A NEW STUDY OF UNBALANCED PRODUCTION LINE WITH OPTIMIZATION

EN NY INSIKT ANGÅENDE OBALANSENAD PRODUKTIONS LINJE MED HJÄLP AV OPTIMERING.

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Attestation

With this attestation the author certify that this thesis fulfills the requirement and follows the academic guide line according to University of Skövde. The author attests that all figures, tables, optimization results are the author’s own design if not otherwise specified. All references are using Harvard system accordingly.

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Abstract

This project is a continuous research of a topic well-known in the literature, namely, the performance study of unbalanced unpaced production system. In the literature, there were many studies that investigated the statistical outputs of an unbalanced production line using simulation. This project focuses on researching the outputs like average buffer level and idle time that are rarely studied in previous research by using optimization tools from discrete event simulation software FACTS.

The models used in the article (Shaaban & McNamara, 2009) have been used as a guideline during the development of the simulation models for this project. Two simulation models were created, each using different discrete event simulation software, namely FACTS analyzer and Plant simulation. Those simulation models fulfills its role in verification & validation stage, with their statistical outputs compared to each other and with Shaaban and McNamara’s results. After verification & validation comes optimization of those simulation models, by using optimization tools from FACTS.

The research area expanded during the optimization phase. Originally Shaaban et.al analyzed unbalanced production line with one fixed value of coefficient of variation. In order to expand the view on the properties of an unbalanced production line, three more coefficient variation were added with total of four in this project. As a result, 12 optimization results were created at the end of this project. Each optimization has 30 000 iterations to ensure its convergence.

The first step of analysis is done by locating all Pareto-optimal solutions with optimization tools in FACTS. The raw data of all solutions are later transferred and converted into EXCEL files. Using scatter graph and putting all outputs against each other in EXCEL, it creates visual graph that can be used to analyze and to investigate interesting behavior in an unbalanced production line.

The analysis on the optimization results showed several interesting behaviors from production line with different settings. One being that if a production line possess worse coefficient of variation than its competition. By raising the inter-stage buffer level of the production line with inferior coefficient of variation, it can achieve the same level, if not greater outputs than its competitor who possess better coefficient of variation. The other interesting behavior are optimization results with highest outputs in regard of either idle time or average buffer level, with deep analyzation using optimization tools from FACTS. Certain operation time pattern and inter-stage buffer pattern could be observed from those results.

Key words

Discrete event simulation, unbalanced production line, optimization, Plant simulation, Facts analyzer, lognormal distribution, process time pattern.
Preface

Optimization being one of my interested subject during those three years in the university. And I am most grateful to be given such opportunity to be working with optimization as a subject for my thesis.

I want to thank all who have supported and helped me during my thesis work.

I want to thank Prof. Amos Ng for being my advisor during thesis and gave me tremendous amount of support during my final year project. While I was new to the subject of optimization, you have been a patient supervisor while answering all my questions during this project, giving me countless advice and lastly thank you for being an enthusiastic teacher.

I want to give a special thanks to Marcus Frantzén for providing me with advice regarding simulation models and Tehseen Aslam for giving me opportunity to work with optimization as the topic of final year project.

Lastly I want to give my warmest regard to my family for always been there for me during those three years in university.
Abbreviation

Down below are the abbreviations used in this report. They provide basic and necessary information regarding each subjects. The intention is to provide the necessity knowledge for reader in order for them to have an easier understanding while reading this report.

TH Throughput, is a measure on the rate of product which is processed per time unit.

WIP Work in Process, the amount of product being processed in a production line.

ABL Average buffer level, the average capacity of all buffer in a production line.

IT Idle Time, the total time of a machine while it’s not working. Idle time is the summary of waiting time and blocking time of one or several machines.

DI Degree of imbalance, is the range of possible values once an output deviates from its mean value.

FACTS Factory Analyzer, is a discrete-event simulation software with optimization engine that is specifically used for multi-objective optimization. It’s developed by university of Skövde.

Plant Plant simulation, is a discrete-event simulation software that can be used to create digital model of logistic system which later can be used for experimentation and analyzation for data such as bottleneck, statistic etc.

CV Coefficient of Variation represent the variability of a series of numbers. By dividing the standard deviation of these numbers with the mean value of these numbers will result in CV represented as a ratio.

\[
\text{Coefficient of variation} = \frac{\sigma}{\mu}
\]
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1 Introduction

This chapter describes the purpose and goal of this research study while also present its aim and objectives. Furthermore, a summary of the relation between this final year project and sustainable development will be presented. Finally, this chapter ends with a brief description of the limitations of this project, the method used and the disposition of this report.

1.1 Background

Ever since Ford developed mass production strategy to be able to answer the demand of cars in early 1900s with lowest possible cost and high efficiency. However the demands decreased over time and mass production were no longer profitable due to cost outweighs profit at that time. Industrial companies started to cut down the cost of their production lines without losing much of the efficiency of production line. Unfinished products in buffer and a machines waiting/blocking time is a waste of company’s resource. Therefore by lowering the idle time and the average buffer level in the line can result considerable savings over a long period. But the aspect of throughput and work in process of a production line is just as important, if not more important than ABL and IT of a line.

A study written by Shaaban & McNamara (2009) shows how the result of IT and ABL can vary due to different designs of production lines. The author suggests that there are certain patterns of production line designs that are more efficient than other lines in terms of ABL and IT. According to the author, certain behavior of interaction exist between buffers, IT, ABL and degree of imbalance (DI). The author analyzed those interactions by using simulation on four different line patterns with predetermined buffer and degree of imbalance. Thus their conclusions are based on the simulation outputs.

Therefore this final year project will focus on the findings of the most effective line pattern with regard to ABL, IT, TH and WIP. This project will recreate simulation models based on Shaaban & McNamara’s study i.e. different process line patterns with varieties of DI and buffer level. Instead of finding the best process time pattern similar to Shaaban’s report, this project will use optimization to study and analyze the efficiency and behavior of unbalanced production line with Shaaban et.al report as basis for this final year project.

1.2 Aim and Objectives

The aim of this project is to study the unbalanced workload and buffer allocation patterns through a new methodology, namely multi-objective optimization. To complete this aim, two project objectives must be met:

- Develop simulation models in FACTS Analyzer and verify their performance outputs, with respect to several different processing time probability distributions, by using some identical models developed in Plant Simulation. The results shall also be checked and compared against the numerical results in the literature.
- Carry out multi-objective optimization experiments using IT and ABL as the optimization objectives and then analyze the results.
1.3 Research methodology

The purpose of the method in this project is to provide a way to study the efficiency of unbalanced production line. The methodology will be based on Banks (2010) model of simulation study, however the priority of focus will be laid on verification, validation and optimization, which leads to a slightly different method in comparison. In this final year project, Shaaban’s report will be used as source of data collection for quantitative data, for example the values of different types of outputs in his report will provide important information which will help the progress of this research. Hence why it’s included in the methodology.

Basically the simulation models are recreations based on Shaaban & McNamara’s report (2009), using simulation parameters and conditions in theirs report. In order to justify the validity of the simulation models, two simulation models were created using FACTS and Plant simulation.

Those models will be verified by comparing its statistic outputs with each other and with output data from Shaaban & McNamara’s report (2009). During experimentation/optimization stage, multiple objectives will be optimized by using the optimization engine in FACTS. The results from optimization may provide new insight and knowledge. Which is necessary for analysis and arguments in conclusion. Figure 1 illustrate the methodology that is based on Banks (2009) and adapted along the objectives of this project.

Figure 1. Methodology based on Banks model
1.4 Limitation

The focus of this project is to analyze, discuss and gain new insight regarding unbalanced production line. There will be restrictions since the simulation models are created based on Shaaban’s report, hence the simulation parameters Shaaban used will become the guideline for this project’s simulation. Due to the large time expended on optimization in this project, together with trials and errors. This project have limit its research range to five workstations, therefore simulations result of eight workstation that Shaaban researched will not be included in this project. And aspects outside the focus of research territory i.e. the economical aspect, sustainability etc. Will not be included in the report. Hence no economic evaluation will be regarded.

1.5 Sustainable development

Humans have always affected the surrounding environment. It was manageable from the very beginning when humanity haven’t yet developed agriculture technology. Human hunted and scavenged for food and when there are no more prey they moved on to next territory and so on. The area that were left recovers in due time and human did not cause any more impact as other species. The very first impact human caused on nature didn’t start until the development of agriculture, which enabled more people to live per unit area (Gröndahl, 2010). But it wasn’t until industrialization at 1900s that humanity caused great impact on ecology on nature. The recovery speed of nature could no longer sustain the evolution nor the consumption caused by industrialization.

At 1970s, people realized their continuous development and growth are causing global problems and represent a threat for future generations. It wasn’t later at 1987 the term of sustainable development spread around the world by FN commission, thanks to the report written by Brundtland, who described sustainable development with following quote: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, 1987).

Sustainable development can be divided into three dimensions: Social, Economy and ecology. The ecology dimension concerns the function of ecology system and its natural resources. The social dimension covers the humanity aspect, including its politics & culture and the human resources. The economy dimension concerns the worth of possessions and built society, represented in the economic system. (Gröndahl, 2010) Those dimensions are integrated with each other and impact on one dimension will affect other two as well. According to Dahlin (2015) for a good sustainable solution withhold its sustainability through all three dimensions to be considered sustainable.
This thesis leans toward the economic dimension of sustainable development since its final objective involves analysis regarding the efficiency of unbalanced production line. If positive results shown, the analysis can provide answers and method that can raise productivity in factory, and making the production line more productive can result a significant economical savings and less energy is required to keep up the same rate of production. The savings can be translated into profit which in turn can be used to invest in non-polluting energy source which affects the ecology dimension of sustainability. And with less energy consumption cause less waste which have a positive influence on ecology dimension, given that the energy source are not environmental friendly. Then the energy saving can be translated into economical savings nonetheless.
1.6 Report disposition

This thesis consists of seven chapters. This section can be used to quickly understand each chapter’s content.

1 Introduction - Chapter 1 introduce readers the aim & objective in this thesis, as well as methods used and limitation applied in this project.

2 Theoretical framework - Chapter 2 brings up theoretical knowledge that being used in this thesis.

3 Literature review - In chapter 3 several case studies and research relevant to thesis were analyzed and summarized.

4 Description of simulation model - Chapter 4 introduce and explains briefly the simulation models used in this project.

5 Verification and validation - Chapter 5 using the results gained from simulation models in order to verify models integrity and validate by compare to Shaaban’s results.

6 Result and analysis - Chapter 6 represent the optimization results based on simulation models used in this project. Optimization result will be observed and analyzed.

7 Discussion - In chapter 7 writer evaluate and discuss the project as a whole.

8 Conclusion & future work Chapter 8 brings forth a short conclusion of this thesis and suggestion for future work.
2 Theoretical Framework

This chapter will take up topics regarding different definitions, concepts and theories that are of relevance for this project. The topic chosen for the theoretical framework must be specific, and is associated with the content of the project. The purpose of this theoretical framework is to give the reader the necessary knowledge for better understanding of this project.

2.1 Simulation

“A simulation is the imitation of the operation of a real-world process or system over time” (Banks, 2010). A good simulation model is a powerful tool used to predict the actual outcome of the real world system it’s imitating. It can even be used to analyze many “what if” scenarios without disturbing the real world system. Therefore a good simulation model can save a company a lot of financial resources and while generate constant improvement to their production system. However many real world system are hard to imitate and to be represented artificially, due to the complexity of real world system that is hard to solve with mathematic means. It’s worth to mention that a simulation model ought to be verified and validated before use i.e. the data are collected as if the real system were being observed (Banks, 2010). An unverified model can cause financial or efficiency consequence for a company due to it is incorrect and must be avoided at all cost.

Simulation is not without flaws and sometime one should consider its advantages and disadvantages depending on the situation or requirements that needs to be fulfilled. Below is a short summary on when it’s appropriate or inappropriate to use simulation and its advantage & disadvantages (Banks, 2010).

2.1.1 Appropriate use of simulation & advantages

Simulation provides the opportunity to perform experiments or study the system without disturbance to the real world system. During experimentation one can gain insight of the system or knowledge of great value which later can be used to improve the system. One example is bottleneck analysis, it is not uncommon to use simulation to detect bottlenecks in the system, since if wrong solution applies to the system it will make the matter worse. Therefore ideas and thoughts of improvisation should be tested on simulation model to gain insight on possible outcome from implementations without committing or losing any resources. The same principle goes for applying new design in a system (Banks, 2010).

Phenomenon that occurs and observed in the real world system can be solved or very least study its nature with simulation. (Banks, 2010)

2.1.2 Inappropriate use of simulation & disadvantages

Simulation itself doesn’t bring any disadvantages for the company nor the user under any circumstances if a correct model being used. Rather the flaws or inappropriate use of simulation comes whenever a simulation model is worth the effort to resolve problems. Most of the time it’s about cost contra savings.
A simulation should not be used when the problem can be solved by common sense or if direct experiment cost less than simulation. It is also pointless to simulate if the cost of simulation exceeds the possible savings. The most inappropriate use of simulation is building a simulation despite the lack of data. A good simulation model takes a lot of data and if the data are insufficient for simulation model, it will produce inaccurate result and decision based on that result will cause serious damage to a company. Note that a simulation model should always be verified and validated to detect and prevent use of incorrect model. (Banks, 2010)

The disadvantages of simulation are mostly requirements of some sort. Model building requires individual with special education within the subject and the more experience the individual possess the more efficient the model will become. For example two individuals with different competence regarding simulation building respectively model with same goal. The model might looks similar but it’s unlikely the efficiency will be the same. The second disadvantage of building a simulation model is the consumption of time and resources. Therefore one must prepare the cost before attempting to build a simulation model (Banks, 2010). Like aforementioned there isn’t any disadvantage with simulation, but rather requirement of using and building one.

2.1.3 Discrete and continuous system
“Few system in practice are wholly discrete or continuous, but since one type of change predominates for most systems, it will usually be possible to classify a system as being either discrete or continuous” (Law, 2007). Systems can be separated into two different types of simulation models: Discrete or continuous. The state of a discrete system change only one at a time. It means only one change occurs for a single event at a specific time. An example can be the amount of customer in the bank, the state (amount of customer) of this system (bank) change only when customer arrives or amount of customer who received services. The state of a continuous system changes continuously over time. It’s because variable(s) in the system change the state exponentially. For example the amount of water behind a dam, it increases with rain but at the same time evaporation decrease the water. Those variable are affecting the system constant i.e. continuously.

2.2 Multiple Objective Optimization
Multi-objective optimization derives initially from single-objective optimization. While single-objective optimization and its solution are focused on single objective, which as the name implies. The multi-objective optimization involves multiple objectives and there is not a single “best” solution for an MMO (multi-objective optimization) problem but a set of solutions with different trade-offs i.e. one extreme solution in respect of one objective have to make compromise for the other objective(s), thus there can’t exist a solution that can satisfy multiple objectives (Deb, 2001). The solutions are namely Pareto-optimal solutions which is explained later in the theoretical framework.

2.2.1 Two different approaches to multi-objective optimization
The purpose of optimization is to find the best solution for a problem in respect of multiple objectives. Optimization gives a set of optimal solutions and in order to determine the best solution, the user have to use higher-level qualitative consideration to make a choice, in other words it is users preference that will play the key factor in final decision making. This approach follows the principle for an ideal multi-objective optimization procedure (Deb, 2001).(See figure 3)
Figure 3. Ideal multi-objective optimization interpreted from Deb (2001)

- Step 1: Multi-objective optimization found a set of trade-off solutions.
- Step 2: Using higher-level information to determine the best solution for the problem.

The second approach is simply a reverse of procedure compared to the ideal optimization in figure above, which means this procedure is heavily based and sensitive to the user preference. Due to the fact that the preference are highly subjective, an proper analysis on the preferences is required in order to prevent wrong optimal solutions are being produced, which can cause disastrous consequences. This procedure is called a preference-based multi-objective optimization. (Deb, 2001)(See figure 4)
Multi-objective optimization problem
Minimize $f_1$
Minimize $f_2$
......
Minimize $f_n$
Subject to constraints

Single-objective Optimization problem
$F = w_1f_1 + w_2f_2 + \ldots + w_nf_n$
Or
A composite function

Estimate a relative importance vector $(w_1, w_2, \ldots, w_n)$

Higher-level information

Step 1: Use higher-level information (preference) to obtain a preference vector, which is used to construct a composite function.

Step 2: Function is optimized by single-objective optimization to find a single trade-off solution.

2.3 Pareto front

When two or more conflicting criteria are applied in optimization, as aforementioned it is impossible to find one single best solution since some of them are inferior to each other depending on the criteria. Instead the optimization will create a set of solutions with best trade-off depending on the criteria, those solutions also known as Pareto-optimal. The rest of the solutions are not considered in the final choice making since they are worse than the solutions on Pareto front in respect of the criteria.

Finding Pareto front solutions are important in MOO since it speeds up the optimization process while clears a large amount of non-optimal. Which leaves only a small set of solutions with best tradeoffs. (Frantzén, 2014)
2.4 Distribution

Distribution is a set of raw data that is used for interpretation of its characterization. Usually a curve is used for visual representation. By applying specific conditions or restrictions on the raw data, the shape of the curve might change and can be interpreted into a distribution with certain characterization. The characterization of the distribution depend on whether the data is discrete or continuous (Salkind, 2010).

In this project only continuous distribution are being used for simulation (Lognormal & Weibull), therefore the discrete distribution are not included in theoretical framework.

2.5 Continuous distribution

Continuous distribution are based on continuous variable. Continuous variables is are the values that exist within an interval i.e. between two values. Continuous variable that exist within the interval can be theoretically assumed to be infinite. Which leads to a *smooth* curve on representation in contrast of discrete distribution that tends to represent edgy curve. (Salkind, 2010)(See figure 5)

![Curve with standard normal distribution](image)

Figure 5. Continuous distribution interpreted from Salkind (2010)

2.6 Weibull distribution

Weibull distribution is named after the Swedish engineer Waloddi Weibull. This distribution can be used to provide good model for various data sets and offers a density function for reliability calculation. Weibull distribution can be used to analyze reliability, identify failure type of troubleshooting in areas such as engineering, biostatistics and psychology. (Salkind, 2010)

There are three parameters that is being used in Weibull distribution (Dodson, 2006).

- \( \gamma \) is the location parameter that can be used to shift the distribution.
- \( \theta \) is the scale parameter that can be used to shrink or stretch the distribution.
- \( \beta \) is shape parameter that can be used to change the shape of distribution.
2.7 The bowl phenomenon

When operation time in stations within a production line are shaped like a bowl i.e. stations with fastest operation time are assigned in the middle and slowest are placed at the both ends in production line. Certain outputs have been confirmed to perform better in bowl pattern than other production pattern such as ascending order, descending order and inverted bowl shape (Shaaban & McNamara, 2009). This phenomenon is also called as the bowl phenomenon. Despite the lack of concrete mathematical proof of this phenomenon, most researcher and theirs experimental work confirms its existence. It’s confirmed that bowl line pattern can achieve 1 or 2% throughput improvement in a production system and if this system is designed for high volume production, the bowl phenomenon can result in a lot of financial savings for the company. (Papadopoulos, 2009)

![The bowl phenomenon of 5 workstations](image)

*Figure 6. The bowl phenomenon interpreted from Papadopolous (2009)*

The first people to observe this phenomenon were Hillier and Boling (1966). They ran simulation with four stations and buffer capacity ranging from one to four units, it’s showed in the report that they achieved an increase in TH if the operation time were to follow exponential distribution, however it was not clear on what factor that caused the increase of throughput.

This phenomenon occurs mainly in non-automatized assembly lines with workers who perform the tasks. It’s understood that workers have high variability and is the cause of coefficient of variation in the production line. This CV is one of the key components required to calculate the production lines data such as throughout, work in process, idle time and average buffer level. During an experiment with 5 machines performed by Shaaban and Hudson (2010), the author stated that the bowl shape is the best way to distribute an imbalanced line. According to the result the bowl shaped operation time reduce the most of IT among the stations in the line (Shaaban, 2010).
3 Literature Review

This chapter will present different studies regarding experiments around bowl phenomenon and unbalanced production line that was performed by those researchers. It will be represented in chronological order from as early as 1966 to 2012. This chapter will describe each study with a short summary, followed by a short summation of all literature studies.

3.1 Literature review: Efficiency of unbalanced production line

In 1966 Hillier and Boling presented a study regarding the efficiency of unbalanced production line. In theirs study they performed various experiments and analysis on unbalanced production lines with varying operation time on each machine. Several restrictions and conditions were applied to be able to determine the nature of its behavior. It were assumed that there were always supplies for the first machine i.e. this station would not suffer from waiting time. Another assumption was that there were always a storage buffer for every machine except the first and they are all of equal amount of space. The storage level being tested in this study varies from 0 to 4 (Hillier, 1966).

Boling and Hillers study also shed revelation that the productivity of a production line follows a pattern when it is heavily influenced by the number of the workstations and the level of storage buffer. The productivity decreases as amount of workstation increase and it decreases less for larger storage buffer. The conclusion were large amount of workstations have idle time percentage compared to production line with lesser amount of workstations.

During their experiments they found out that a certain production line pattern can yield maximum productivity. It occurs when workstation(s) with fastest operation time lies in the middle and slowest workstations were positioned at the start and end, and it was hereafter referred as “bowl phenomenon”. However the effect of this phenomenon decreases and become less significant as the level of storage buffer increases (Hillier, 1966).

Hillier and Boling’s experiments showed that by assigning unbalanced operation time in an appropriate way can yield higher productivity than a perfectly balanced production line. It is stated in their conclusion that the potential improvement can reach up to one percent and it will result in a considerable saving under a long operation period (Hillier, 1966).

The study performed by El-Rayah (1979) further strengthens Hillier’s & Bolings theory regarding bowl phenomenon. El-Rayah verified Hillier’s and Bolings experiment where the effect of bowl phenomenon was at its largest, that was when N=3(number of machines), B=0(inter-stage buffer storage capacity), Service time=Exponential. The result, as already stated by Hillier & Boling is an improvement over a perfectly balanced line, which usually is the optimal line of choice to improve TH (El-Rayah, 1979). In that study, El-Rayah also verified the production arrangement low-medium-high suggested by Davis (1966), where low being the fastest operation, medium being the intermediate and high being the slowest operation. Turned out to be less efficient than Hillier’s & Bolings unbalanced production line and a perfectly balanced line in terms of TH.
The author stated that, the bowl phenomenon undoubtedly yields improvement potential to reach higher TH than of a balanced line. However, the effect of bowl phenomenon will decrease as variability of service time decreases or buffer capacities increases to an extent where the effect is almost nonexistent.

The author further expanded its research territory by experimenting four- and twelve-station production line. The result of these study strengthens the argument that the bowl pattern can be considered in production line with limited inter-stage storage, since a balanced line with nearly unlimited buffers can yield the maximum possible production rate (TH) but that scenario is also very unlikely.

However El-Rayah argue that since a perfect balanced line is technically impossible. It is easier to deliberately unbalance a production line than balancing it perfectly (El-Rayah, 1979). Therefore unbalancing a production line with limited storage has its merits.

In 2004 M.S.Hillier and F.S. Hillier conducted a research to study the characteristics of patterns regarding the interactions between work allocation and buffer allocation under bowl phenomenon. The condition for optimization was similar to their previous research, which means the first station always had a unit to work with and together with block mechanism. Exponential and Erlang distributions were used to optimize the result of buffer and work allocation of production line with four machines and three buffers, lastly another optimization were conducted with Erlang distributions on production line with five machines and four buffers. (Hillier & Hillier, 2006)

They conducted three optimizations with following parameters.

- Erlang distributions, three buffers, four workstations.
- Exponential distributions, three buffers, four workstations.
- Exponential distributions, four buffers, five workstations.

During their optimization experiments they found out that the dominant pattern (most optimal pattern) of buffer allocation shifts depending on the size of the storage buffer in a line and the same goes with work allocation for stations in the line. All three optimizations shows the same characteristics pattern behavior (Hillier & Hillier, 2006). The dominant pattern of buffer allocation often shifts between balanced and bowl shaped buffer allocation (larger buffer placed in the center of the line) within smaller number of buffer spaces. Bowl shaped buffer allocation pattern becomes dominant once it surpass certain threshold i.e. size of buffer space, the buffer will continuously increase in size relative to the size of the total buffer space. For example the dominant buffer space \((n)\) pattern is \((n, n+1, n)\) for buffer >20, \((n, n+2, n)\) for buffer >60 and \((n, n+3, n)\) for buffer > 80. At the same time the effect of bowl workload allocation becomes less pronounced for unbalanced buffer allocation with the increase of buffer storage.

Their results indicate the importance of buffer space management during optimization, which has a significant impact on the result. The article also concludes that buffer space and workload allocation should vary dependent on how significant the cost of buffer space and inventory are. (Hillier & Hillier, 2006)
In an article written by Shaaban and McNamara (2009), the author presented a new opportunity to increase savings in a production line by deliberately unbalance it rather than balancing it. By studying how an unbalanced production line affect parameters such as average buffer level, idle time and compare its result over balanced line, in the result the author represented a theory which state that a unbalanced production line yield significant improvement in regard of ABL and less significant in term of IT. Which can lead to financial savings depends on the specifics cost of inventory. The improvements from an unbalanced production line in comparison to balanced line can vary between 10.02% and 87.56% in term of ABL & 0.31% and 3.46% in term of IT. It is worth mention that IT improvement only applies on lower buffer size, with a large buffer size the balanced line yield far superior performance in regard of IT efficiency in comparison. Also the author applied degree of imbalance and coefficient on mean work time on workstations in order to achieve more realistic simulation environment (Shaaban & McNamara, 2009).

A case study made by Ng et al. (2010) presented a methodology that address the optimal buffer allocation problems for unbalanced production line with different kind of production control mechanism (PCM) and buffer capacities. The methodology, which is simulation-based multi-objective optimization were being used to analyze the difference on the outputs that different kind of PCM can influence on a production line. The article pointed out that PCMs that are adapted to the working environment/situation have more significant positive impact than a generalized PCM for all production lines (Ng, et al., 2010).

In a study represented by Afshin A.Malaki (2012), the author performed simulations and analysis on both balanced and unbalanced assembly lines with walking line worker and compared their efficiency. In this case study the workers skill level determines the CV of the operation time i.e. a highly skilled worker have lower CV compared to low skilled worker. The author created various pattern with the positioning of the operator and documented the throughput value of each experiments. It is later shown in the study that a perfectly balanced line yields the highest TH and line pattern that were ranked as second best were inverted bowl worker line, whereas the highly trained workers are placed at the beginning and the end of the line and low skilled workers are placed in the middle. (Malaki, 2012)

However the conditions are different compared to other similar research using worker as a means to express CV in production line. In a line with walking worker, the operator follows a product through different machines from the start to the end. After the worker executes his/hers last assembly job, the worker walks back to the beginning and start working on a new product. Hence the walking time and rotation of worker is what differs from previously done research which must be take into account (Malaki, 2012).

As aforementioned in the case study of El-Rayah (1979), a perfect balanced line yields highest TH and there is no unbalanced line that can surpass it. But Malaki stated that unbalanced line yields the highest quantity of possible improvements. Since realistically a perfect balanced production line is near impossible in a real world system, especially when the system involves human factor. Hence it’s worth to look further into the possibility of improving unbalanced line. Not to mention the author proved in his study that rearrangement of worker can lead to a difference in efficiency in regard of TH (Malaki, 2012).
3.2 Short summary of literature review

Studying above literature have given vast knowledge in regard of the potential efficiency of unbalanced production line hold. Every author have conducted experiment and analysis on the subject from different perspective, different range of simulation parameters and environments. Nonetheless, according to this literature review, the result of authors’ research have pointed out several noticeable characteristic that are specific for an unbalanced production line.

- The positive effect of unbalanced production line is most noticeable under specific circumstances, such as limited buffer storage, small number of workstations and large differences of CV among workstations. The effect becomes less significant in production lines with large buffers available and minor differences in CV.

- As mentioned a perfectly balanced line is practically impossible to maintain without any deviation over a long period of time. However, it’s easier to deliberately unbalancing a production line and still yield same if not better performance over a perfectly balanced line, which holds a merit.

- Several experiments have been conducted to research unbalanced production line, the amount of machines used in simulation were still small in comparison to a long production line in a factory. None of the authors in the literature review have experimented with 13 or more workstations in their production lines. An unbalanced production line is most efficient with limited storage and moderate differences in CV amongst the stations, and as mentioned its effect become less the larger the buffer is.

Although no author above have conducted such research, hypothetically there is a possibility that an unbalanced production line might not yield satisfying result in a long production line.
4 Descriptions of simulation models

This chapter will briefly explain simulation models used in this project. There are two simulation models, each created with different software, namely FACTS and Plant Simulation. Those simulation models fulfill the same functionality. In order to confirm that, their result will be compared to each other in verification & validation chapter.

4.1 Simulation parameter

As stated earlier this project is a research based on Shaaban’s experiment, hence the simulation parameters should follow his guideline accordingly.

4.1.1 Shaaban’s simulation parameters

- Five workstations
- The first station will always have an unit to work on and last station is never blocked
- Inter-stage buffer between stations are either set as 1, 2 or 6
- Coefficient of variation is fixed at 0.274
- Degree of imbalance for all workstations are set as either 2 %, 5 %, 12 % or 18%
- Weibull distribution
- Monotone increase (/), monotone decrease (\), bowl (V) and inverse bowl (\_\_\_) workstation time pattern were used.
- All buffer starts half-full when simulation starts up
- Steady state for simulation is 5000 TU (Time units)
- Simulation length is 30 000 TU

(All buffer/degree of imbalance must the same for the whole simulation model i.e. different combinations between buffers and different mix between degree of imbalance is not allowed)

4.2 Limitations and obstacles

Because of the limitation in FACTS analyzer, the buffer in the simulation model can’t be half full before start of simulation while plant simulation is fully capable of doing so. Therefore this simulation parameter is not included and due to the length of simulation period, the consequence of lacking that parameter will not affect the result gravely. However it’s still a factor that should be taking into consideration in verification & validation. The amount of replication is undefined in Shaaban’s report, therefore five replications were decided to be the default amount as simulation length.

Other simulation models with lognormal distributions were created in order to use its statistical result in verification stage.
4.2.1 Modified simulation parameters for this project

- Buffers starts without any units before a simulation run (Previous parameters regarding half-full buffer is therefore ignored)
- Five replications
- Lognormal distribution

4.3 Facts model

The simulation model below (see figure 7) is an example of a model based on Shaaban’s report and simulation parameters suited for this project. In this model there are five workstations, four buffers, one source to deliver units for stations to work with and one sink to pass on finished units. CV is fixed as 0.274 for all workstations. Above the simulation model is a textbox with necessary information for this specific simulation model.

In order to achieve, for example a monotone increase work pattern with 2 % DI. The operation time for the first two workstations will be using equation 1 (Salkind, 2010):

\[
(CV)0.274 = \frac{std(X)+1.02}{Operation\ time+1.02} \quad \text{Equation (1)}
\]

With middle station untouched, the last two stations operation time will be using equation 2 (Salkind, 2010):

\[
(CV)0.274 = \frac{std(X)+0.98}{Operation\ time+0.98} \quad \text{Equation (2)}
\]
4.4 Plant simulation

Simulation model below is created with simulation software Plant simulation (see figure 8). Its purpose is to fulfill the same function like the simulation model created with FACTS. It use the same equation above for lognormal distribution in order to achieve degree of imbalance and at the end of simulation, numerical variables will calculate simulation models outputs such as throughput, work in process, average buffer level and idle time.

Figure 8 Simulation model using Plant simulation
5 Verification and Validation

This chapter presents the statistic data of idle time & average buffer level from simulation models in Chapter 4. The procedure of verification is done by comparing the statistical result from above mentioned simulation models with each other. And lastly validate by comparing the result with Shaaban’s results. The results are separated into three groups. Each group have different inter-stage storage level in the production line and within each group, the results are further separated by process time patterns and degree of imbalance.

5.1 Verification

In order to verify models credibility, the statistical results from simulation models, created with two different simulation software will be compared. Since the focus point of Shaaban’s research are around ABL and IT, it is those statistical results that will be compared between FACTS and Plant simulation models. Due to the limitations of FACTS, in regard of handling DI with Weibull distribution, the data from simulation model using Weibull distribution can’t be produced. Instead lognormal distributions were used.

When compared, according to the statistical data from appendix A and B. The largest differences for ABL between those models are 0.437(12.74%) and 0.256(8.53%) comes second, while the rest of the data shows much less significant deviation, from 0.001(0.033%) to 0.177(5.63%). Since the total number of statistic data of ABL are 96, gathered from FACTS and Plant Simulation from appendix A & B. In other words 4 of 96 (4, 16%) data result shows significant deviation when compared to the data of Shaaban’s research.

Hypothetically the cause of deviation might come from differences between software and the one parameter that were excluded (buffer did not start as half-full). However, the most important part is that the data follows the intended pattern.

For example, according to appendix A and B, the case with ABL that have an alarming deviation up to 4.23, it rarely breaking its pattern, the IT of A have a tendency of being (/) < (\) < (A) < (V) with (/) having the largest idle time and (V) with the least. The pattern becomes even more convincing when the data of ABL are taken into consideration, in other words the work pattern of ABL have a strong tendency of being (/) < (V) = (A) < (\) with (/) have worst efficiency and (\) with best efficiency.
5.1.1 Verification of optimization results *Buffer2.CV=0.5*

To be on the safe side a verification for optimization results of *Buffer2.CV=0.5* (figure 28 & figure 29 in appendix D) was done by using simulation model created with FACTS. Those figures shows detailed information on optimization results with highest value in regard of ABL & IT.

Both simulation models have exact same data regarding process time and buffer capacities. The outputs of TH, ABL, WIP and IT were compared between simulation and optimization results. As shown in table 2, there were no large deviation hence the optimization result can be assumed to be credible.

<table>
<thead>
<tr>
<th>Comparison of data</th>
<th>Plant simulation (figure 16)</th>
<th>FACTS (figure 16)</th>
<th>Plant simulation (figure 17)</th>
<th>FACTS (figure 17)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TH</td>
<td>51.609</td>
<td>51.808</td>
<td>46.591</td>
<td>47.385</td>
</tr>
<tr>
<td>WIP</td>
<td>8.348</td>
<td>8.425</td>
<td>5.397</td>
<td>5.537</td>
</tr>
<tr>
<td>ABL</td>
<td>0.935</td>
<td>0.95</td>
<td>0.3486</td>
<td>0.444</td>
</tr>
<tr>
<td>IT</td>
<td>0.138</td>
<td>0.137</td>
<td>0.222</td>
<td>0.211</td>
</tr>
</tbody>
</table>

*Table 1 Comparison of output data between simulation result and optimization result using same simulation software*
5.2 Validation

After verification, the simulation model will be validated by comparing the statistical data from Shaaban’s report in appendix C. Shaaban’s statistical data consists of a combination between B (buffer), DI (Degree of imbalance) and the four work pattern: monotone increase (/), monotone decrease (\), bowl (V) and inverse bowl (ʎ).

The comparison of statistical data between Shaaban’s report and data from this project shows significant deviation. While the pattern behavior remains intact for both ABL and IT. The numerical differences from IT have an alarming difference up to 6.939 units (81%). At this stage the simulation models credibility would have been taken into question. Surprisingly, the numerical differences in ABL is 0.952 and 0.657 comes as second largest differences, while rest of deviations being lower than 0.5. In terms of difference of percentage in ABL. It also exists three abnormal differences that can differs up to 500 % when DI is at 18 %. Which is understandable that the larger DI gets, the more unstable becomes the result. However it’s important to take in mind it could result a skew perspective when viewed those abnormal differences in percentage. Because when compared the same value with numerical values, it results only a small difference, for example it could be a difference between 0.32 and 0.16 units and in percentage it’s 200 % of difference.

While the data of ABL being more stable than IT, the fact that it’s the same model that created those statistical data raises question whenever the simulation model is acceptable or not.

As mentioned in previous section there are few factors that can contribute to deviation in data. Another factor is how Shaaban managed to manipulate DI with Weibull distribution. In his their report, the author did not mention the procedure of handling DI with Weibull distribution (Shaaban & McNamara, 2009). Further consulting with Shaaban didn’t give satisfying answer. Nonetheless, with the credibility of simulation being in question. One of the strongest argument to credibility of this model is due to the fact that work pattern is still the same in regard of ABL and IT. But it’s utterly important that this point is not to be ignored and will be taken up in discussion chapter.
6 Results and analysis

This chapter will present the optimization result obtained from the software FACTS. With introduction of different parameters and constraints used in optimization together with a couple of optimization results later referred in appendix A. The focus will be to analyze different patterns regarding average buffer level vs idle time vs throughput. The pattern with point of interest will be presented with scatter graph using EXCEL and optimization tool from FACTS.

6.1 Optimization parameters & constraints

The multi-objective optimization will be focusing on idle time and average buffer level, since throughput is an important attribute in the design of a production line, it’s also included in optimization. Additionally this project has further expanded its research area by optimizing increased amount of different coefficient of variations and degree of imbalance is set as 18 % for all optimizations, in order to be able to analyze it from different views.

- The CV used in optimization are 0.1, 0.274, 0.5 and 0.75, in other words three additional CV were added.

- The amount of iteration are 30 000 for each optimization run, reason being that 5000 iteration equals one replication of a simulation model (Frantzén, 2014) and the additional 5000 iteration works as a safety margin to ensure optimizations stability. In total each optimization exists of 6 replications which sums up to 30 000 iterations.

- DI is set as 18 % for every station, which means that the operation time of a workstation can vary between 50 and 70 seconds.

As the name suggest, input constraints are formulas that puts restrictions on the optimization. It enables the user to optimize with control, in other words optimization can’t optimize outside its restricted area. For example according to first constraint in figure 9, the total number of buffer capacity is set to 8. Which means the optimization can’t optimize variables with combinations that exceeds the total number of 8 buffer. The second line of constraint fulfills same purpose which restrict the total operation time for all workstation to 300 seconds with 60 seconds being standard for every station. Those constraints runs together with fixed CV which is placed in model section of FACTS (figure 10).
Custom outputs are formulas that enable the collection of statistical data from desired entity in the simulation model. For example in figure 10, the idle time is the total time of a machine while it’s not working e.g. the machine is blocked or it’s waiting a unit to work on, and the formula summarize every stations idle time and divide by the number of stations. The result is the average idle time for each station. The same principle goes for average buffer level as well.

The details on equation for custom output formulas is below.

\[
\text{Idletime} = \frac{(OP1\_Waitingportion+OP2\_Waitingportion+OP3\_Waitingportion+OP4\_Waitingportion+OP5\_Waitingportion+OP1\_BlockingPortion+OP2\_BlockingPortion+OP3\_BlockingPortion+OP4\_BlockingPortion+OP5\_BlockingPortion+)/5}{5}
\]

\[
\text{ABL} = \frac{(Buffer1\_OccupationPortion+Buffer1\_OccupationPortion+Buffer1\_OccupationPortion+Buffer1\_OccupationPortion+Buffer1\_OccupationPortion)+4}{4}
\]

The optimization result of IT vs ABL can be viewed in appendix D. One of the result have NDS filter applied which enable the user to find Pareto-optimal solutions, more information regarding this subject can be found in chapter 2.
6.2 Analysis TH v ABL

In this section the values of TH and ABL with different settings of buffer & coefficient of variation will be compared to each other in order to find point of interest in this collection of optimization results. The focus will be to find the point with best value in regard of ABL or TH, which is high TH and low ABL.

![TH vs ABL](image)

*Figure 11 TH vs ABL. Pareto-optimal result of all optimization.*

In figure 12, the optimization with CV=0.1 is superior in regard of both ABL and TH, it’s not surprising nor interesting to investigate those optimization since this thesis focus is about analyzing efficiency of unbalanced production line and with CV=0.1, it’s hardly unbalanced. Therefore in this case optimization Buffer=6.CV=0.274 (figure 25 in appendix D) is particularly more interesting. Because compared to another optimization which possess same CV but lower average buffer level, namely Buffer=2.CV=0.274 (figure 26 in appendix D). The largest difference in ABL can be as big as 0.067 in units and 66.55 % as percentage. All the while their IT remains around the same level. A common feature between those optimizations is that both of their operation time shows sign of (\(\uparrow\)) work pattern. Which further strengthens argument that (\(\uparrow\)) have obviously best efficiency in regard of ABL. Furthermore when optimization reach approximately the same level of ABL, the differences in TH could reach up to 4.212 units with Buffer=6.CV=0.274 being the superior, by comparing figure 27 and figure 28 in Appendix D. In short, adding buffers will result in significant raise in ABL and TH given that one of the parameters remains at same level.
Another interesting optimization result is $\text{Buffer}=6.\text{CV}=0.5$. Despite of having almost double the CV of $\text{Buffer}=1.\text{CV}=0.274$, it still possess better ABL in comparison. However the most interesting is the fact that, while $\text{Buffer}=2.\text{CV}=0.274$ can achieve higher ABL than $\text{Buffer}=6.\text{CV}=0.5$. As soon as they reach the same level of ABL. Their differences in TH becomes less significant the larger ABL becomes, with $\text{Buffer}=6.\text{CV}=0.5$ being the result with slightly lesser TH than $\text{Buffer}=2.\text{CV}=0.274$. Such behavior can also been observed in $\text{Buffer}=6.\text{CV}=0.75$. All that above leads to conclusion that even if a production line possess a more ineffective CV compared to other production lines, by raising the level of inter-stage buffer, it creates room for improvement and potential to surpass other line with better CV in term of TH. (Note the statistic data of ABL, produced by FACTS optimization shows in percentage which differs from Shaaban’s result. Therefore it’s important to multiply with inter-stage buffer level with ABL before proceed comparing against Shaaban’s data.)

6.3 Analysis ABL vs IT

![Figure 12 TH vs ABL. Pareto-optimal result of all optimization](image)

This time the focus of analysis will be the pattern behavior of operation time from workstations and pattern of buffer level. Consequently all optimization with inter-stage buffer=1 will be excluded from this analysis since they will not provide information regarding buffer pattern.
The first step is to allocate optimization result with highest value in regard of ABL & IT. The top ten optimization result with highest ABL/IT will used for analyzation and the character of pattern is determined by majority of the specific pattern. If no majority can be concluded from a group of optimization results. The results of analysis will be regarded as a mix of different pattern that exist in that result.

Table 2 Result of analysis on optimization result. Pattern Zic Zac is a work pattern with tendency of fast-slow-fast-slow pace.

<table>
<thead>
<tr>
<th>Buffer level</th>
<th>Coefficient of variation</th>
<th>Operation time pattern (ABL)</th>
<th>Operation time pattern (IT)</th>
<th>Inter-stage buffer level (ABL)</th>
<th>Inter-stage buffer level (IT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buffer 2</td>
<td>CV=0.1</td>
<td>(-)</td>
<td>(/)</td>
<td>(-)</td>
<td>(-)</td>
</tr>
<tr>
<td>Buffer 2</td>
<td>CV=0.274</td>
<td>(-)</td>
<td>(-)</td>
<td>(-)</td>
<td>(-)</td>
</tr>
<tr>
<td>Buffer 2</td>
<td>CV=0.5</td>
<td>(V)</td>
<td>(-)</td>
<td>(-)</td>
<td>(λ)</td>
</tr>
<tr>
<td>Buffer 2</td>
<td>CV=0.75</td>
<td>Mix of (V),(-),</td>
<td>(-)</td>
<td>(λ)</td>
<td>(/)</td>
</tr>
<tr>
<td>Buffer 6</td>
<td>CV=0.1</td>
<td>(-)</td>
<td>(/)</td>
<td>(-)</td>
<td>Mix of (-),(/),(/,λ)</td>
</tr>
<tr>
<td>Buffer 6</td>
<td>CV=0.274</td>
<td>(-)</td>
<td>Mix of (/),(λ)</td>
<td>(-)</td>
<td>(-)</td>
</tr>
<tr>
<td>Buffer 6</td>
<td>CV=0.5</td>
<td>(-)</td>
<td>(λ)</td>
<td>(-)</td>
<td>(λ)</td>
</tr>
<tr>
<td>Buffer 6</td>
<td>CV=0.75</td>
<td>Mix of (λ), Zic Zac</td>
<td>Mix of (/),(λ)</td>
<td>(λ)</td>
<td>(/)</td>
</tr>
</tbody>
</table>

According to the analysis. It shown that optimization results with highest IT possess a strong pattern of (λ), which is nothing unusual since both Shaaban and this project statistical data have already shown in this thesis that results with highest IT have always monotone decrease pattern (λ) in operation time.

The more interesting discovery are the fact that the dominant operation time pattern for results with highest ABL are balanced work pattern (--) with total 5 out of 8. Which is different from Shaaban’s result that shows (/) have highest value in ABL. Granted that the DI are not fixed compared to his result and might be the cause of differences. Furthermore optimization result for CV=0.1 follows almost the same pattern except for the inter-stage buffer level (IT). The cause might be due the increased possible variation of different buffer level compared to inter-stage buffer=2, which has far less possible combination in comparison.

Another discovery is the pattern of inter-stage buffer for high IT optimization results. It follow a distinct design which is dependent on CV. Since it’s natural for low CV to have balanced inter-stage buffer since they possess stable work flow. Therefore it’s more interesting to investigate production line with large CV, such as 0.5 and 0.75.
The pattern of inter-stage buffer level are as follows:

- \( CV(0.1) = \text{Inter-stage buffer pattern (--) with exception of buffer 6} \)
- \( CV(0.274) = \text{Inter-stage buffer pattern (--)\text{)} \)
- \( CV(0.5) = \text{Inter-stage buffer pattern (A)} \)
- \( CV(0.75) = \text{Inter-stage buffer pattern (/)} \)

During the observation, it was discovered that (/) inter-stage buffer pattern manipulates certain parts of IT for workstations. Specifically the blocked portion of workstation, it can be manipulated to as low as 1.11\%. While the heavier part of workload seems to have been placed at operation 2 & 3 and naturally leads to more workload for the buffers (figure 14 & figure 15).

![Figure 13 ABL vs IT. Buffer 2. CV=0.75](image1)
![Figure 14 ABL vs IT. Buffer 6. CV=0.75](image2)
Lastly, both of the optimization results of CV=0.5 possess inverse bowl buffer pattern. By comparing Buffer\_OccupationPortion between figure 16 &17, it’s easily noticed that the frontline buffer from figure 16 suffers heavy workload in comparison to figure 17 which have a balanced workload throughout its buffer workload. The possible cause of this behavior lies with the number of buffer in the line and the storage size of first buffer. Although as mentioned earlier both optimization possess (A) pattern for buffers. The first buffer in figure 16 has only one single unit of buffer storage to work with, therefore it doesn’t matter which buffer pattern optimization got. The same thing can be noted at figure 15, Buffer1\_occupationPortion.

---

### 6.4 Variability vs Buffer

Following analysis shows the difference of adding more buffers in a production line, while Buffer=6.CV=0.1 works as an example of how an ideal/good production line output would be like. Optimization result in figure 18 shows that all pareto-optimal solutions forms a straight line when ABL vs WIP. In other words the best solution in ABL also triggers corresponding best solutions in regard of WIP. Which leads to conclusion that ABL and WIP are mutual interacted with each other.
Figure 17 ABL vs WIP. Optimization with different buffer size

In figure 19 shows pareto-optimal solutions in regard of TH vs ABL. Unlike figure 12 this graph shows optimization results after it reached its highest outputs in TH. It can be observed that all four optimizations reach its highest output in TH when their ABL level are around 0.5. It’s however important to grasp the fact that ABL=0.5 indicates the total average buffer level are around 50%, it doesn’t necessary indicate that every buffer attains the same level throughout the production line.

Figure 18 TH vs ABL Optimization with different buffer size
Figure 20 shows the interaction of pareto-optimal solutions between TH & WIP. It shows the effect of buffer application on a production line. While it’s known that applying buffers will most likely raise TH in a production line, however the graph in Figure 20 also clearly indicate that production line with a lower CV can get equal or higher values of TH in comparison to a line with worse CV. As continuously adding more buffer to optimization with CV=0.274, it will eventually surpass Buffer=6.CV=0.1 in term of TH. But by then the WIP would reach to a tremendous high amount. In the end it comes to a decision making whether TH or WIP should have higher priority depending on the circumstances in the factory.

Figure 19 TH vs WIP. Optimization with different buffer size
7 Discussion

In this chapter the author will bring forth discussion regarding the project as a whole. Evaluations and some thoughts regarding methods and models used in this project. Lastly author’s view on what could have been done differently in this project.

7.1 Simulation parameters

During the creation of simulation models, this project encountered several obstacles mentioned in Chapter 4. The simulation models is basically an attempt to recreate Shaaban’s model that should fulfill the same function. However the information provided in his report were insufficient to make a correct simulation model or a model with the same function. With the most critical factor being how Shaaban handled operation time of Weibull distribution while applying both CV and DI remains unknown. Several attempts to create such formula and consultation with Shaaban were made but did not lead to a satisfying result. For that reason this project switched focus on operation with lognormal distribution instead, since both Weibull and Lognormal being continuous probability distributions and the later are commonly found in real world operation time distributions (Dudley, 1963). Fortunately the structure of model itself is relative easy and did not require advanced knowledge to create them.

7.2 Limitation of software

Except the lack of information on certain necessary simulation parameters, there are also other simulation parameters that can’t be achieved due to limitation of FACTS. The focus of this project should have switched to Plant simulation to being the tool for optimization while FACTS were used to verify models tenability. Unfortunately optimization with Plant simulation is a very complex matter compared optimization tools that exist in FACTS. Since optimization is the focus of this thesis and with the encouragement from the supervisors, hence FACTS became the choice for optimization.

7.3 Projects progress

From the beginning the purpose and aim were clear and I understood the approach on how to do in most of the area in this project e.g. simulation, optimization, literature review etc. That is until this project encountered a bottleneck which the information regarding simulation parameters became unclear and while waiting for Shaaban’s reply, it felt that any continuous effort on simulation model without his information might be wasted. Therefore I switched the type of probability distribution in operation time as mentioned earlier in this thesis. Supervisor/professor Ng advised to create simulation models before working on the report, and when this problem was encountered I could work on the report in meanwhile so that I could be as time efficient as possible.
7.4 Time consumption of optimization

During the lower half of project, the optimization became more tedious than expected. While the difficulty of understanding optimization tool were time consuming at the beginning, with support of supervisor the optimization became easier to understand. The most tedious part is its time consumption and the fragility of the software. With optimization it randomly crashes from time to time, so it was hard to collect all optimization results on time. Granted that it was a beta version of simulation software FACTS this project were using which might be the cause of software crashing. I was later informed by supervisor that there are options to reduce the likeliness of crashing, thereafter the number of times of FACTS crashing reduced but it still occurs from time to time. With one successful optimization takes 2 hour to complete, the estimated time were one week became suddenly two whole week to complete. In short the estimated time consumption on optimization were underestimation on my part.
8 Conclusions and future work

In this chapter the author will summarize all results and analysis from Chapter 6. Lastly based on the knowledge and experience obtained throughout this project, the author will give suggestion for future work.

8.1 Conclusions

The aim and objective in this thesis is to create simulation models that fulfill the same function as Shaaban’s simulation model in his report. While the main focus is to analyze the optimization results from previous simulation models and find, observe and document any point of interest. Below is summary of the progress to achieve those objectives in this thesis.

- Develop simulation models in FACTS Analyzer and verify their performance outputs, with respect to several different processing time probability distributions, by using some identical models developed in Plant Simulation. The results shall also be checked and compared against the numerical results in the literature.

While not being the main focus in this project, it’s an important stage to complete before running any optimization. By studying Shaaban et.al report (2009) and using the same simulation parameters to create simulation model using FACTS. This object have been partially achieved, with reason being a different type of continuous probability distribution is being used instead of the original Weibull distribution that Shaaban were using. Together with lack of information in his report and limitation of discrete event software FACTS. The simulation model can’t fulfill the exact same function like Shaaban’s model. Despite the numerical differences in statistical outputs, the process time pattern remains the same, which gives some credibility to the simulation models. Since the focus of this project is to study unbalanced production line. It’s not necessary to have the exact same data as in Shaaban’s result.

- Carry out multi-objective optimization experiments using IT and ABL as the optimization objectives and then analyze the results.

Twelve optimization results were produced with each of it contains statistical outputs to fulfill the objective of this thesis, namely ABL and IT. After the Pareto-optimal solution were located from all results, the raw data of those results is later converted into excel and became the base for visual scatter graph. Which provided a wider view of the optimization result and gave new insights. During the analysis TH were also added into being part of its result. Since from a production manager point of view, TH is one of the important aspects of a production line. Hence why it is included as part of analysis.

Aside from the expansion of analysis field. Few interesting behavior of outputs, process time etc. were discovered. Those cases are later logically explained, suggesting possible theories that caused those behaviors, backed by statistical data from optimization as argument to support my theories.
8.2 Possible industrial application

In Chapter 6.2 and 6.4, the outputs of pareto-optimal solutions in regard of TH and ABL were shown. The analysis discovered interesting interactions between the outputs and how buffer application can affect the production line. It was discovered in Chapter 6.2 that when certain amount of buffers were applied on a production line, it was possible for the line with inferior CV to overcome the differences in CV and yield the same if not greater outputs in comparison. While in chapter 6.4 (figure 19) it also shown that by applying more buffer, the line would eventually surpass other production lines with better CV in term of TH. Although the positive effect of buffer application would diminish gradually with the increase of amount of buffer, which will leads to a tremendous amount of WIP in the line (figure 20).

Those discoveries provides further insight on the effect of unbalanced production with different buffer size and CV. It could provide some fundamental basis for decision making in regard of raising productivity in an unbalanced production line.

8.3 Future work

The first thing to suggest for future work would be find a way to simulate and optimize with Weibull distributions. In that way the simulation model would have gain more credibility compared to this projects simulation model. Although it is skeptical that such change would bring large differences in statistic outputs, because both Weibull and Lognormal are continuous probability distribution with lognormal being the one that is commonly used in real world process time. But it is still important to verify the simulation model as best as possible before proceed to optimization.

The second suggestion would to analyze TH vs WIP aspect from optimization results. Since Shaaban et.al (2009) did not investigate those outputs in their report. If discovered during the analysis that certain unbalanced pattern yield higher TH than a balanced production line. It could spark a great interest from a production manager if this specific analyzation was included in the report. Because from the productivity point of view, TH & WIP weights more than ABL & IT. Since one of the advantage unbalanced pattern possess is that it’s easier to deliberately unbalance a production line than perfectly balancing it, hence the interest.
References


Appendix A

This appendix consists of statistical data obtained from simulation models of FACTS.

Lognormal distribution (FACTS)

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Table 3 Statistical data of IT using lognormal distribution.

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Table 4 Statistical data of TH using lognormal distribution.

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Table 6 Statistical data of ABL using lognormal distribution

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Table 6 Statistical data of ABL using lognormal distribution
Appendix B

This appendix consists of statistical data obtained from simulation models of Plant simulation.

Lognormal distribution Plant simulation

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Table 7 Statistical data of IT using lognormal distribution

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Table 8 Statistical data of ABL using lognormal distribution

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Table 9 Statistical data of WIP using lognormal distribution
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*Table 10 Statistical data of TH using lognormal distribution*
Appendix C

This appendix consists of statistical data from Shaaban

**Table 1**  IT data for unbalanced and balanced line configurations ($N = 5$)

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**Table 2**  ABL data for unbalanced and balanced line configurations ($N = 5$)

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Appendix D

This section contains optimization results used for analysis and references.

Figure 20 ABL vs IT optimization result of 30 000 iterations with buffer 2 and CV=0.5 as parameters

Figure 21 ABL vs IT optimization result of 30 000 iterations with NDS filter. Same parameters as figure 12.
Figure 22 TH vs ABL optimization result of 30 000 iterations with buffer 2 and CV=0.5 as parameters.

Figure 23 TH vs ABL optimization result of 30 000 iterations with NDS filter. Same parameters as figure 14.
Figure 24: TH vs ABL optimization result. Buffer 6 CV=0.274

Figure 25: TH vs ABL optimization result. Buffer 2 CV=0.274
Figure 26 TH vs ABL optimization result. Buffer 6 CV=0.274
Figure 27 ABL vs IT optimization result. Buffer 2 CV=0.5
Figure 28 ABL vs IT optimization result. Buffer 2 CV=0.5