13.467	15.221
286	4	3	4	7	2	117921.9	191.249	13.461	15.453
287	4	3	5	2	6	118022.2	193.143	13.473	14.725
288	4	3	5	3	5	118086.1	198.319	13.48	14.957
289	4	3	5	4	4	118051.4	196.436	13.476	15.189
290	4	3	5	5	3	118062.7	201.002	13.477	15.421
291	4	3	5	6	2	117946.9	191.523	13.464	15.653
292	4	3	6	2	5	118013.4	193.858	13.472	15.157
293	4	3	6	3	4	118048.9	195.585	13.476	15.389
294	4	3	6	4	3	117998.7	195.726	13.47	15.621
295	4	3	6	5	2	117949.8	191.452	13.465	15.853
296	4	3	7	2	4	118042.2	193.968	13.475	15.589
297	4	3	7	3	3	118066.1	199.814	13.478	15.821
298	4	3	7	4	2	117948.6	189.434	13.464	16.053
299	4	3	8	2	3	117979.1	193.849	13.468	16.021
300	4	3	8	3	2	117936.5	190.517	13.463	16.253
301	4	3	9	2	2	117905.2	191.152	13.459	16.453
302	4	4	2	2	8	117597.7	193.673	13.424	13.6

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
303	4	4	2	3	7	117821.2	197.055	13.45	13.832
304	4	4	2	4	6	117798.4	194.328	13.447	14.064
305	4	4	2	5	5	117887.3	196.248	13.457	14.296
306	4	4	2	6	4	117830.8	196.227	13.451	14.528
307	4	4	2	7	3	117852.3	196.519	13.453	14.76
308	4	4	2	8	2	117696.9	187.173	13.436	14.992
309	4	4	3	2	7	117904.3	191.088	13.459	14.032
310	4	4	3	3	6	118007.2	194.499	13.471	14.264
311	4	4	3	4	5	118001.1	195.908	13.47	14.496
312	4	4	3	5	4	118025.5	195.699	13.473	14.728
313	4	4	3	6	3	117970.1	197.014	13.467	14.96
314	4	4	3	7	2	117921	191.453	13.461	15.192
315	4	4	4	2	6	117902.5	192.175	13.459	14.464
316	4	4	4	3	5	118019.2	196.988	13.473	14.696
317	4	4	4	4	4	117965.3	196.182	13.466	14.928
318	4	4	4	5	3	117993.2	197.858	13.47	15.16
319	4	4	4	6	2	117831.4	187.418	13.451	15.392
320	4	4	5	2	5	118027.4	193.621	13.473	14.896
321	4	4	5	3	4	118064.6	195.75	13.478	15.128
322	4	4	5	4	3	118014.5	196.682	13.472	15.36
323	4	4	5	5	2	117965.8	192.724	13.466	15.592
324	4	4	6	2	4	117963.2	192.867	13.466	15.328
325	4	4	6	3	3	118009.9	196.49	13.471	15.56
326	4	4	6	4	2	117846.9	185.385	13.453	15.792
327	4	4	7	2	3	117998	194.648	13.47	15.76
328	4	4	7	3	2	117955.9	191.573	13.465	15.992

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
329	4	4	8	2	2	117796.1	187.584	13.447	16.192
330	4	5	2	2	7	117993.6	193.531	13.47	13.771
331	4	5	2	3	6	118110.7	198.085	13.483	14.003
332	4	5	2	4	5	118105.1	198.53	13.482	14.235
333	4	5	2	5	4	118132.8	200.488	13.485	14.467
334	4	5	2	6	3	118073.6	203.355	13.479	14.699
335	4	5	2	7	2	118023.4	195.982	13.473	14.931
336	4	5	3	2	6	118137.5	194.971	13.486	14.203
337	4	5	3	3	5	118217.7	201.542	13.495	14.435
338	4	5	3	4	4	118178	200.349	13.491	14.667
339	4	5	3	5	3	118195.6	205.202	13.493	14.899
340	4	5	3	6	2	118067.8	195.822	13.478	15.131
341	4	5	4	2	5	118147.2	197.616	13.487	14.635
342	4	5	4	3	4	118188.4	200.546	13.492	14.867
343	4	5	4	4	3	118134.2	202.411	13.486	15.099
344	4	5	4	5	2	118083.7	195.716	13.48	15.331
345	4	5	5	2	4	118182.8	199.885	13.491	15.067
346	4	5	5	3	3	118212.3	205.4	13.495	15.299
347	4	5	5	4	2	118086.2	194.538	13.48	15.531
348	4	5	6	2	3	118119.6	201.151	13.484	15.499
349	4	5	6	3	2	118077.1	195.163	13.479	15.731
350	4	5	7	2	2	118044.6	196.54	13.475	15.931
351	4	6	2	2	6	117952.5	190.34	13.465	13.942
352	4	6	2	3	5	118098.4	197.889	13.482	14.174
353	4	6	2	4	4	118038.4	199.275	13.475	14.406
354	4	6	2	5	3	118074.3	202.056	13.479	14.638

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
355	4	6	2	6	2	117898.4	192.863	13.459	14.87
356	4	6	3	2	5	118122.6	194.339	13.484	14.374
357	4	6	3	3	4	118171.7	198.871	13.49	14.606
358	4	6	3	4	3	118116.1	200.871	13.484	14.838
359	4	6	3	5	2	118067.3	195.238	13.478	15.07
360	4	6	4	2	4	118073.7	197.407	13.479	14.806
361	4	6	4	3	3	118126.5	201.337	13.485	15.038
362	4	6	4	4	2	117952.7	190.142	13.465	15.27
363	4	6	5	2	3	118115.7	199.999	13.484	15.238
364	4	6	5	3	2	118073.9	195.155	13.479	15.47
365	4	6	6	2	2	117906.9	191.592	13.46	15.67
366	4	7	2	2	5	118139.4	196.579	13.486	14.113
367	4	7	2	3	4	118195.8	201.442	13.493	14.345
368	4	7	2	4	3	118138.3	203.772	13.486	14.577
369	4	7	2	5	2	118090	198.288	13.481	14.809
370	4	7	3	2	4	118196.9	199.389	13.493	14.545
371	4	7	3	3	3	118234.3	206.178	13.497	14.777
372	4	7	3	4	2	118099.5	195.058	13.482	15.009
373	4	7	4	2	3	118145.3	201.091	13.487	14.977
374	4	7	4	3	2	118104	196.467	13.482	15.209
375	4	7	5	2	2	118068.8	197.387	13.478	15.409
376	4	8	2	2	4	118053.9	196.852	13.476	14.284
377	4	8	2	3	3	118127.2	202.687	13.485	14.516
378	4	8	2	4	2	117939.1	191.41	13.463	14.748
379	4	8	3	2	3	118120	198.661	13.484	14.716
380	4	8	3	3	2	118084.6	196.194	13.48	14.948

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
381	4	8	4	2	2	117919.7	192.074	13.461	15.148
382	4	9	2	2	3	118114.5	199.122	13.483	14.455
383	4	9	2	3	2	118083.1	197.816	13.48	14.687
384	4	9	3	2	2	118045	194.818	13.475	14.887
385	4	10	2	2	2	117862.2	188.367	13.455	14.626
386	5	2	2	2	9	119032.9	174.275	13.588	13.41
387	5	2	2	3	8	119379.8	178.965	13.628	13.642
388	5	2	2	4	7	119392.8	176.12	13.629	13.874
389	5	2	2	5	6	119511.6	174.812	13.643	14.106
390	5	2	2	6	5	119489.5	174.927	13.64	14.338
391	5	2	2	7	4	119519.4	177.043	13.644	14.57
392	5	2	2	8	3	119426.7	175.15	13.633	14.802
393	5	2	2	9	2	119345.7	169.396	13.624	15.034
394	5	2	3	2	8	119559.1	185.077	13.648	13.842
395	5	2	3	3	7	119778.8	186.642	13.673	14.074
396	5	2	3	4	6	119749.9	184.485	13.67	14.306
397	5	2	3	5	5	119837.1	187.309	13.68	14.538
398	5	2	3	6	4	119768.6	187.136	13.672	14.77
399	5	2	3	7	3	119779.3	185.872	13.673	15.002
400	5	2	3	8	2	119581	177.701	13.651	15.234
401	5	2	4	2	7	119623	185.636	13.656	14.274
402	5	2	4	3	6	119788.8	186.546	13.675	14.506
403	5	2	4	4	5	119775.8	185.832	13.673	14.738
404	5	2	4	5	4	119813.7	188.218	13.677	14.97
405	5	2	4	6	3	119713.5	183.516	13.666	15.202
406	5	2	4	7	2	119627.8	178.741	13.656	15.434

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
407	5	2	5	2	6	119815.4	184.562	13.678	14.706
408	5	2	5	3	5	119934.1	191.59	13.691	14.938
409	5	2	5	4	4	119867.7	188.999	13.684	15.17
410	5	2	5	5	3	119882.9	188.446	13.685	15.402
411	5	2	5	6	2	119680.9	179.721	13.662	15.634
412	5	2	6	2	5	119796.9	185.229	13.675	15.138
413	5	2	6	3	4	119862	189.331	13.683	15.37
414	5	2	6	4	3	119769	182.323	13.672	15.602
415	5	2	6	5	2	119684.4	179.149	13.663	15.834
416	5	2	7	2	4	119847.8	186.159	13.681	15.57
417	5	2	7	3	3	119889.2	188.265	13.686	15.802
418	5	2	7	4	2	119685.1	177.814	13.663	16.034
419	5	2	8	2	3	119734.3	181.195	13.668	16.002
420	5	2	8	3	2	119664.9	178.724	13.66	16.234
421	5	2	9	2	2	119608.3	174.64	13.654	16.434
422	5	3	2	2	8	119869.6	193.364	13.684	13.581
423	5	3	2	3	7	120129.4	197.433	13.713	13.813
424	5	3	2	4	6	120096.9	193.578	13.71	14.045
425	5	3	2	5	5	120200	196.394	13.721	14.277
426	5	3	2	6	4	120120.9	197.883	13.712	14.509
427	5	3	2	7	3	120135.7	198.52	13.714	14.741
428	5	3	2	8	2	119914.7	186.761	13.689	14.973
429	5	3	3	2	7	120204.2	194.915	13.722	14.013
430	5	3	3	3	6	120327	199.699	13.736	14.245
431	5	3	3	4	5	120314.2	198.61	13.734	14.477
432	5	3	3	5	4	120337.7	200.029	13.737	14.709

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
433	5	3	3	6	3	120252.6	199.71	13.727	14.941
434	5	3	3	7	2	120167.4	193.61	13.718	15.173
435	5	3	4	2	6	120198.9	195.413	13.721	14.445
436	5	3	4	3	5	120338.6	199.823	13.737	14.677
437	5	3	4	4	4	120262.7	199.501	13.729	14.909
438	5	3	4	5	3	120281.2	199.529	13.731	15.141
439	5	3	4	6	2	120054.4	186.744	13.705	15.373
440	5	3	5	2	5	120339.7	197.184	13.737	14.877
441	5	3	5	3	4	120379.9	200.715	13.742	15.109
442	5	3	5	4	3	120301.2	198.551	13.733	15.341
443	5	3	5	5	2	120218.5	193.943	13.724	15.573
444	5	3	6	2	4	120245.2	197.691	13.727	15.309
445	5	3	6	3	3	120293.6	198.27	13.732	15.541
446	5	3	6	4	2	120063.1	186.224	13.706	15.773
447	5	3	7	2	3	120268	198.145	13.729	15.741
448	5	3	7	3	2	120196.5	190.743	13.721	15.973
449	5	3	8	2	2	119978.6	184.85	13.696	16.173
450	5	4	2	2	7	119892.9	192.451	13.686	13.752
451	5	4	2	3	6	120109.7	194.775	13.711	13.984
452	5	4	2	4	5	120095.5	193.125	13.71	14.216
453	5	4	2	5	4	120147.5	197.37	13.715	14.448
454	5	4	2	6	3	120035.8	195.035	13.703	14.68
455	5	4	2	7	2	119943.1	186.609	13.692	14.912
456	5	4	3	2	6	120171.6	192.454	13.718	14.184
457	5	4	3	3	5	120327	198.039	13.736	14.416
458	5	4	3	4	4	120248.8	197.79	13.727	14.648

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Table C.1 – *Continued from previous page*

Exp. no.	L1	L2	L3	L4	L5	Mean volume	SD	MT	Cost factor
459	5	4	3	5	3	120274.5	198.497	13.73	14.88
460	5	4	3	6	2	120040.4	186.504	13.703	15.112
461	5	4	4	2	5	120190.6	194.919	13.72	14.616
462	5	4	4	3	4	120272.1	201.004	13.73	14.848
463	5	4	4	4	3	120165.5	194.449	13.718	15.08
464	5	4	4	5	2	120072.6	187.571	13.707	15.312
465	5	4	5	2	4	120258.8	197.419	13.728	15.048
466	5	4	5	3	3	120310.9	198.964	13.734	15.28
467	5	4	5	4	2	120077.7	187.422	13.708	15.512
468	5	4	6	2	3	120136.8	194.078	13.714	15.48
469	5	4	6	3	2	120060.6	186.601	13.706	15.712
470	5	4	7	2	2	119997.9	184.605	13.698	15.912
471	5	5	2	2	6	120241.9	192.91	13.726	13.923
472	5	5	2	3	5	120417.1	200.315	13.746	14.155
473	5	5	2	4	4	120332.4	199.816	13.737	14.387
474	5	5	2	5	3	120362.1	202.024	13.74	14.619
475	5	5	2	6	2	120116.2	190.469	13.712	14.851
476	5	5	3	2	5	120432.8	197.88	13.748	14.355
477	5	5	3	3	4	120490.8	203.441	13.755	14.587
478	5	5	3	4	3	120403	201.502	13.745	14.819
479	5	5	3	5	2	120317.2	196.734	13.735	15.051
480	5	5	4	2	4	120360.2	199.992	13.74	14.787
481	5	5	4	3	3	120416.8	201.926	13.746	15.019
482	5	5	4	4	2	120171.9	190.337	13.718	15.251
483	5	5	5	2	3	120389.3	201.548	13.743	15.219
484	5	5	5	3	2	120315.9	193.984	13.735	15.451

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
485	5	5	6	2	2	120090.9	188.08	13.709	15.651
486	5	6	2	2	5	120208.9	191.803	13.722	14.094
487	5	6	2	3	4	120320.1	202.186	13.735	14.326
488	5	6	2	4	3	120204.8	197.224	13.722	14.558
489	5	6	2	5	2	120115.4	190.775	13.712	14.79
490	5	6	3	2	4	120320.8	197.449	13.735	14.526
491	5	6	3	3	3	120390.9	201.525	13.743	14.758
492	5	6	3	4	2	120137.6	189.916	13.714	14.99
493	5	6	4	2	3	120220.7	195.163	13.724	14.958
494	5	6	4	3	2	120147.8	190.448	13.716	15.19
495	5	6	5	2	2	120080.1	186.934	13.708	15.39
496	5	7	2	2	4	120320.8	196.976	13.735	14.265
497	5	7	2	3	3	120404.7	205.168	13.745	14.497
498	5	7	2	4	2	120141.3	192.223	13.715	14.729
499	5	7	3	2	3	120381.6	200.621	13.742	14.697
500	5	7	3	3	2	120314.6	195.997	13.735	14.929
501	5	7	4	2	2	120095.2	187.874	13.709	15.129
502	5	8	2	2	3	120168.5	191.78	13.718	14.436
503	5	8	2	3	2	120113	192.471	13.712	14.668
504	5	8	3	2	2	120042.4	185.414	13.703	14.868
505	5	9	2	2	2	120004.3	182.947	13.699	14.607
506	6	2	2	2	8	120053.5	162.586	13.705	13.562
507	6	2	2	3	7	120454.5	168.406	13.751	13.794
508	6	2	2	4	6	120406.3	165.757	13.745	14.026
509	6	2	2	5	5	120569	166.34	13.764	14.258
510	6	2	2	6	4	120455.8	165.14	13.751	14.49

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
511	6	2	2	7	3	120486.1	165.636	13.754	14.722
512	6	2	2	8	2	120191	161.709	13.72	14.954
513	6	2	3	2	7	120622.5	170.988	13.77	13.994
514	6	2	3	3	6	120820.4	173.18	13.792	14.226
515	6	2	3	4	5	120800.8	172.948	13.79	14.458
516	6	2	3	5	4	120846.2	173.371	13.795	14.69
517	6	2	3	6	3	120720.9	171.896	13.781	14.922
518	6	2	3	7	2	120612.9	168.886	13.769	15.154
519	6	2	4	2	6	120618.4	170.205	13.769	14.426
520	6	2	4	3	5	120843.8	173.502	13.795	14.658
521	6	2	4	4	4	120726.7	171.918	13.782	14.89
522	6	2	4	5	3	120769.4	171.775	13.786	15.122
523	6	2	4	6	2	120451.8	163.805	13.75	15.354
524	6	2	5	2	5	120861.1	172.151	13.797	14.858
525	6	2	5	3	4	120931.2	176.378	13.805	15.09
526	6	2	5	4	3	120814.2	172.599	13.792	15.322
527	6	2	5	5	2	120705.4	171.894	13.779	15.554
528	6	2	6	2	4	120723.2	170.672	13.781	15.29
529	6	2	6	3	3	120806.3	172.314	13.791	15.522
530	6	2	6	4	2	120482.7	163.38	13.754	15.754
531	6	2	7	2	3	120776.8	171.605	13.787	15.722
532	6	2	7	3	2	120684.8	171.469	13.777	15.954
533	6	2	8	2	2	120376	160.233	13.742	16.154
534	6	3	2	2	7	120899.7	178.677	13.801	13.733
535	6	3	2	3	6	121134.8	182.568	13.828	13.965
536	6	3	2	4	5	121112.9	182.222	13.826	14.197

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
537	6	3	2	5	4	121165.6	182.618	13.832	14.429
538	6	3	2	6	3	121028	180.12	13.816	14.661
539	6	3	2	7	2	120909.6	177.412	13.802	14.893
540	6	3	3	2	6	121196.3	179.615	13.835	14.165
541	6	3	3	3	5	121369.2	187.118	13.855	14.397
542	6	3	3	4	4	121272	183.361	13.844	14.629
543	6	3	3	5	3	121291.7	186.906	13.846	14.861
544	6	3	3	6	2	121009.5	175.926	13.814	15.093
545	6	3	4	2	5	121212.4	180.875	13.837	14.597
546	6	3	4	3	4	121299.2	186.455	13.847	14.829
547	6	3	4	4	3	121165.5	179.566	13.832	15.061
548	6	3	4	5	2	121046.1	176.823	13.818	15.293
549	6	3	5	2	4	121279.9	181.833	13.845	15.029
550	6	3	5	3	3	121331.5	187.551	13.851	15.261
551	6	3	5	4	2	121048	175.92	13.818	15.493
552	6	3	6	2	3	121127.6	176.947	13.827	15.461
553	6	3	6	3	2	121027.5	175.606	13.816	15.693
554	6	3	7	2	2	120945.2	171.677	13.807	15.893
555	6	4	2	2	6	120842.2	172.89	13.795	13.904
556	6	4	2	3	5	121127.4	182.164	13.827	14.136
557	6	4	2	4	4	120997.8	178.74	13.813	14.368
558	6	4	2	5	3	121053.7	181.272	13.819	14.6
559	6	4	2	6	2	120700.7	170.067	13.779	14.832
560	6	4	3	2	5	121178.6	179.632	13.833	14.336
561	6	4	3	3	4	121280.2	184.397	13.845	14.568
562	6	4	3	4	3	121143.9	179.769	13.829	14.8

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
563	6	4	3	5	2	121027.8	175.96	13.816	15.032
564	6	4	4	2	4	121069.4	174.686	13.821	14.768
565	6	4	4	3	3	121169.9	180.095	13.832	15
566	6	4	4	4	2	120810.2	170.232	13.791	15.232
567	6	4	5	2	3	121139.4	176.919	13.829	15.2
568	6	4	5	3	2	121039.1	175.758	13.817	15.432
569	6	4	6	2	2	120707.1	164.335	13.779	15.632
570	6	5	2	2	5	121233.6	178.799	13.839	14.075
571	6	5	2	3	4	121350.7	186.518	13.853	14.307
572	6	5	2	4	3	121209.2	180.857	13.837	14.539
573	6	5	2	5	2	121093.2	177.751	13.823	14.771
574	6	5	3	2	4	121344.5	183.549	13.852	14.507
575	6	5	3	3	3	121416	189.635	13.86	14.739
576	6	5	3	4	2	121109.9	176.302	13.825	14.971
577	6	5	4	2	3	121221.4	178.427	13.838	14.939
578	6	5	4	3	2	121121.9	176.959	13.827	15.171
579	6	5	5	2	2	121034.6	172.058	13.817	15.371
580	6	6	2	2	4	121051.8	172.046	13.819	14.246
581	6	6	2	3	3	121191.7	181.3	13.835	14.478
582	6	6	2	4	2	120803.1	169.481	13.79	14.71
583	6	6	3	2	3	121170.6	178.142	13.832	14.678
584	6	6	3	3	2	121080	175.922	13.822	14.91
585	6	6	4	2	2	120753.7	164.067	13.785	15.11
586	6	7	2	2	3	121154.7	176.679	13.83	14.417
587	6	7	2	3	2	121074.5	177.004	13.821	14.649
588	6	7	3	2	2	120984.4	168.261	13.811	14.849

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Table C.1 – *Continued from previous page*

Exp. no.	L1	L2	L3	L4	L5	Mean volume	SD	MT	Cost factor
589	6	8	2	2	2	120639.8	160.85	13.772	14.588
590	7	2	2	2	7	121328.5	165.144	13.85	13.714
591	7	2	2	3	6	121679.7	168.618	13.89	13.946
592	7	2	2	4	5	121652	168.806	13.887	14.178
593	7	2	2	5	4	121739	169.907	13.897	14.41
594	7	2	2	6	3	121550.8	168.127	13.876	14.642
595	7	2	2	7	2	121409.8	165.308	13.86	14.874
596	7	2	3	2	6	121826.8	173.884	13.907	14.146
597	7	2	3	3	5	122088.6	175.832	13.937	14.378
598	7	2	3	4	4	121950.6	174.835	13.921	14.61
599	7	2	3	5	3	121988.3	175.95	13.926	14.842
600	7	2	3	6	2	121605.1	168.062	13.882	15.074
601	7	2	4	2	5	121854.1	173.517	13.91	14.578
602	7	2	4	3	4	121995.5	177.33	13.926	14.81
603	7	2	4	4	3	121810	171.692	13.905	15.042
604	7	2	4	5	2	121662.3	171.152	13.888	15.274
605	7	2	5	2	4	121982.1	174.806	13.925	15.01
606	7	2	5	3	3	122067.2	178.112	13.935	15.242
607	7	2	5	4	2	121682.4	168.989	13.891	15.474
608	7	2	6	2	3	121773.5	169.944	13.901	15.442
609	7	2	6	3	2	121659.3	168.997	13.888	15.674
610	7	2	7	2	2	121555.9	165.452	13.876	15.874
611	7	3	2	2	6	122058.8	174.866	13.934	13.885
612	7	3	2	3	5	122364.1	180.986	13.969	14.117
613	7	3	2	4	4	122210.8	176.585	13.951	14.349
614	7	3	2	5	3	122259.2	182.231	13.957	14.581

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
615	7	3	2	6	2	121843	169.206	13.909	14.813
616	7	3	3	2	5	122410.1	181.401	13.974	14.317
617	7	3	3	3	4	122519.8	186.061	13.986	14.549
618	7	3	3	4	3	122350.7	183.383	13.967	14.781
619	7	3	3	5	2	122196.4	177.872	13.949	15.013
620	7	3	4	2	4	122281.8	178.281	13.959	14.749
621	7	3	4	3	3	122381.1	183.432	13.97	14.981
622	7	3	4	4	2	121958.5	170.815	13.922	15.213
623	7	3	5	2	3	122334	177.86	13.965	15.181
624	7	3	5	3	2	122203.1	175.045	13.95	15.413
625	7	3	6	2	2	121824.4	167.258	13.907	15.613
626	7	4	2	2	5	122030.1	173.212	13.93	14.056
627	7	4	2	3	4	122216.8	176.34	13.952	14.288
628	7	4	2	4	3	122014.9	173.853	13.929	14.52
629	7	4	2	5	2	121866.6	171.486	13.912	14.752
630	7	4	3	2	4	122234	175.477	13.954	14.488
631	7	4	3	3	3	122352.2	182.387	13.967	14.72
632	7	4	3	4	2	121919.8	169.127	13.918	14.952
633	7	4	4	2	3	122058.7	169.342	13.934	14.92
634	7	4	4	3	2	121942.4	169.212	13.92	15.152
635	7	4	5	2	2	121828.8	165.558	13.907	15.352
636	7	5	2	2	4	122258.7	171.122	13.956	14.227
637	7	5	2	3	3	122401.2	179.814	13.973	14.459
638	7	5	2	4	2	121946.6	168.698	13.921	14.691
639	7	5	3	2	3	122362	173.165	13.968	14.659
640	7	5	3	3	2	122243.5	172.339	13.955	14.891

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
641	7	5	4	2	2	121877.5	163.158	13.913	15.091
642	7	6	2	2	3	121996.2	163.394	13.927	14.398
643	7	6	2	3	2	121906.6	166.461	13.916	14.63
644	7	6	3	2	2	121792.5	158.572	13.903	14.83
645	7	7	2	2	2	121739.3	156.273	13.897	14.569
646	8	2	2	2	6	122286.3	165.65	13.96	13.866
647	8	2	2	3	5	122723.9	165.681	14.01	14.098
648	8	2	2	4	4	122519.3	165.382	13.986	14.33
649	8	2	2	5	3	122606	160.704	13.996	14.562
650	8	2	2	6	2	122093.3	154.722	13.938	14.794
651	8	2	3	2	5	122843.1	164.519	14.023	14.298
652	8	2	3	3	4	122999.8	165.234	14.041	14.53
653	8	2	3	4	3	122778.4	161.292	14.016	14.762
654	8	2	3	5	2	122603.6	158.16	13.996	14.994
655	8	2	4	2	4	122670.2	162.701	14.003	14.73
656	8	2	4	3	3	122825.5	159.737	14.021	14.962
657	8	2	4	4	2	122295.2	155.887	13.961	15.194
658	8	2	5	2	3	122783.2	155.957	14.016	15.162
659	8	2	5	3	2	122635	155.735	13.999	15.394
660	8	2	6	2	2	122152.4	151.423	13.944	15.594
661	8	3	2	2	5	123031.4	165.471	14.045	14.037
662	8	3	2	3	4	123224.5	167.325	14.067	14.269
663	8	3	2	4	3	122987.4	161.54	14.04	14.501
664	8	3	2	5	2	122800.3	158.522	14.018	14.733
665	8	3	3	2	4	123231	164.006	14.067	14.469
666	8	3	3	3	3	123338.6	168.859	14.08	14.701

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
667	8	3	3	4	2	122843.7	156.736	14.023	14.933
668	8	3	4	2	3	123020.8	159.836	14.043	14.901
669	8	3	4	3	2	122866.2	158.581	14.026	15.133
670	8	3	5	2	2	122725	156.345	14.01	15.333
671	8	4	2	2	4	122772.2	162.349	14.015	14.208
672	8	4	2	3	3	122984.1	161.163	14.039	14.44
673	8	4	2	4	2	122401.6	157.616	13.973	14.672
674	8	4	3	2	3	122959.4	159.116	14.036	14.64
675	8	4	3	3	2	122820.1	156.555	14.021	14.872
676	8	4	4	2	2	122343.1	151.81	13.966	15.072
677	8	5	2	2	3	122955.2	156.678	14.036	14.379
678	8	5	2	3	2	122831.4	155.54	14.022	14.611
679	8	5	3	2	2	122689.5	150.056	14.006	14.811
680	8	6	2	2	2	122202.4	149.967	13.95	14.55
681	9	2	2	2	5	122621.5	159.491	13.998	14.018
682	9	2	2	3	4	122899.7	164.405	14.03	14.25
683	9	2	2	4	3	122634.3	159.84	13.999	14.482
684	9	2	2	5	2	122467.4	159.433	13.98	14.714
685	9	2	3	2	4	122970.6	156.345	14.038	14.45
686	9	2	3	3	3	123147.3	157.524	14.058	14.682
687	9	2	3	4	2	122578.3	157.138	13.993	14.914
688	9	2	4	2	3	122745.4	153	14.012	14.882
689	9	2	4	3	2	122615.1	153.548	13.997	15.114
690	9	2	5	2	2	122486.3	148.527	13.982	15.314
691	9	3	2	2	4	123119.6	156.742	14.055	14.189
692	9	3	2	3	3	123330.5	160.327	14.079	14.421

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Table C.1 – *Continued from previous page*

Exp. no.	**L1**	**L2**	**L3**	**L4**	**L5**	**Mean volume**	**SD**	**MT**	**Cost factor**
693	9	3	2	4	2	122722.4	159.336	14.009	14.653
694	9	3	3	2	3	123301.5	153.226	14.076	14.621
695	9	3	3	3	2	123145.8	152.817	14.058	14.853
696	9	3	4	2	2	122658.2	150.942	14.002	15.053
697	9	4	2	2	3	122803	153.034	14.019	14.36
698	9	4	2	3	2	122697.5	158.593	14.007	14.592
699	9	4	3	2	2	122571.9	148.987	13.992	14.792
700	9	5	2	2	2	122526.3	151.578	13.987	14.531
701	10	2	2	2	4	123025.9	166.028	14.044	14.17
702	10	2	2	3	3	123331	157.139	14.079	14.402
703	10	2	2	4	2	122640.9	162.613	14	14.634
704	10	2	3	2	3	123356.2	156.244	14.082	14.602
705	10	2	3	3	2	123213.1	153.759	14.065	14.834
706	10	2	4	2	2	122631.5	153.58	13.999	15.034
707	10	3	2	2	3	123454.3	155.982	14.093	14.341
708	10	3	2	3	2	123325.4	158.653	14.078	14.573
709	10	3	3	2	2	123178.5	152.217	14.061	14.773
710	10	4	2	2	2	122580.6	160.766	13.993	14.512
711	11	2	2	2	3	123227	156.186	14.067	14.322
712	11	2	2	3	2	123145.6	153.568	14.058	14.554
713	11	2	3	2	2	123043.9	147.449	14.046	14.754
714	11	3	2	2	2	123062.3	156.647	14.048	14.493
715	12	2	2	2	2	122375.7	166.741	13.97	14.474

Appendix D

NICT Example

The purpose of this section is to calculate and validate the proposed method to estimate NICT.

D.1 R Code

```r
#-----------------------------------------------------------------------
#- NICT calculation and verification simulation
#- Author: Willem Grobler, NICT validation function adapted
#- from Dr. Elias Willemse, University of Pretoria
#- ----------------------------------------------------------------------
#- Run get_NICT() to validate results from W. Grobler PhD
# - or alternativly use different values for different results


get_NICT <- function(mu = 15, shape = 11.17, USL_certainty = 0.999, save
scale <- get_scale(mu, shape)
NICT <- qweibull(USL_certainty, shape, scale)
print(NICT)
validate_NICT(mu, shape, USL_certainty, FALSE, NICT, scale)
return(NICT)
}

get_scale <- function(mu = 15, shape = 11.17) {
scale <- mu/(gamma(1 + 1/shape))
print(scale)
return(scale)
}
```

```
validate_NICT <- function(mu = 15, shape = 11.17, USL_certainty = 0.999,
available_days <- 300
reqAverage <- mu
upper_spec <- NICT # can be increased or decreased
hoursPerShift <- 8
nShifts <- 2
production_target <- ceiling(hoursPerShift*nShifts*available_days*reqAver

nSims <- 10000
actual_production <- rep(NA, nSims)
for (i in 1:nSims)
{
sim_production_ph <- rweibull(n = available_days, shape = shape, scale =
trunc <- sim_production_ph > upper_spec
actual_production_ph <- sim_production_ph
actual_production_ph[trunc] = upper_spec

mean(actual_production_ph)

actual_production[i] <- sum(actual_production_ph*hoursPerShift*nShifts)
}

if(saveFile) {
png(”./fig/03_NICT_Validation.png”,width=2000,height=1200,res=200)
}
par(family=”serif”)
hist(freq = TRUE, actual_production, xlim = c(min(production_target, min(
abline(v = production_target, col = ”black”, lty = 1, lwd = 2)
```

```
text(cex = 0.8, pos=4, production_target+10,1600,paste0("Production_targe
print(mean(actual_production_ph))
if(saveFile) {
dev.off()
}
}
```

D.2 Results

Shape: 15.69, USL: 18.66, NICT: 192.93

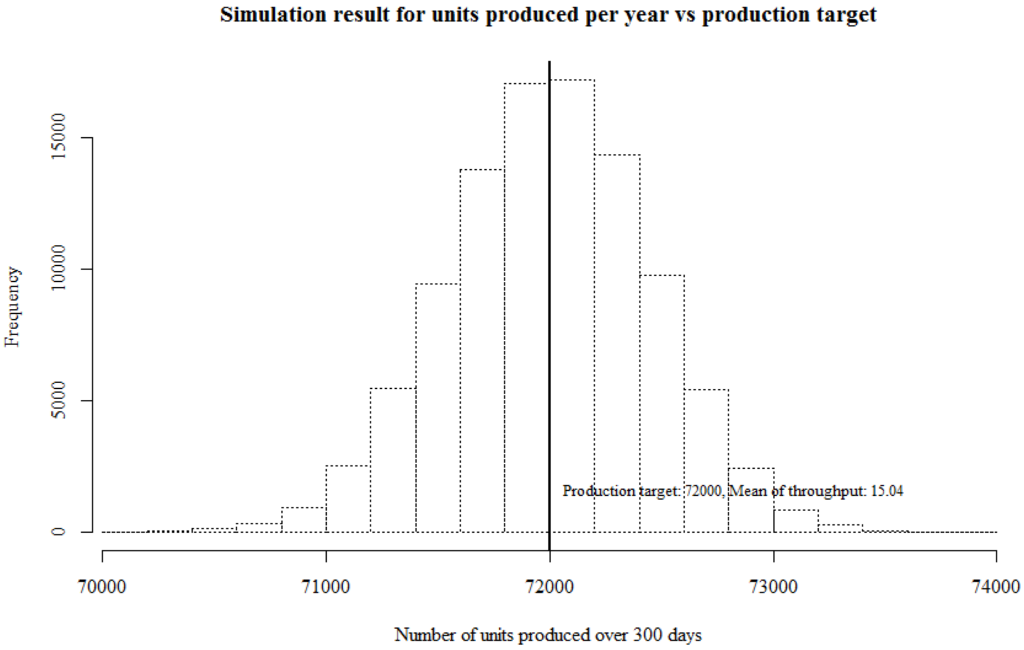

Figure D.1: Net ideal cycle time validation.