Arab Academy for Science, Technology and Maritime Transport

College of Engineering and Technology

Industrial and Management Engineering

B. Sc. Final Year Project

Energy-aware Operations Scheduling

Presented By:

Ali Mohamed Fathy *Mostafa Ayman Nabhan*

Huda Ahmed Afifi *Pola Adel Mahrous*

Supervised By:

Prof. Khaled S. El-Kilany

July – 2021

DECLARATION

We hereby certify that this report, which we now submit for assessment on the programme of study leading to the award of Bachelor of Science Industrial and Management Engineering is all my own work and contains no Plagiarism. By submitting this report, we agree to the following terms:

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Student Name: Ali Mohamed Fathy
Registration Number: 16100972

Signed: _________________________

Date: 9 – 7 – 2021

Student Name: Mostafa Ayman Nabhan
Registration Number: 16100927

Signed: _________________________

Date: 9– 7 – 2021

Student Name: Huda Ahmed Afifi
Registration Number: 16100107

Signed: _________________________

Date:9 – 7 – 2021

Student Name: Pola Adel Mahrous
Registration Number:

Signed: _________________________

Date: 9 – 7 – 2021

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ACKNOWLEDGMENT

Models developed for this work are built using the ExtendSim™ Pro v10.0.7 simulation environment from Imagine That, Inc. The tool has been offered to the final year project group as a grant for research purposes as part of the ExtendSim Research Grant Program.

We would like to thank Prof. Khaled S. El-Kilany for his continuous support and help in our project, along with every member of the industrial engineering staff who were always there for any inquires.

ABSTRACT

Recently, the need for sustainable manufacturing has been ever-growing and crucial to help sustain the dying resources that earth has provided human beings with, which leaves us with a mission to help save these resources by finding new ways to minimize the use of them. Out of the three main sustainability pillars, social, environmental and economic pillars, the focus in the industrial field is now shifting towards the environmental pillar and especially the energy aspect. Recent research propose different methods and techniques to help reduce the energy consumption on production lines through different strategies. Operations scheduling and sequencing is an important process in any industrial facility, where the utilization of the resources is one of the main objectives. Integrating the concepts of operations scheduling with the sustainability aspect yielded very promising results recently, where optimization models and simulation models where applied to solve the scheduling problem in an energy-aware manner. The focus of this project is to present the recent work that has been done on this topic, and study the concepts used in these papers. A simulation-based approach is proposed and tested on a real-life case study, applying operation scheduling techniques and energy-saving methods.

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Chapter One

1 INTRODUCTION

Sustainable manufacturing, which can be defined as the creation of products while maintaining an economically-sound processes that reduce the environmental implications while saving energy and resources, is recently being thought about on the operational level where job scheduling and sequencing can help utilise the resources to the maximum, while maintaining an energy-efficient operation. Recent years showed that human kind are in a huge need of preserving the planet's resources and the researches done in the past years were more focused than ever on finding a solution for the ever-growing environmental issues that faces the industrial companies, such as the inflated energy prices, shortage of raw materials and the customers' demands for environmentally-friendly products. Sustainability can be divided into three pillars; economic, environmental and social. In this report, the focus is thoroughly on the environmental pillar, and specifically reducing the energy consumption in manufacturing. According to a study by the Energy Information Administration, nearly 5% of the total industrial energy consumption in the United States is consumed by food processing industries. Sustainability can be achieved on an operational level and on the supply chain. Environmental sustainability can be categorized into three categories; carbon dioxide emission reduction, water use throughout the operation processes and energy reduction. This project focuses on an energy-based operation scheduling perspective, and the main objective is working on a case study and try to minimize the energy consumption of the production line's machines through sequencing of jobs and resource allocation.

In this report, a definition of the sustainable operation scheduling problem is discussed, an introduction to the real-life case study and the implications that face the implementation of the various solution techniques that can be utilised to achieve a sustainable manufacturing environment. The following chapter classifies the reviewed papers and clarifies the research methods used to search for the reviewed papers related to the project's topic. Diverse solution techniques are reviewed and discussed, and the application and feasibility of these techniques are analysed. All solution techniques mentioned in this report have effectively the same performance measures and objective functions which are thoroughly clarified. Findings and data collected form the reviewing are then examined and the most feasible solution techniques are chosen with the most fitting objective functions and the implications that face the real life problem. The case study will be carried out in a food processing plant, and a brief information about the plant and its Production lines, machines, product mix and numerical data is collected and presented in the third chapter. According to the plant capacity limitations, changeover requirements, due dates and customer demand, while maintaining the sustainable approach, a simulation model is developed, and all results were analysed to choose the best alternative that meets the project objectives. All model development steps are documented.

1.1 PROBLEM DEFINITION

In the past years, companies realised the urgent need of sustainable manufacturing practices, and when applying the concept on operation scheduling, some obstacles and trade-offs started to appear. The volatile energy prices and dying resources drove the industries to look for solutions and techniques to overcome those prices by minimizing the machines' energy consumption. This can be achieved by sequencing the jobs and assigning machines to jobs in the most-energy efficient sequence possible. Different changeover schedules can have huge impacts on energy consumption and also the throughput and productivity of the line, where the energy consumed by idle machines and changeover tools during setups can be reduced simply by finding better schedules and sequences for changeovers A trade-off between machine speed and energy consumption was assumed, where simply increasing the machine's speed would result in a shorter makespan, but resulting also in an increase in energy consumption, and though energy costs. Product mix and the multiple changeovers needed to respond to the quickly-varying market demand is widely discussed in this report and the articles reviewed to construct this report. Another aspect of sustainability that is often put in perspective is worker himself. Labour costs (which is also and economical aspect), overtime and no work on weekends are all considered as constraints when formulating a model to achieve a specified objective function.

1.2 AIMS AND OBJECTIVES

The aim of this work is to arrange, control and optimize work and workloads in a production process by telling a production facility when to make, with which staff, and on which equipment in such a way that the **cost** and **time** of production is minimized, the goods produced are **delivered** on due dates, and the **energy** consumed in producing these goods are minimized.

This report proposed approaches that aim to analyse sustainability in manufacturing through the second decade of the twenty-first century that solves the potential environmental impact and minimizes resource scarcity. The major objective is energy consumption variable and the mixed strategies used to minimize energy consumption. The extent of sustainability objectives was investigated to test different scheduling approaches and methods. All constraints were studied and put into consideration in order to get achievable results that can be implemented. All solution techniques assessed in the project are all tested and proven for their impact on energy consumption and the environment. A timeframe was established to fulfil all of the specified objectives in the required period.

1.3 REPORT OUTLINE

The report is composed on five chapters. This chapter is an introduction to the topic and the report. The remaining chapters are outlined as follows:

- Chapter 2: is a review of relevant literature that addressed the operation scheduling problems in a sustainable manner. Solution techniques and previous work on the topic ate analysed

- Chapter 3: presents the case study used in this work. A background on the production lines and the products of the company are reviewed, while presenting numerical, operational and structural data.

- Chapter 4: A simulation model was developed after defining the problem, collecting necessary data and developing conceptual and computer models.

- Chapter 5: The experimental design is discussed, along with the results of the different experiments made. All results are analysed and the best alternative is chosen

- Chapter 6: Conclusions and finding, recommendations for future work

Chapter Two

2 LITERATURE REVIEW

2.1 OVERVIEW

In this chapter, an extensive research was done to better understand the scheduling problem in general, and the integration of the sustainability parameters within these various scheduling problems. This report takes into account the operational and tactical level, which is operation scheduling. A detailed classification of the reviewed articles, along with the research methods taken to obtain these scoped articles, is discussed in the coming sections. The numerous types of scheduling problems, solution techniques used to solve the scheduling problem whether qualitative or quantitative methods, and performance measures are the main topics to be discussed. After the papers are fully reviewed and classified, analysis and findings of the resulting information will be examined.

2.2 RESEARCH METHOD

Based on articles regarding a sustainable operation schedule approach, a set of keywords were identified; “Sustainability*” AND “Scheduling”. These two keywords were combined in order to gather more than 7,000 wide-scoped articles. Elsevier Engineering Village Engine, Scopus Database, Springer Materials Database and Taylor & Francis Database were used in identifying pre-reviewed articles having this combination of keywords.

Further research was made on selected papers to narrow the scope by adding additional limitations and keywords such as “Energy saving” AND “Optimization”. After applying a filtered search, the number of papers were limited to nearly 2000 paper, all concerning an energy-efficient operation scheduling in various industrial fields. Very little amount of papers were found before 2000 and the early 2000s, with the number of articles concerned with this specific scope rising with the start of 2006. A filter was then applied to only consider articles published after 2009 and until 2020. To accommodate with the case study, which will be later discussed in this paper, articles with “changeover times*” and “product mix” in the keywords, title, abstract or introduction were identified and reviewed.

As a result, 60 papers were selected, and as Figure shows, a trend is found in the 1-2 number of literatures concerning sustainable scheduling as a topic. These numbers were acquired on the total number of paper reviews found. More than 90% of the total literature reviews are after 2010, and that shows how this topic is concerning all modern industries. All articles collected for review were added to the Mendeley platform which was mainly used for referencing and citations, and also manage the articles.

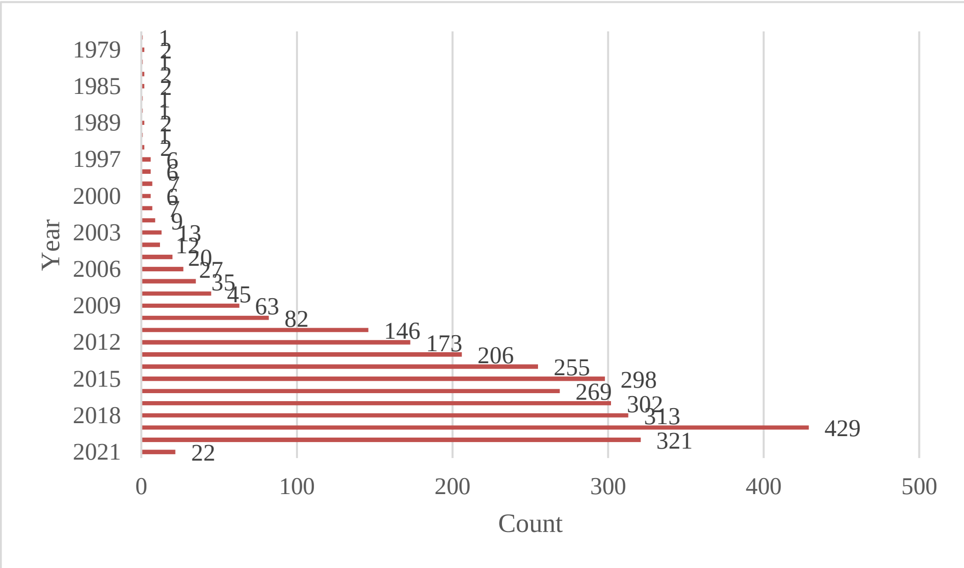


Figure 2-1: Number of articles found according to year

2.3 Performance Measures and Objective Functions

Performance measures in any production plant can be fairly the same, where the most important Key Performance Indicator (KPI) would be the Count; the amount of products created per period. Another crucial KPI would be the quality of products created and the rate of which these good products are made. Downtime and changeovers are considered as an important KPI in industries where there is a variety in the product mix and high responsiveness is required on the production line in order to satisfy the sudden changes in plans.

When it comes to conventional and basic operation scheduling problems, varying from a single JSP to FJSP and Periodic JSSP, cycle time and makespan are considered to be the most important performance measures to evaluate the efficiency of the scheduling.

An article [1] discussed the various objectives of a detailed operation scheduling. Minimizing the total completion time might be the customary performance measure where the sum of all the completion times of all jobs are optimized. Tardiness and lateness are commonly discussed and optimized when it comes to scheduling problems.

As this project puts more focus on operation scheduling from a sustainable perspective, the performance measures shifts to an environmental point of view, rather than an economical one. After extensive research on the specified topic, a clear view of the objective functions used was made as shown in Figure .2-2Minimizing the total energy consumption was the leading objective when it comes to sustainable scheduling, whether it is a single objective or in a multi-objective model.

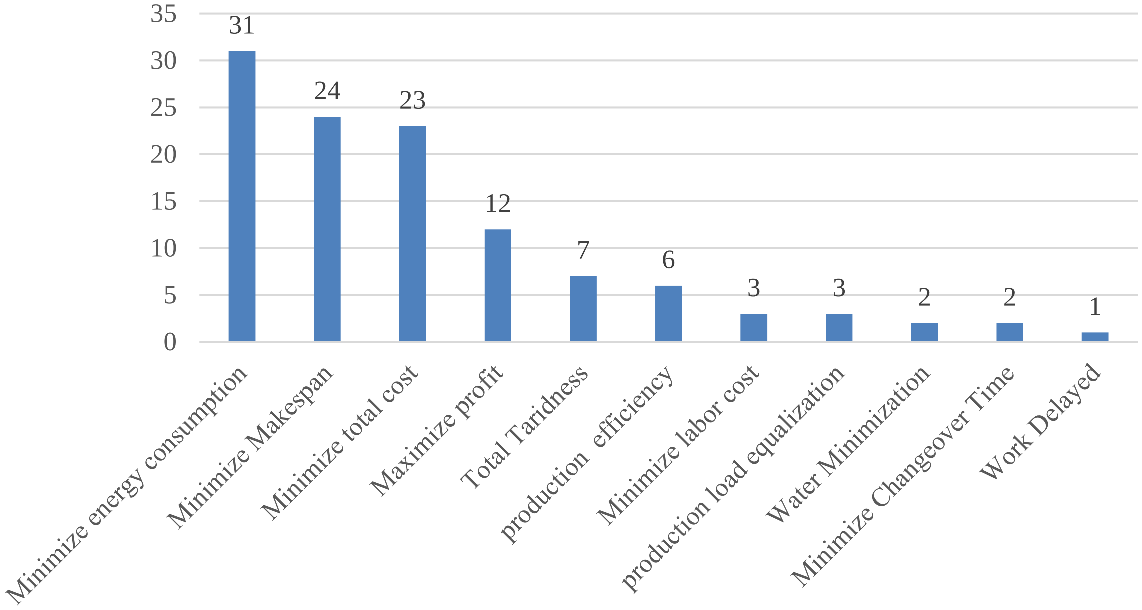


Figure 2-2: Objective functions identified in literature

Out of the 60 papers reviewed, there was a close split between the models on which approach should be taken; single-objective or multi-objective. In more than 60% of the papers that took the single-objective approach, minimization of the total energy consumption or energy cost was the leading objective function due to the need to reduce the environmental impacts that occur from the manufacturing processes especially in food processing industries. More recent reviews decided to minimize the total manufacturing cost, while including the energy costs in the equation along with holding costs, setup costs and labour costs. This approach integrates the three sustainability pillars; Social, Environmental and Economic impacts.

When it comes to multi-objective optimization models, Economical and environmental objectives are optimized simultaneously to achieve the optimal job sequencing. Various metaheuristic algorithms were used to solve the complex models with conflicting objective functions, and Pareto-optimal solutions were obtained. In some papers, various algorithms were used and the results were compared and analysed in an attempt to identify the most suitable algorithm to be used.

2.4 Literature Classification

2.4.1 Optimization Models

After reviewing a total of 60 papers, optimization models where the most used techniques when it comes to operation scheduling problems. Many recent publications delivered various ways and algorithms to solve the complex scheduling problem models formulated. Most recent reviews considered Energy cost to be the single objective function of the model. For example, Xu Gong [3] proposed a generic MILP model with a single objective of minimizing energy consumption, in terms of cost, without exceeding the intended due dates in a classic Job shop scheduling problem by assigning jobs to single machines. He [4] revisited the topic later, while putting into consideration more than just the energy cost. Three objective functions were formulated in this paper in a single-objective manner. Energy cost and Labour cost were jointly optimised in a single machine production scheduling. Jeonghan Ko [5] developed optimization models using mixed integer programming to minimize manufacturing line cost. The developed models will help enhance task-station assignment in multi- and mixed- model production by increasing line cost effectiveness and reducing line changeover impact as well as shortening long re-balancing processes.

Industry 4.0 and smart Manufacturing are considered to be the next revolution in the industrial field, and should be mentioned when discussing the sustainable manufacturing topic. Various papers had industry 4.0 in perspective when showcasing the sustainable scheduling problem. For example, Giuseppina Ambrogio [6] integrated industry 4.0 and sustainability to formulate mathematical models to save energy in the first place. The paper proposes a model in a FJSP where the single objective was to minimize the total energy consumption while using the On/Off strategy. Yuanyuan Li [7] also integrated the machine learning concept with optimization models by modelling a FJSP to minimize production makespan and integrating it with machine learning to automate the rescheduling with minimal human interaction.

A production planning approach was taken by Renzo Akkerman [8], where the total production costs are minimized. From a sustainable perspective, environmental impacts were considered in the setup cost, as they significantly include energy use, as well as water and cleaning agents use. Multiple models were formulated in this paper according to scheduling level. Farhad Angizeh [9] formulated a model as a MILP problem with the main objective function being minimizing the total manufacturing costs, energy costs included. This paper focuses on multi-product flexibility in various production lines. An important scheduling problem, the no-wait permutation flow shop scheduling problem, is studied in the literature provided by Yüksel Damla [10].

This scheduling problem has significant practical applications in food processing as no interruptions between machines and sequential operations is allowed. A MILP model is formulated with a bi-objective of minimizing total tardiness and total energy consumption simultaneously. Changing and adapting machine speeds is discussed in the literature in order to help in minimizing the energy consumption. Various algorithms are proposed; Multi-objective Generic Algorithm (MOGA), MODABC and MOGALS, and the results are analysed along with the MILP results. Jun Zheng [11] discussed minimizing energy utilization and emission in a traditional way to support sustainable manufacturing can be gained by reducing the defective products. The paper supports the sustainability of manufacturing methods, using optimization model MILP.

When formulating a mathematical model for the scheduling problem, there may be single objective function, whether minimizing total cost, minimizing total energy consumption or maximizing profit. In these models, a single solution will be found, with the optimality of the solution depending on the algorithm used to solve the model. Table shows the amount of articles that took the single-objective approach, while 1-2 .clarifying the objective function and date of publication

Table 2-1 Single-objective optimization models reviews:

Author	***Year***	***Economical objective function***	***Environmental objective function***
Gong, Xu et al.[3]	2015	-	Minimize energy consumption
Ambrogio, Giuseppina et al.[6]	2020	-	Minimize energy consumption
Gong, Xu et al.[4]	2017	Minimize total cost	Energy cost
Akkerman, Renzo et al.[8]	2019	Minimize total cost	Energy cost
Angizeh, Farhad et al.[9]	2020	Minimize total cost	Energy cost
Nazarian, Ehsan et al.[9]	2020	Minimize total cost	Energy cost
Velez, Sara et al. [12]	2017	Minimize makespan	-
Li, Yuanyuan et al.[7]	2020	Minimize makespan	-
Hu, Chenlian et al.[13]	2020	Maximize profit	-
Diego C. Cafaro et al. [14]	2020	Minimize total cost	Energy cost
Manish Shukla & Manoj Kumar Tiwari[15]	2017	Minimize total cost	Energy cost
Hanxin Feng et al.[16]	2018	Minimize makespan	-

When formulating a single-objective optimization model, economic and environmental objectives are optimized as a single equation, where the energy consumption is formulated in terms of cost, and the total production costs, including the machine-energy costs, are minimized. Minimizing makespan, tardiness or production output simultaneously with energy consumption is not possible in single-objective models, and that is why articles are now using complex multi-objective models to improve the overall production efficiency. Table 2-2 clearly identifies articles where multi-objective models were developed to minimize environmental and economic objectives simultaneously.

Table 2-2: Multi-objective optimization models reviews**.**

Author(s)	*Year*	*Economical objective function*	*Environmental objective function*
Yüksel, Daml[10]	2020	Minimize tardiness	Minimize energy consumption
Gungor, Z. E.[17]	2015	Maximize profit	Minimize energy consumption
Barak, Sasan[18]	2020	Minimize total cost	Minimize energy consumption
Andrzej Bożek & Frank Werner[19]	2017	Minimize total cost / Maximize profit	-
Joost Berkhout et al.[20]]	2020	Minimize tardiness / Minimize makespan	-
Abedini, Amin et al.[21]	2020	Minimize total cost	Minimize energy consumption
Akbar, Muhammad et al.[22]	2018	Minimize total cost	Minimize energy consumption
Coca, Germán et al.[23]	2019	Minimize total cost / minimize makespan	Minimize energy consumption
Gong, Xu et al.[24]	2019	Minimize total cost	Minimize energy consumption
Liu, Zhifeng et al.[25]	2020	Minimize makespan / minimize changeover time	Minimize energy consumption
Anghinolfi, Davide et al.[2]	2020	Minimize makespan	Minimize energy consumption
Minghai Yuan et al.[26]	2017	Minimize Total cost / Maximize production efficiency	-
Cleber Damião Rocco & Reinaldo Morabito[27]	2014	Minimize changeover time	Minimize energy consumption
Roth, Stefan et al.[28]	2020	Minimize total cost / Maximize profit	Minimize energy consumption
Shi, Lei et al.[29]	2019	Minimize makespan	Minimize energy consumption
Abedini, Amin et al.[30]	2020	Minimize makespan	Minimize energy consumption
Hesran, Corentin Le et al.	2018	Minimize total cost	Minimize energy consumption
Chaturvedi, Nitin Dutt et al.[31]	2014	Maximize production efficiency	Water-use Minimization
Liu, Qihao et al.[32]	2019	Minimize makespan / minimize Tardiness	Minimize energy consumption
Ebrahimi, Ahmad et al.[33]	2020	Minimize tardiness	Minimize energy consumption
Hojae Lee, Christos T. Maravelias [34]	2020	Maximize profit / Minimize Total cost	Minimize energy cost
Yufeng Li et al.[35]	2020	Minimize makespan	Minimize energy consumption
Pablo Vallejos-Cifuenteset al.[36]	2019	Minimize makespan	Minimize energy consumption
Joachim Lentes et al.[37]	2017	Maximize production efficiency	Minimize energy consumption
Chao Lu et al.[38]	2021	Minimize makespan	Minimize energy consumption
Shijin Wanga et al.[39]	2016	Minimize makespan	Minimize energy consumption

2.4.1 Machine Energy-saving Strategies

To save energy, two strategies were mentioned and discussed in the reviewed papers. First, the on/off strategy is sometimes efficient in many cases, where an adequate amount of energy can be saved if the machine is turned off in its idle time. Min Dai [40] implemented the on/off strategy in flexible flow shop problems to minimize the total energy consumption and makespan. Giuseppina Ambrogio [6] also applied the on/off strategy in his mathematical model that minimized the total energy consumption.

Liu, Qihao [32] addressed the on/off strategy while illustrating a Power-Time curve, as shown in Figure 2-3. This curve shows that keeping machine 1 on standby between operations is the Pst * Tidle. In the second curve, a decision of turning off the machine in its idle time was taken, and thus switching the machine off increases the power curve at first, but then falls sharply to 0, and the power consumption can be described as the area under the curve. If the value of Pst* Tidle is bigger than the area under the curve in the second curve, the on/off strategy should be followed, otherwise it should remain on standby mode. Fadi Shrouf [41] proposed a MILP model to minimize the total cost, depending on the machine status and the energy prices.

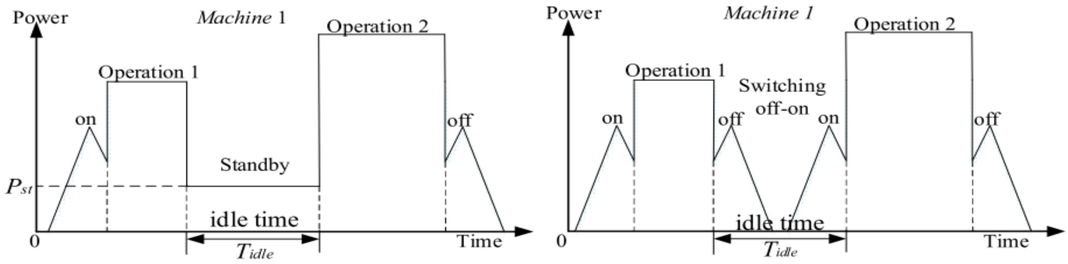


Figure 2-3: Power-Time curves for different machine decisions.

As much as this strategy yields great success in saving energy, it is sometimes inapplicable due to high machine start-up times and costs. Due to these concerns, an exciting study was raised in 2011 that underlined the speed scaling strategy, where the speed of machines is adjusted according to the job being processed. Yüksel Damla [10] formulated a mathematical model that applies the speed scaling method to the machines to minimize total tardiness and total energy consumption respectively.

In figure 2-4, the trade-off between the makespan and the machine energy consumption is shown. The higher the machine speed, the faster the job will be done but the energy consumed will increase, and vice versa. The decision variable in this situation would be the machine speed that would give optimal energy consumption while also fulfilling demands and due dates.

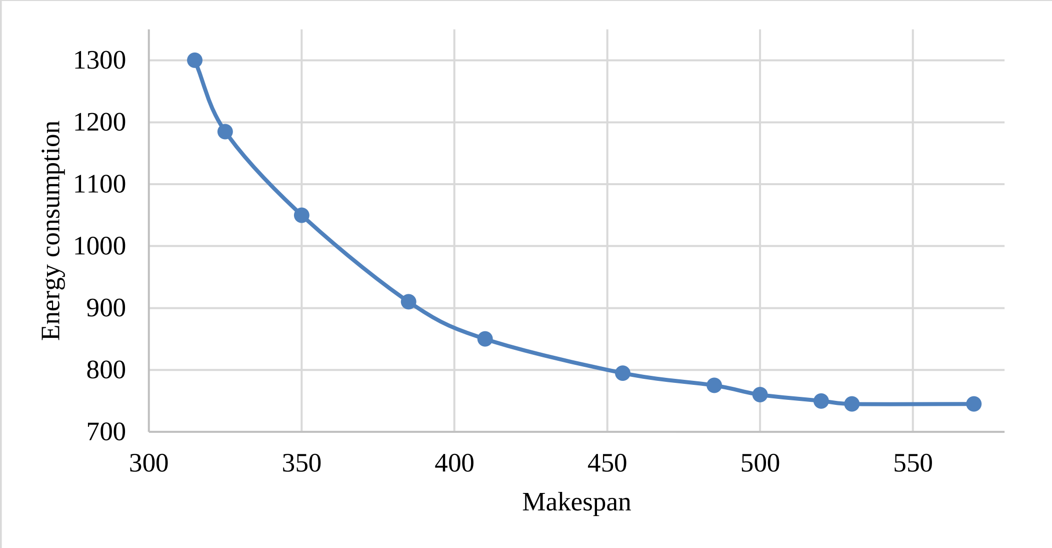


Figure 2-4: Relationship between makespan and energy consumption

2.4.2 Job Shop Scheduling Problem

The operation scheduling problem has many different variations, based on the machine and job orientations. The Flexible Job shop Scheduling problem (FJSP), which is a variation of the classical job shop scheduling problem, is basically allowing an operation to be processed by any machine, and assigning and sequence the operations on the machines to achieve the required objective. Liu Qihao [32] addressed the complex FJSP in a bi-objective model, a more complex version of a single-objective FJSP model. Improved genetic algorithm, rather than NSGA-II, along with tabu search was used to solve the MILP model, with the on/off strategy constraint added in the model. German Coco [23] In his paper discussed the inclusion of sustainability principles in the scheduling of flexible job shop systems (FJS) has focused on the evaluation of energy consumption and key economic indicators makespan and total weighted tardiness, enabled the estimation of the performance of each sustainability dimension. Optimization models NSGA-II and NSGA-III method are used in order to carry out the multi-objective evaluation process, he used three values of objective functions environmental, social, and economic applying NSGA-II and NSGA-III method to identify the corresponding structure of the Pareto optimal fronts. Yufeng Li [35] proposes in his paper an energy conscious, optimization method in flexible machining job shops considering dynamic events. In this paper, A Optimization method which updates the roles and machine plan status when dynamic events occur is proposed. The strategy considers two states for machine energy consumption: actual machining and machine idling/stand-by. He formulated a Multi Objective model to reduce both makespan and energy consumption. Giuseppina Ambrogio [6] formulated a single MILP model to minimize total energy consumption. A set of assumptions were made to solve the flexible job shop scheduling problem, such as that all parameters of the model are deterministic. Another assumption made was that each machine cannot process more than one job at a time, and that operations cannot be done on several machines simultaneously but the sequence of these operations can be varied.

Another scheduling problem is the conventional job shop problem, where jobs are assigned to machines, with the limitation that each operation must be done on a specific machine and only one job can be processed on the machine at a time. [41] The rising cost of energy encourages decision-makers to tackle this problem in different manners, a mathematical model used to minimize energy consumption costs for single machine production scheduling during production processes. To obtain optimal solutions, an analytical heuristic solution provides the minimum cost and the best possible schedule for minimizing energy cost.

2.4.3 Simulation

A system variables change on a discrete and different separate points runs throughout a time. Simulation modelling can be applied to solve scheduling problems by studying the behaviour of real systems using software on a computer and a visual system can be represented to understand and gain system insights and compare it to the real plans and adjusting it before implementing it. Job scheduling and sequencing problems can be solved by testing different scenarios on a simulation model, analysing the results and adjust inputs to obtain the optimal energy costs. [42] Renewable energy sources became one of the main sources for eco-sustainable manufacturing that minimize CO2 emission from fossil fuels and their cost. Renewable energy sources have an issue in the variability conditions of solar and wind energy are not at constant rate, due to the climate. To maintain the usage of energy for production the author thought an appropriate study that its cable to use the renewable energy sources for production and usage of regular fossil fuel when needed. In this research [42] Monte Carlo simulation and real-time discrete event simulation as an energy management model. K.T. Shibin [43] raised the concepts of sustainable flexible technique ways to solve the scheduling problem through simulation optimization rather than conventional optimization techniques, putting into consideration the sustainable constrain factors that include economic, environmental, social factors. The purpose of his article is to introduce new products into a production line, while analysing the bottlenecks that may arise.

2.5 REVIEW FINDINGS

2.5.1 Solution Techniques

Out of the 60 papers reviewed, a diverse selection of solution techniques were found. Khalid Mustafa et al. (2017), for example, simulation based approaches were taken in order to improve production changeover times and sequences as well as maintain a sustainable production system. Figure 2-5 shows the distribution of the different solution techniques used to tackle the scheduling problem. Nearly 80% of the literature took the optimization approach in order /to achieve a set of objectives due to the high precision that can be obtained from different optimization models. Simulation-based approaches were also used in 21% of the papers.

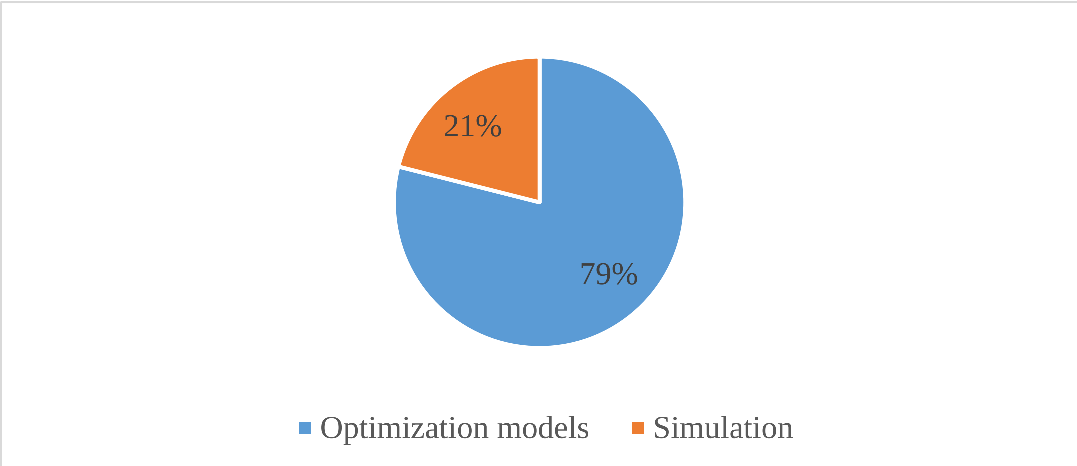


Figure 2-5: Solution Techniques

2.5.2 Optimization Models and Solving Algorithms

A MILP model was formulated in 95% of the articles that took the optimization approach. Heuristic and metaheuristic algorithms are used in optimization models that solve more complex models with conflicting objective functions and real-life restrictions. Figure 2-6 shows the distribution of the two algorithm groups found during the research

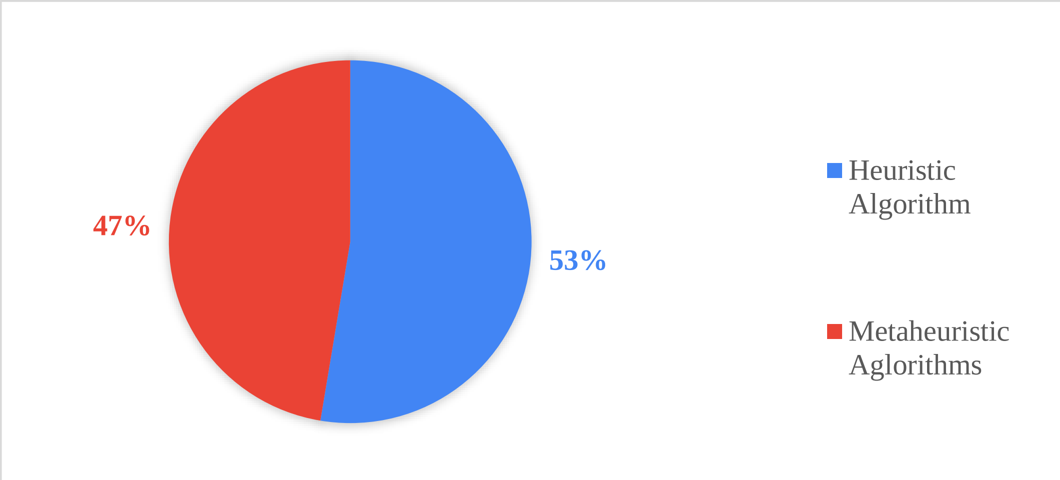


Figure 2-6*:* Algorithms used to solve models

As shown above, most models are solved using heuristics and metaheuristics. Metaheuristics are typically a more generalized solving method, unlike heuristics that solve specific problems. Heuristic algorithms are known for finding near optimal solutions quickly and easily. Genetic algorithms, simulated annealing and tabu search are the most common heuristic algorithms applied to obtain quick solutions. [2]. the use of sensitivity analysis techniques when approaching a single-objective model is examined to see how the decision variables are affected when changing the constraints and other variables.

Although nearly 80% of the articles reviewed chose to formulate mathematical models to solve the scheduling problems, only 10% of these articles included a case study in their review. Only analysis of proposed mathematical models and solving algorithms were viewed in the articles, and there was a lack of real-life data and application of those models and no real-life results to evaluate the different accuracy of algorithms and the feasibility of the models. A set of assumptions were made in 90% of the models where the model developed were deterministic, meaning that all the output values are determined by the parameters, which are assumed to be known with certainty. This is a far simpler model than stochastic models, but does not reflect the real-world circumstances.

2.5.3 Simulation Models

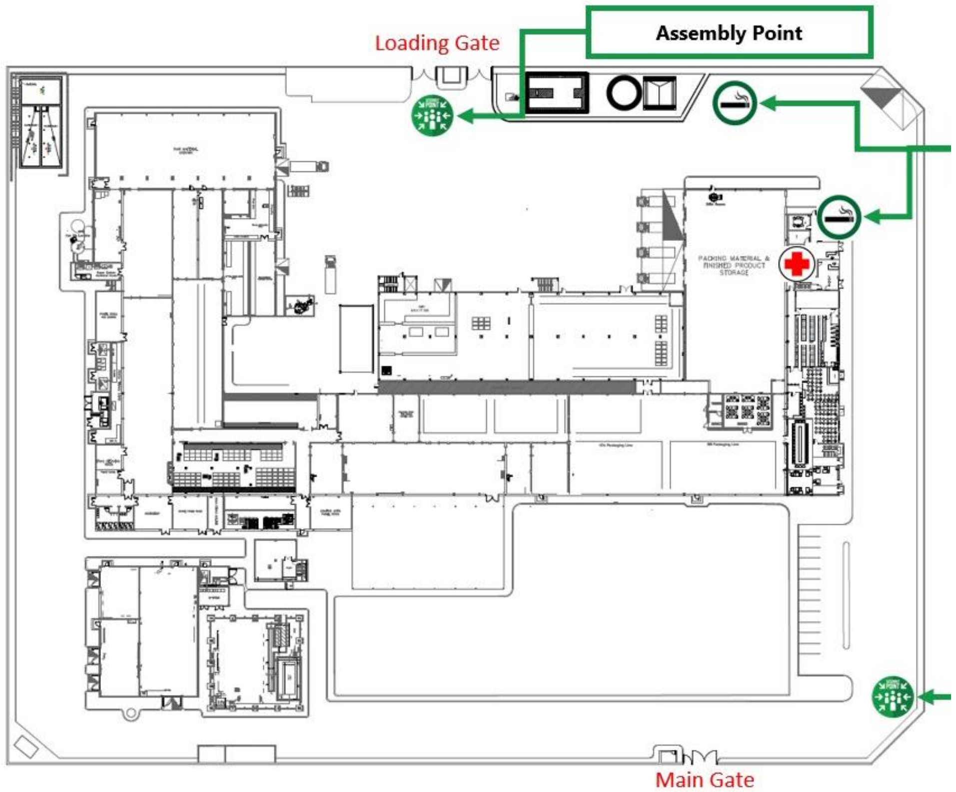
After reviewing the optimization models, the simulation approach was studied and how it differs from the optimization modelling approach. After thorough analysis, it was deduced that modelling a production line simulation would be more appropriate for the case study presented later as the response of the line to different inputs can be visualized and analysed, making it easier to understand how the line operates and where bottlenecks may rise with different inputs. Multiple scenarios can easily be tested at once to evaluate different alternative solutions and choose the best scenario.

Chapter Three

3 CASE STUDY

3.1 HISTORY

Solution techniques reviewed are to be applied on XYZ Gum Company with a diverse product portfolio that reaches local and globally, where 35% of the total supply is exported to Morocco, Nigeria and South Africa. The company already apply sustainability practices in the supply chain, focusing on reducing carbon dioxide emissions and water use. In 2019, 14, 857 tonnes of volume where produced, yielding in a $ 44 million revenue for the company.



3.2 NUMERICAL DATA

In this chapter, a set of numerical data of the plant are presented for each production line, each having different arrival times, capacities, machines and machines utilization. Changeover times between the products are represented.

3.3 OPERATIONAL DATA

For the operational data, flowcharts and value stream maps for each production line are presented, detailing the what, when and how the activities are done. Process flow diagrams for the different production lines are also presented in this chapter, detailing the type of activity done in each process line. These operational data will help develop a model, whether a mathematical or simulation model, with accurate, real-world data and constraints, as the line capacity, demand and utilization are all defined.

3.4 STRUCTURAL DATA

The product portfolio of the company is presented, along with the different production lines. A layout of the plant is also presented detailing the different departments of the company.

3.5 PRODUCTS

In the gum and candy plant, there is a big product mix of different product families. The company has four major gum and candy brands that each have a big contribution locally and globally. Each brand has various SKUs. Figure 3-1 shows the production volume of each of the company's product. Product C is responsible for nearly half of production volume and the company's sale. For each product, a series of unique and precise operations are done on five different production lines, each having different machines that are designed for specific tasks. The presence of a diverse product mix raises the obstacle of high changeover times within each product family, due to having multiple SKUs for each product family.

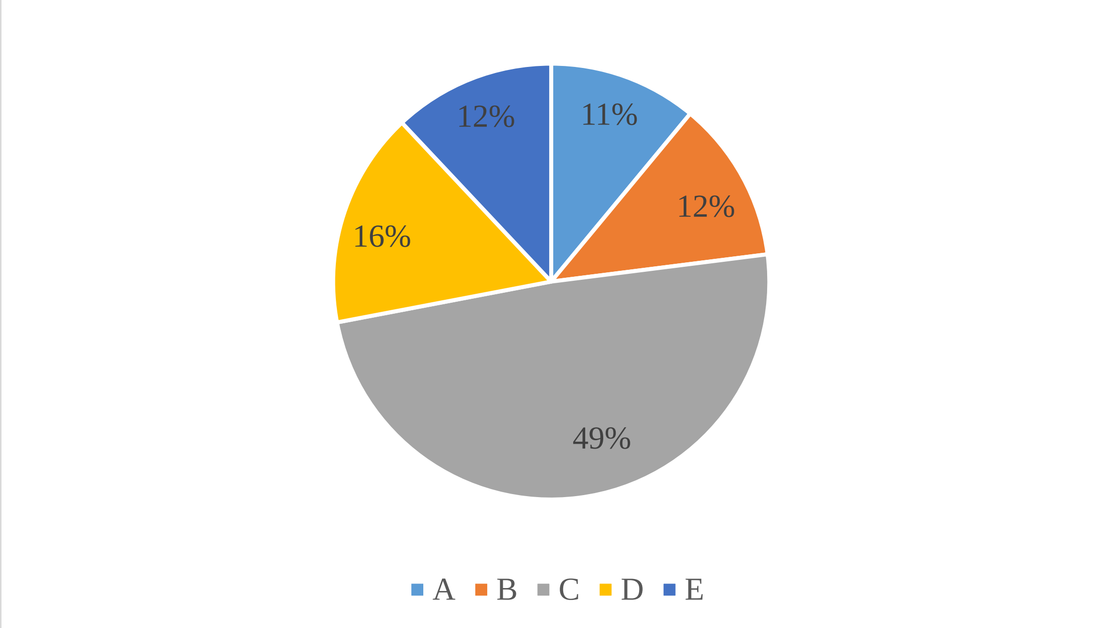


Figure 3-1: Production volume of each product

3.6 Production Lines and Machines

There are a total of 45 SKUs produced by the plant, distributed throughout five main production lines. After reviewing the five production lines, the machine utilization, capacity and energy consumptions, the company saw that applying the solution methods on the single production line is the most appropriate decision. Table Line :1-3 utilizations and capacities details the Utilization of each of the five lines, as well as the capacity of each lines and the number of SKUs produced.

Table 3-1: Production Lines

Line	Line Utilization	Capacity (tons)	SKUs
A	47%	3,588	12
B	39%	1,794	14
C	83%	6,130	14
D	52%	4,261	2
E	75%	2,153	3

3.6.1 Line A

The integrated candy line is the newest introduction to the plant when it was successfully launched in 2018, resulting in increasing the company's exporting markets and the total net revenue. The line is responsible for 10% of the total plant's capacity. The line is not fully utilized, and that is due to specific temperature and humidity requirements that cannot be fulfilled at all times. Due to its low utilization and infrequent availability, acquiring sufficient data to apply the solution techniques on this line was infeasible.

3.6.2 Line C

The most utilized line and the highest line capacity in the plant, this line is responsible for the production of the small sized gum. A series of sophisticated activities take place through four departments, starting by the making of the gum dough, where a mixture of raw materials are mixed together in the mixer. The produced gum dough is then manually transported to a pre-extruder machine where the gum dough is pressed and cut into gum billets. The next activity would be extrusion as the gum billet are rolled in a 4 stage process, until a specific thickness of gum sheets are produced, which are then cut longitudinally and transversely to form a cut sheet ready for tray loading. The sheets are cooled in a conditioning room before they are broken down inside a drum to form uncoated gum pieces. The next process is the coating, where the uncoated gum are thrown into a coater where more raw materials are introduced and added to the coater, producing a coated gum, ready for grading and then packaging. Figure 3-2 and 3-3 clearly shows the flowcharts of the making and coating processes

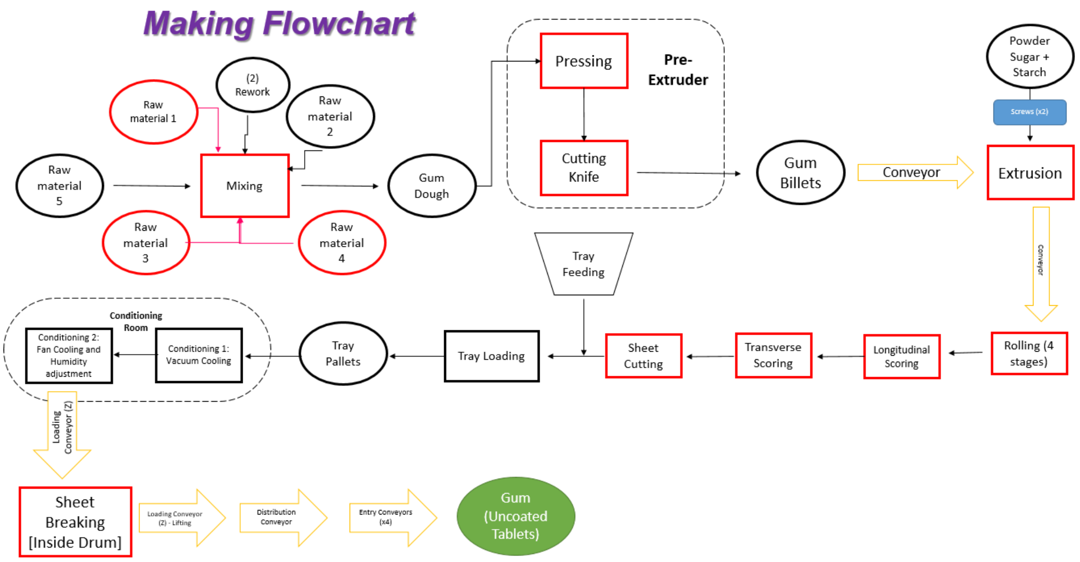


Figure 3-2: Making process flowchart

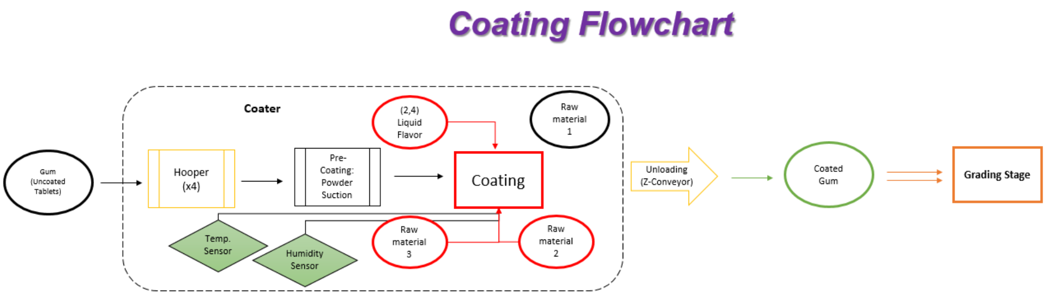


Figure 3-3: Flowchart for coating department

After constructing the flowcharts for the different processes of producing the gum, a value stream map was established, clearly identifying the cycle time (in days), uptime and yield of each activity. The value stream map for the 2s line activities is shown in Figure 3-4. Movements and manual transportations times between each activities are stated (in seconds).

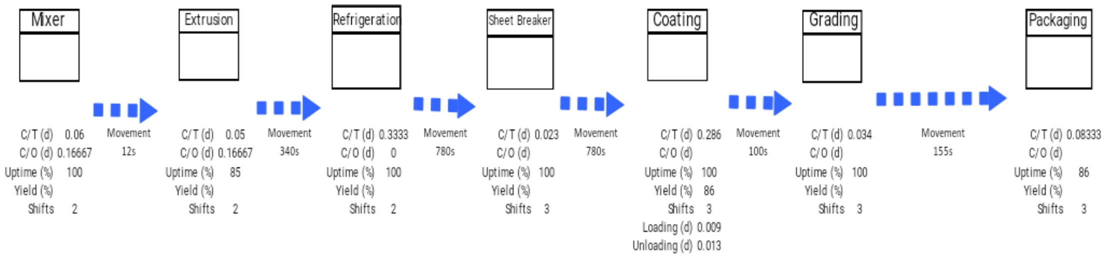


Figure 3-4: Value stream map

3.6.3 Line E

Unlike all other production lines in the plant, line E is an integrated (continuous) production line, meaning that all the departments starting from raw material handling till packaging are a single entity and not located in separate areas. Sixteen batches of four different gum flavours are produced per shift, with each batch needing an average of 90 minutes to be fully processed. Minimal labour is required in this line, as the mixing area worker loads the raw materials into the mixer, wait for the operation to finish, unload the gum dough and transport it to the pre-extruder. The next thing the worker do is wait for the gum dough to transform into semi-finished packed gums. This line is the second most utilized production line at 73%.

Three integrated departments are found in the single production line; the mixing area, making area and the packaging area. This integration of departments increase the coordination within each other, allow for multiple quality inspections along the production line with nearly half the manpower. For example, two workers are needed per department in lines B and C for quality inspections between each operation, which means a manpower of 8 workers are needed for quality inspections along the whole production lines. Integrating the line helps minimize the number of workers and cut the time needed for quality inspections.

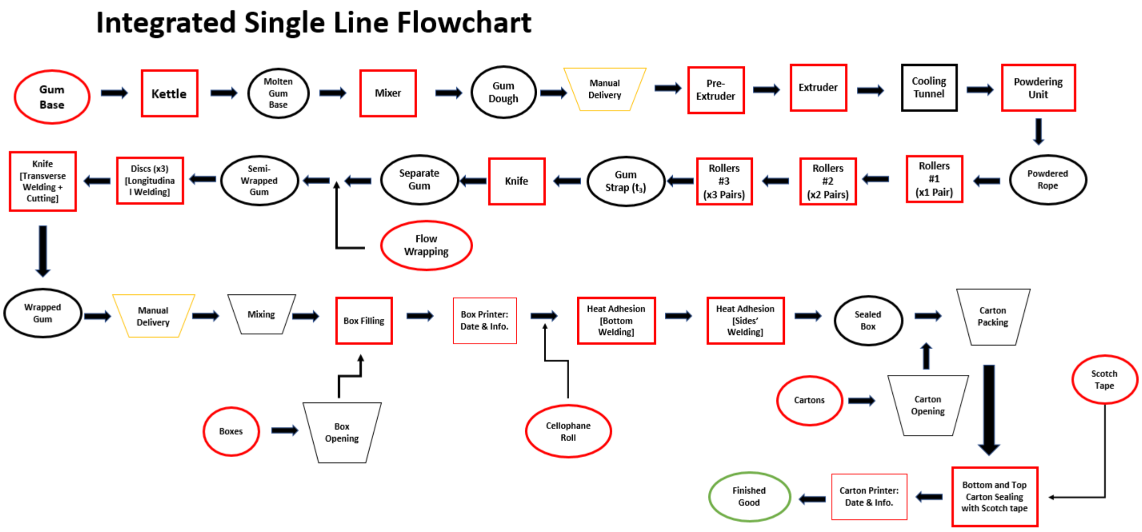


Figure 3-5: Process Flowchart

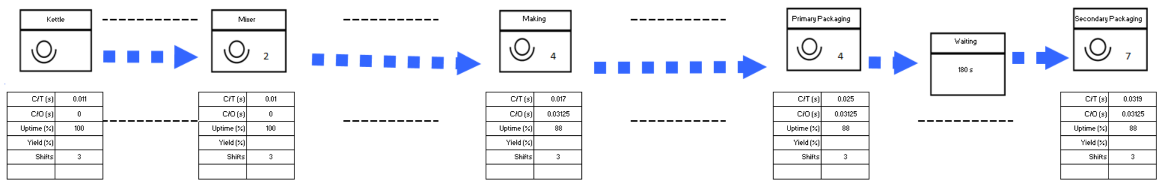


Figure 3-6: Value stream map

Figures 3-5 and 3-6 represents the operational data needed, as the flow chart in figure 3-5 describes the sequence of events occurring during production, while the value stream map in figure 3-6 also offers numerical data such as the arrival times, machine uptime, processing time, activities and the number of machines and workers in each workstation.

These data collectively help define the production line model, and the scheduling problem that needs to be solved. The energy consumption for the five production lines were collected and represented in Table 3-2, along with the number of machines in each line.

Table 3-2: Energy consumption for each line

Line	LU	Power consumption (Kwh)	Number of machines	Capacity
A	47%	488	15	3588
B	39%	228	12	1794
C	83%	496	24	6130
D	52%	8	11	4260
E	75%	410	13	2153

Power consumption in line C appears to be the highest in the plant, but when putting into consideration the number of machines in each line and the capacity of each line, the table below clarifies the power consumption per machine and per unit; where, it is assumed that all machines consume the same share of energy.

Table 3-3: Power consumption comparison

Line	Power consumption (Kwh)	Number of machines	Kwh / machine	Capacity	Kwh/ton
A	487	15	32.5	3588	0.14
B	228	12	19	1794	0.13
C	496	24	20.7	6130	0.08
D	8	11	0.74	4260	0.0019
E	269	13	31.5	2153	0.13

Figure 3-7 clearly shows the distribution of each line in terms of energy consumption per unit. Based on this criterion, a simulation model representing Line E was developed. Operations scheduling and energy saving techniques will be used to minimize the energy consumption on the production line.

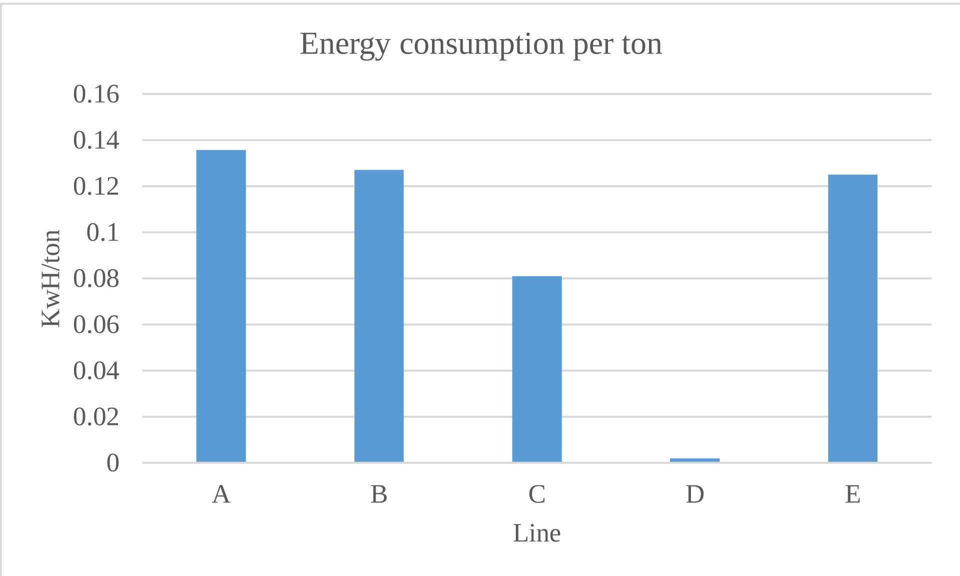


Figure 3-7: Energy consumption per ton

After collecting and studying the data of all the production lines, it was deduced that line E machines consumes more than 30% of the total machine energy consumption in the plant.

Chapter Four

4 MODEL DEVELOPMENT

4.1 METHODOLOGY AND PROBLEM STATEMENT

The energy consumed by the idle machines and changeover tools is huge, given the long changeover time required. The main objective is cutting the high changeover energy costs by 15% in a manner that still fulfils the demand before the due dates. To solve this scheduling problem, a simulation approach will be applied to minimize both energy consumption and makespan by using the scenario manager block embedded in the ExtendSim software which generates and test multiple scenarios for different changeover schedules, and choosing the most appropriate schedule which minimizes the energy consumption, while fulfilling the demand and production mix required

In the case study, a flexible flow shop scheduling problem is present, which is a variation of the classical flow shop problem where there is a number of jobs (J_1, J_2, J_3… J_n), each having a set of operations that need to be processed on different machines (M_1, M_2, M_3….M_n). Each operation can be done on any machine of a given set, where all the machines in that set are identical. This allows the same operation to be done in parallel on more than one machine at a given time. Loading and sequencing are the two main decisions in the problem. Due to the presence of a product mix, with the changeover between each product and another takes a specific period of time. The sequencing of the changes between each of the four products will be studied and taken into consideration. The main objective from solving this scheduling problem is to minimize the total energy consumption/costs of the machines, either by sequencing or routing the operations.

4.2 PROJECT PLAN

A set of performance measures were determined when formulating and building the model. The most important responses in the simulation model were the energy consumed during changeovers, throughput rate per week and the production mix. Production of the four products should be equally distributed among them. To ensure that the production mix is equal, the deviation between the most produced and the least produced product is calculated. A deviation of at most 20 products per month is acceptable. Cycle time will also be monitored during the runs. Due to COVID-19 circumstances, overproduction is not favoured due to expected demand drops, avoiding additional inventory costs and chance of obsolescence. If production can be completed with working days to spare, the machines are turned off and electrical costs are reduced, along with labour costs. Experimental factors such as arrival time of batches, processing times of machines, changeover schedule and the energy consumption on each machine are collected and analysed. The decision variable for the changeover scheduling problem is the sequence of changeovers between the four products that leads to the minimum energy consumption by reducing the total changeover time. To achieve the objectives, a list of constraints were gathered. The following are the model constraints:

- Capacity and utilization constraint; the production line cannot produce more than 1600 tonnes per year.
- Demand constraint; 112 tonnes (approx. 750 batches) is needed every month
- Due Date constraint; Orders must be fulfilled every week (28 tonnes / 188 batches)
- Production mix constraint; equal distribution of production of the four product types for every order
- Starting inventory is assumed to be zero, meaning demand should be fulfilled only from production

4.3 MODEL CONCEPTUALIZATION

Multiple questions were needed to be answered before developing the simulation model. When will the machine changeover process occur? How will the model detect the change? Will new batches arrive during changeover? A logical flow chart, shown in the figure below, answers these questions and will be used when developing the computer model. When a new batch of a different product is ready to be produced, the changeover process should start for a specific amount of tine, depending on the products that are being switched to. As long as the changeover process is going, no new batches should be readied and entered to the production line. Once the changeover process is complete, the batch that was in queue is now processed on the first machine, and a new batch is being prepared to enter the line with the specified arrival time. If between batches, no product type change was detected, the changeover process does not take place.

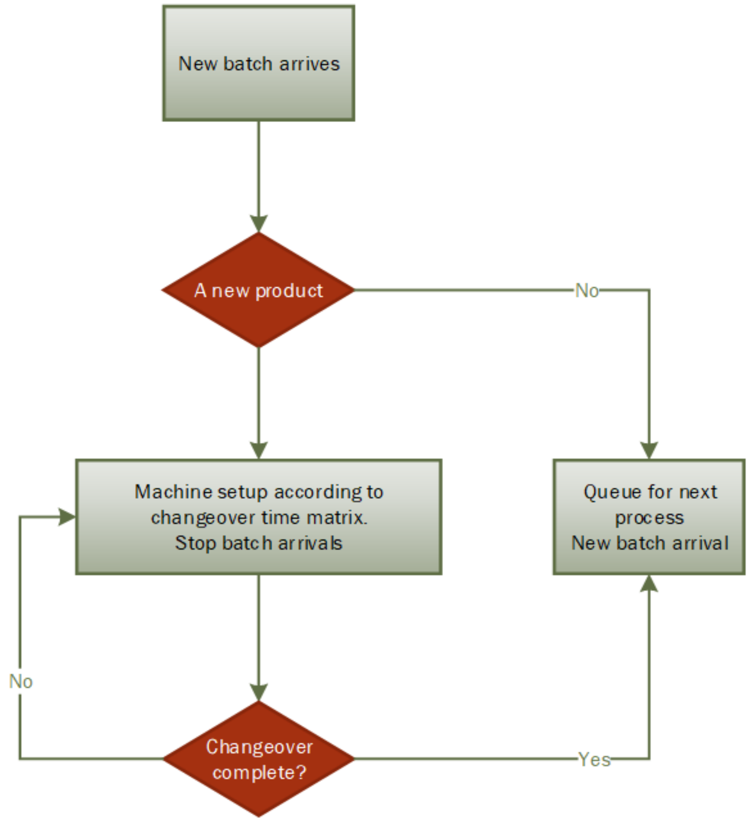


Figure 4-1: Logical flowchart for changeover process

4.4 DATA COLLECTION

After formulating a conceptual model and setting a logical flow chart for the changeover process, the model will be translated onto the extendsim software. In order to build the simulation model, a set of parameters and experimental factors are needed to be added to the model. Flowcharts, process flow diagrams and value-stream maps will be used to model the process flow of the production line, and the processing times of each process will be collected, analysed and added to the model.

Processing times of each machine were collected for a whole 8-hour shift, as shown in table 4-1, and a distribution was deduced using the Statfit software and shown in table 4-2. Arrival rates of new batches are exponentially distributed, with a mean of 2 batches/hour (A new batch is introduced into the system every 30 minutes).The line works 3 shifts per day, and 5 days per week.

The production line works for a total of nearly 28800 minutes, with a demand of 750 batches needed in that time period. The line is fully integrated, meaning that a worker is just needed to load raw materials and unload semi-finished products.

Table 4-1: Data Collection Table

Processing times (minutes)					
	Kettle	Mixing	Making	Primary packaging	Secondary packaging
Batch 1	15.5	14	26	34.2	47.8
Batch 2	16	15.2	25.5	36.8	48.9
Batch 3	16.2	13.1	23	38	47.5
Batch 4	15.8	14.6	24.5	37.7	46.9
Batch 5	16	14.9	25	35.3	48.2
Batch 6	16.2	13.8	25.3	36.8	47
Batch 7	15.7	15	24.3	33.9	47.1
Batch 8	16.1	14.9	25.6	37.1	48.3
Batch 9	16	13.5	23.8	35.2	46.8
Batch 10	15.8	14.8	24.2	37	46
Batch 11	15.7	14.9	24.5	36.8	46.9
Batch 12	16	15.2	26	36.5	49.8
Batch 13	16	14.5	25.1	36.2	48.5
Batch 14	16.3	14.2	24	37.2	45.9
Batch 15	15.9	13.9	23.9	35.9	46.2
Batch 16	16	14.6	24.6	36.8	48.2

Table 4-2: Statfit distributions

Activity	Distribution	Mean (minutes)	St.dev (minutes)
Kettle	Normal	15.9	0.203
Mixing	Normal	14.4	0.608
Making	Normal	24.7	0.82
Primary packaging	Normal	36.6	1.13
Secondary Packaging	Lognormal	42.8	1.52
	Normal	47.5	1.06

Given that the energy consumption is the scope of the project, energy consumption data of the activities in the production line were collected from the facility and recorded in the following table. These data are estimates of what every machine consumes per hour of operation. Average Idle energy consumption of machines and changeover tools consumption gives an estimate of energy consumed per hour of changeover.

Table 4-1: Activities and energy use

Activity	KW.Hr
Kettle & loading	2.50
Mixing	43.20
Making	105.00
Primary packaging	40.00
Secondary packaging	20.00
Changeovers	17.70

The next piece of data that was needed was the changeover time matrix between product switches. Multiple changeovers were inspected to record multiple data of the time needed to switch from each product another, and the results were recorded in the table below. This table will be then imported into extendsim software to create a database for the changeovers occurring on the production line.

Table 4-2: Changeover matrix

	Changeover time (minutes)			
Product	**1**	**2**	**3**	**4**
1	0	92	95	90
2	125	0	115	110
3	110	120	0	115
4	130	135	145	0

4.5 SIMULATION MODEL

After developing a conceptual model and all necessary input parameters were collected and analysed, a software model was structured and created on the extendsim pro simulation software, as the project was submitted to extendsim and a grant was permitted to conduct work on the software. A base model was created using the data collected previously and the model was run for a year for a first-step verification and validation process. Figure 4-2 shows the base model that was created.

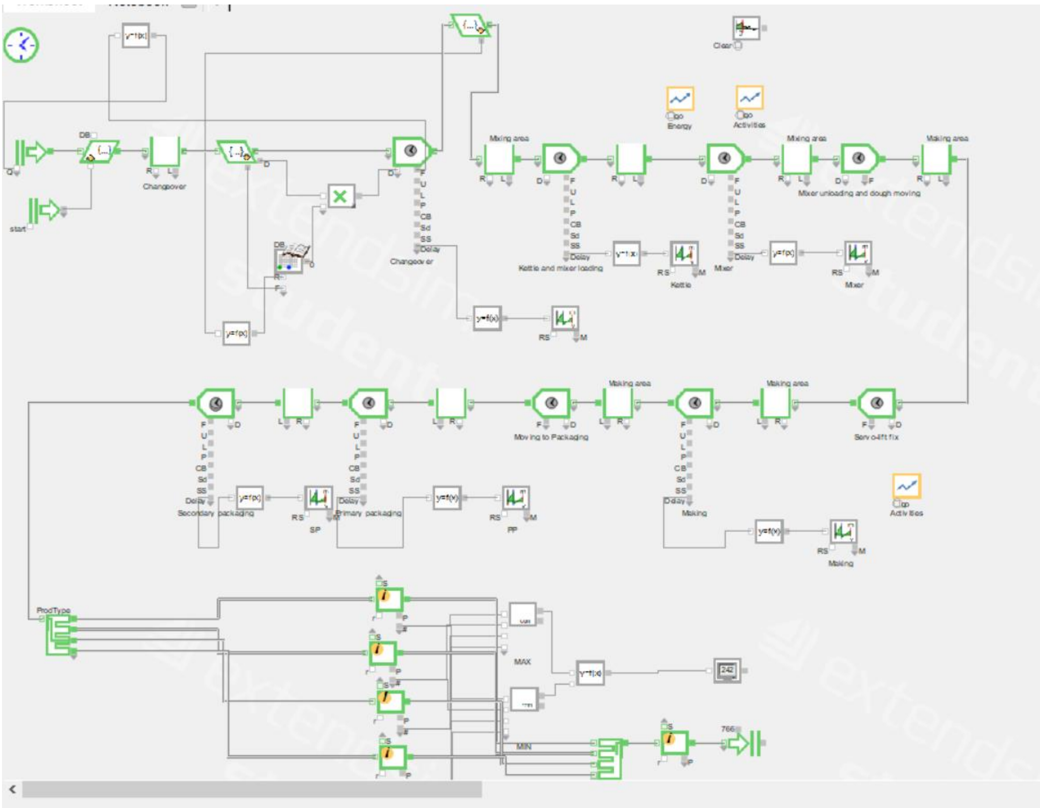


Figure 4-2: Base Model

The model was run for 345600 minutes for a first run. The changeover process was verified after running the model, as it matched with the logical flow chart constructed in the conceptual model. Whenever a change of product was detected, the changeover activity block activated, and the arrival of new products was stopped, until the changeover process was done. Another response was partially validated, as the run average cycle time was 200 minutes, where the actual cycle time was 185 minutes on average. Verification and validation will be done continuously on the model during different test runs and different scenarios. The capacity constraint was tested by reducing the arrival rates of products and a bottleneck appeared in the secondary packaging activity, as expected, when the production capacity was exceeded.

4.5.1 User Documentation

A well-defined user documentation is an important step in developing a simulation model and so in this section the model will be broken down to several groups, where all the processes, features and blocks that were used in the model will be thoroughly explained.

Process flow

- Create block, products are implemented randomly time between arrivals (TBA) using one random distribution, moreover the time unit is in minutes and the distribution for (TBA) is normal, as the data that was collected and submitted to statfit has given the results for normal distribution (30, 0.85) for mean and Std Dev, respectively.

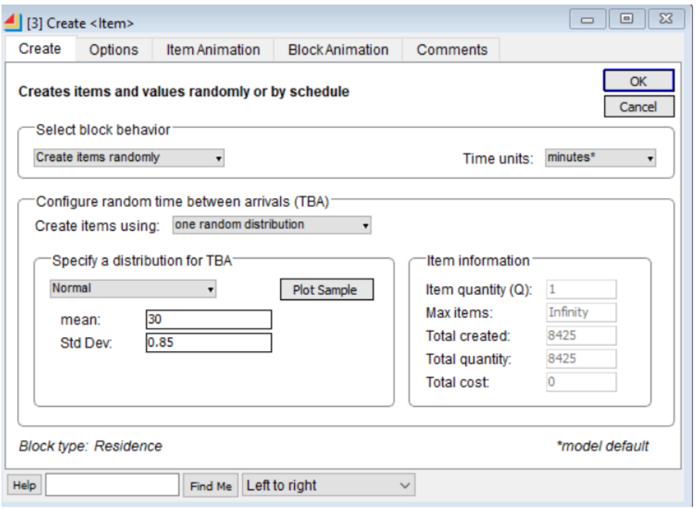


Figure 4-3: Arrivals block

- Queue block, where the products are sorted as, first in, first out and wait for the next activity to be ready
- Activity block this block represents the different processes on the production line. If the activity time is specified by distribution, the most fitting distribution is chosen. For example, the making operation's activity time is normally distributed with a mean and st.dev of 24.5 and 0.82 respectively. These data are entered in the activity block. Number of machines is also specified in this block.

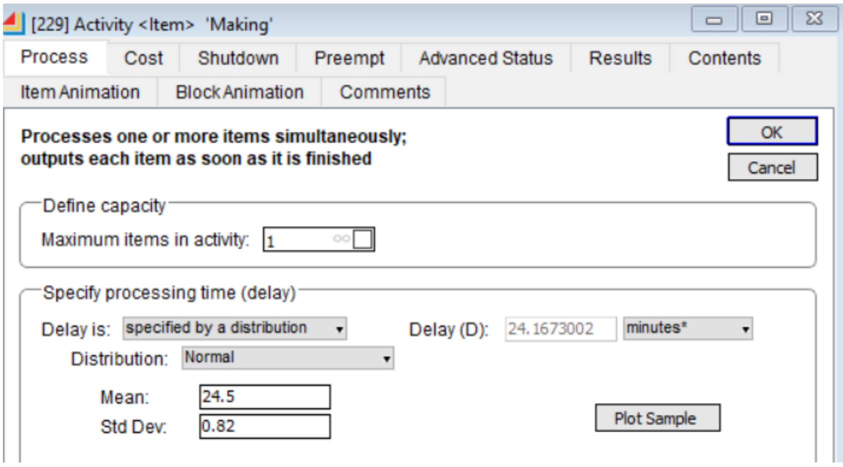


Figure 4-4: Activity Block.

- Equation block; this block is connected with the activity as it is used for calculating the energy consumption of the activity block using equation formula. The block is connected to the delay of the activity block, multiplying this delay (activity time in hours) by the energy consumed on this machine per hour.

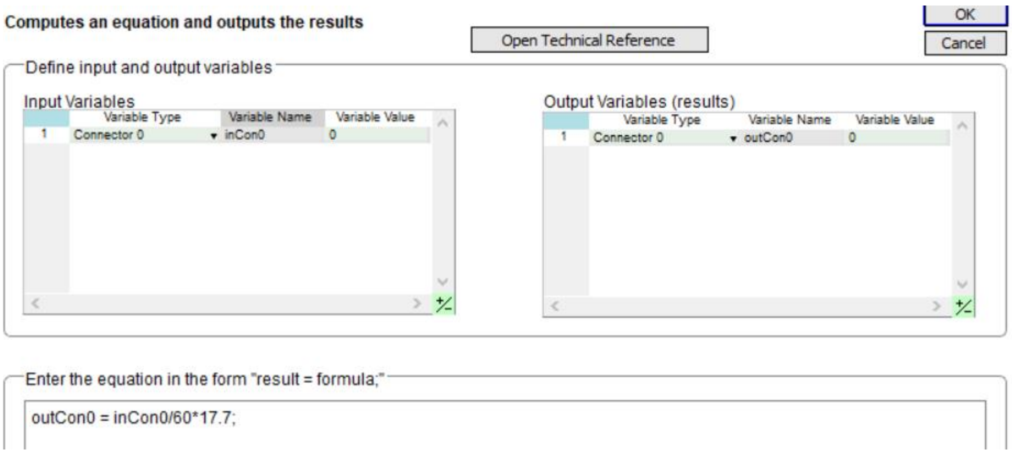


Figure 4-5: Equation block for energy consumption calculations.

- Mean and variance block; the results of the equation block is shown in this block, recording the energy consumed for each batch and the mean of the results gathered.

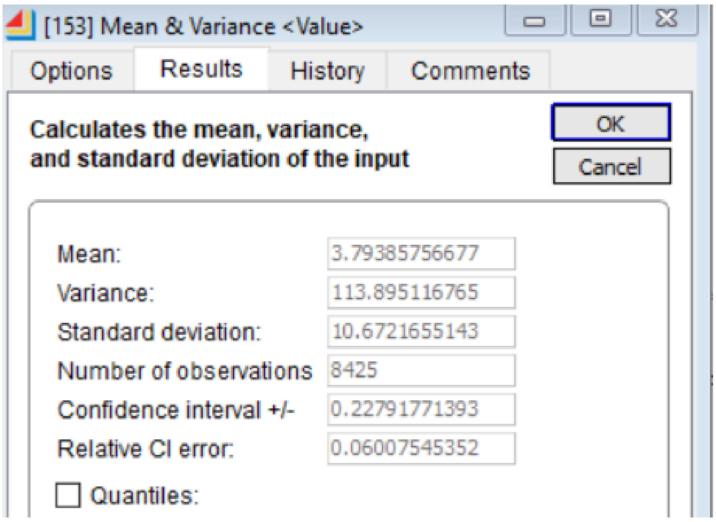


Figure 4-6: Mean and Variance Block.

The Changeover Process

The changeover process; in manufacturing, changeover is the process of converting a line or machine from running one product to another. In order to switch from one product type to another, the worker needs to stop the machine and set it up for the next product type. To realistically represent the changeover process on the simulation model, a number of complex blocks were used to mimic the real-life process.

- First, the create block contains the scheduling of the four products that the line produce using create values by scheduling. Next, building the database for the changeover times is one of the main steps that in building up the simulation model. There are four products; each product takes certain time to switch from one product to another. For instance, to switch from product one to product two it takes 125 minutes, while switching from product two to product one takes 92 minutes.
- A set block was needed in order to define the new value attribute, which is the product type. Then, a read block was needed to define the database which was created. This read block can determine if there is any changeover between products. It also gets its values from two other blocks, the Get Blocks. These blocks detect if there was a change in the product type between each batch. If there is a change, the read block catches the value, and gets the corresponding changeover time value from the database table. To define the changeover time in the activity block, multiply the value received from the database table is multiplied by the delta out connector, which is either zero or one.

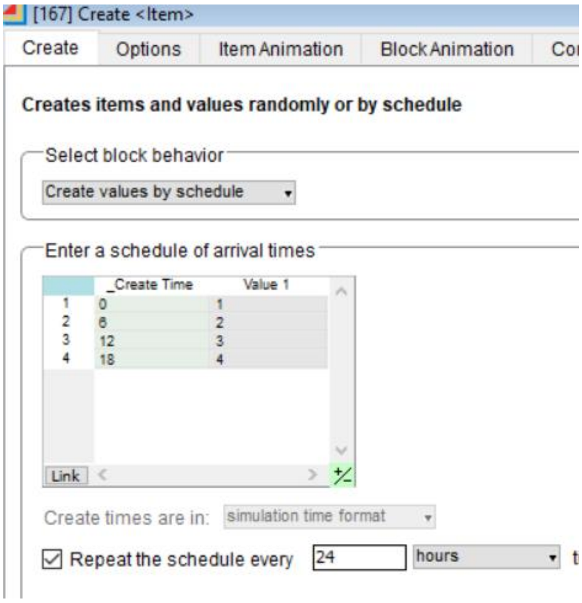
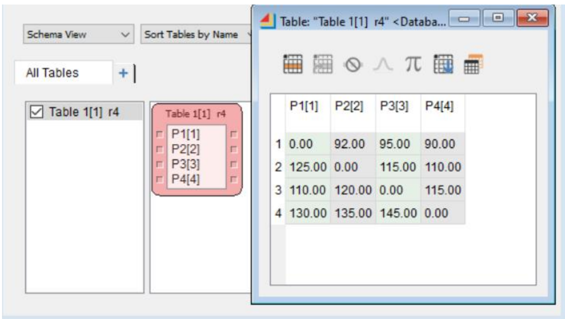


Figure 4-7: Changeover schedule



	P1[1]	P2[2]	P3[3]	P4[4]
1	0.00	92.00	95.00	90.00
2	125.00	0.00	115.00	110.00
3	110.00	120.00	0.00	115.00
4	130.00	135.00	145.00	0.00

Figure 4-8: Changeover Database

- Finally, an If Function is written using the equation block. If there is no value in the get block, this IF function assumes that the first value is product type one, otherwise the Extendsim will report an error. This IF function is needed for the first observation in each run, where there is no previous entries to the model. A Mean and Variance Block is added to show when the changeover occur and the time taken for each changeover cycle.

Results, Analysis, and Reporting

Results, analysis and reporting; after entering all the inputs and experimental factors into the model, the main responses of the model, which are the throughput, cycle time, energy consumption and production mix, must be collected, analysed and reported.

- Once a batch goes through the last operation, which is the secondary packaging, it is now ready to exit the system. Before exiting the system, the batches were separated according to product type using a select items out block. This step was done to inspect the number of batches produced from each of the four product types. Four connectors are released from the select item out block, with each representing a product type. Each connector is then connected to an information block, which reports the cycle time and throughput of the product type.
- Now that there are four information blocks reporting the production of the different products, a maximum and minimum blocks are connected to the information blocks to detect the most and least produced product. An equation block calculate the difference between these two values, and the range result is displayed. This range is a crucial response, as it indicates the production balance and the deviation in the production mix. Any range below 20 is acceptable. The last step is regrouping all the batches together by a select items in block, and an information block is added to show the total throughput and cycle time of the production line. Line chart are plotted for all the performance measures. These charts aids in monitoring the changes and variabilities in the response, and also to determine the warm-up period and simulation run time needed for the model.
- Report blocks are also needed in the simulation model, as all the energy consumption data from all processes can be collected and shown in a single report.

Initial Run Setup

Initial run setup; initializing a simulation model means determining the run length, number of replications and the warm-up period. The simulation run time and number of replications are added from the simulation setup tab found in the "Run" menu. A clear statistics block is added to the model, where the warm-up period can be determined. Discussions of the deciding on these factors are discussed in section 4.6.

Testing Multiple Scenarios

Testing multiple scenarios; testing different changeover schedules each with hundreds of different scenarios won't be applicable to be done manually. The scenario manager block solves this problem, as many scenarios are developed based on the input schedule and different sequences are generated automatically. To generate scenarios, factors (model inputs) and responses (model results) are defined and added to the scenario manager block. In this case, the factors will be the schedules of the changeover; the number of changeovers (slots) and the time between changeovers. Scenarios are then created based on these factors, and hundreds of scenarios of different sequences are generated. The model is run, and results for the specified responses are displayed for each scenario tested. Results are then exported to an excel spreadsheet and the results are analysed.

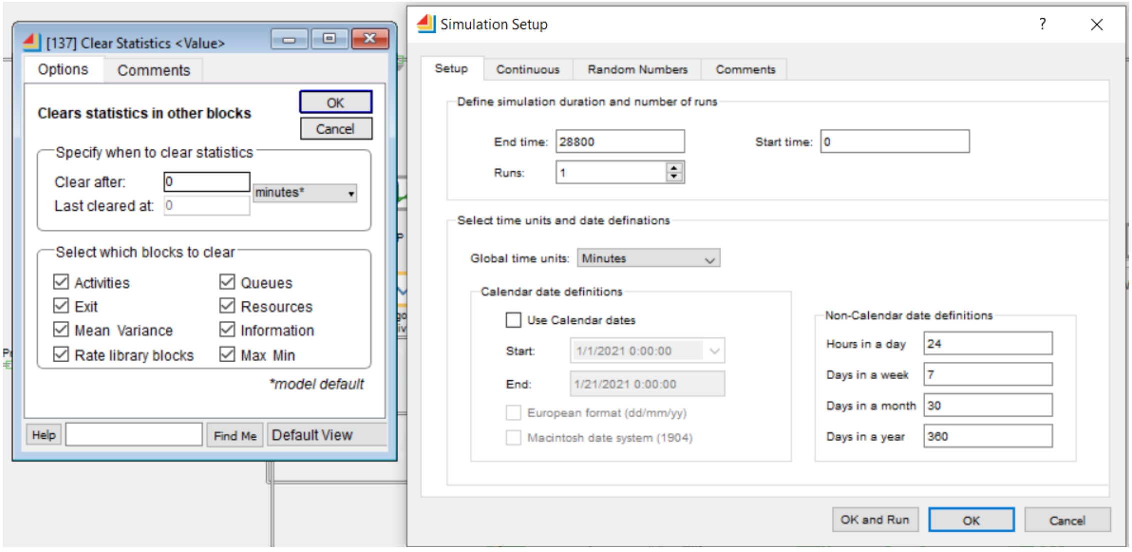


Figure 4-9: Simulation setup.

Chapter Five

5 EXPERIMENTAL DESIGN

To make sure that the simulation model is feeding accurate results, an initialization process must take place before the first rum. The simulation model developed is considered to be a non-terminating, where there is no natural end point for the run, and a simulation run time should be decided upon. Given that the model is a non-terminating model, the output reaches a steady-state, where the output is varying according to a specific distribution. Before reaching that steady state, huge variations occurs at the start of any run and need to be eliminated to ensure that the model is in steady state. The key is determining how long should be the warm-up period be so that the initial transient has passed. The last thing that needs to be known before starting a run is the number of replications to be done that would results in better estimates of the mean performance.

5.1 SIMULATION SETUP

5.1.1 Warm-up Period

Determining the warm-up period of the model is very important when initializing the model and deciding on how long that period should be is the key question. The decision on the period length depends on inspecting the behaviour of the responses in a graphical representation. Multiple runs are needed to smoothen the time-series output and any noise in the data will be removed. To determine the warm up period, the point where the output data appears to be settling into steady state should be identified. Before this point, the model may be running in a way that doesn't mimic the real life, with very high variations in output data. After the warp-up period, the output data should follow a specific trend or distribution, with no sudden rises and falls in the trend.

The simulation run should be much longer than the anticipated to make sure that the output data settled into steady state after the warm up period. On this project, there is more than one crucial response, the energy consumption, cycle time and the throughput, which needs some data clearing. In this case, a time-series for the output data for both responses are inspected, and the warm-up period is determined based on the response that took longer to settle.

The model was run 5 times for 345600 minutes, and the time series output for the three responses are shown below. Figure 5-1 shows the plotting of throughput output data along the runs. A warm-up period of about 18000 minutes is needed before the data is settled.

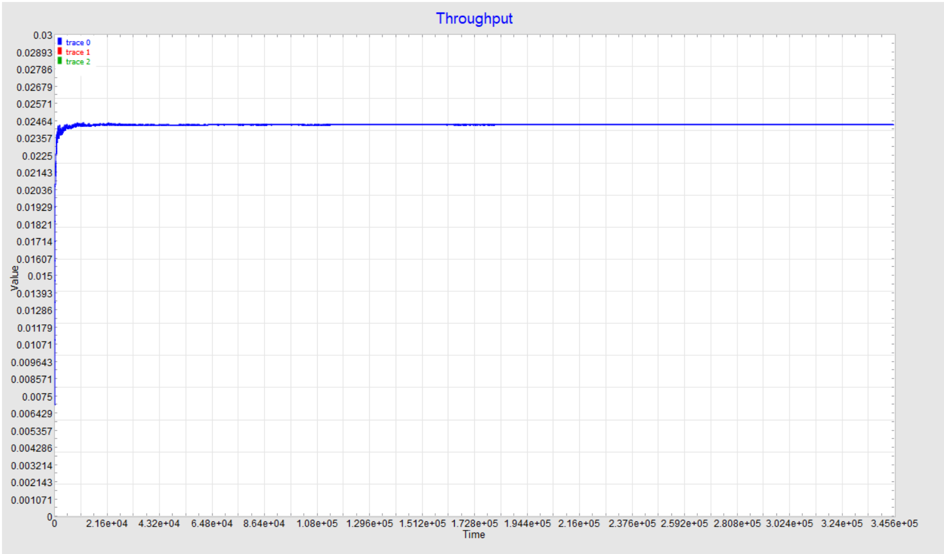


Figure 5-1: Time-series for throughput

For Figure 5-2, the cycle time data needed 25000 minutes before it settled into steady state, which is longer than what the throughput data needed

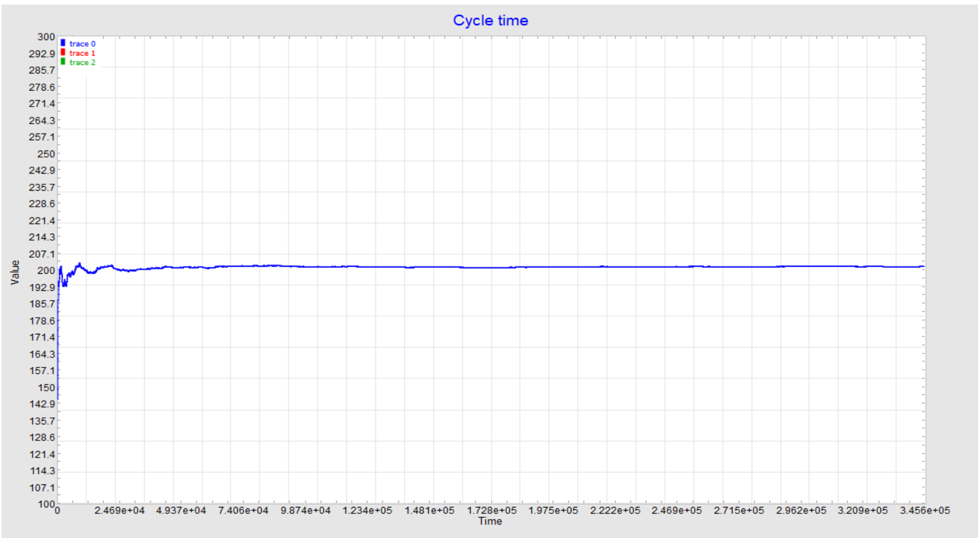


Figure 5-2: Time-series for cycle time

When inspecting figure 5-3, the energy consumption output data took around 40000 minutes before no upwards or downwards trends where observed.

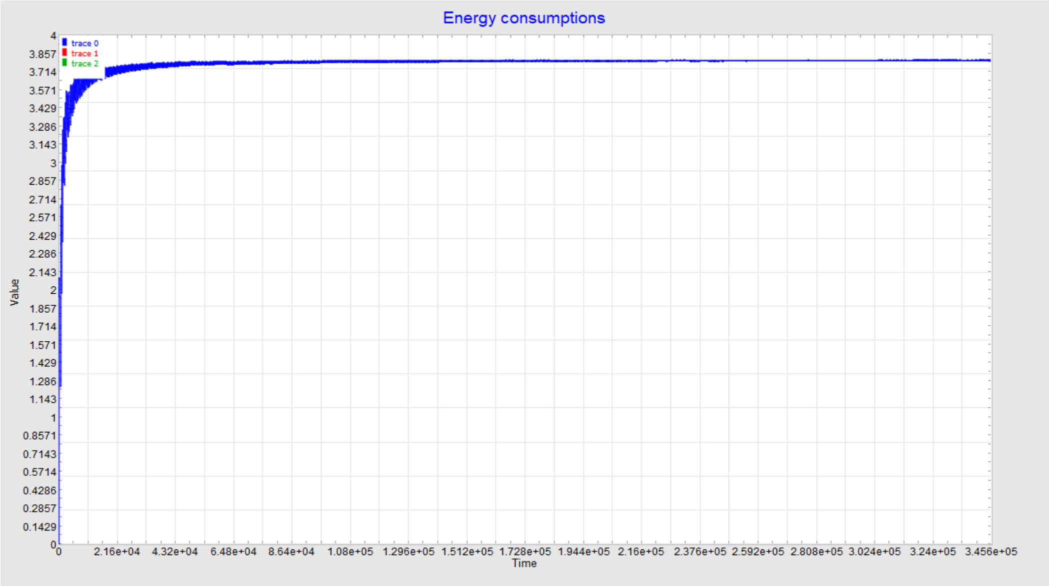


Figure 5-3: Time-series for energy consumption

After analysing the three response outputs time series, it was determined that a warm-up period of about 39000 minutes is needed, and that all data before that period is neglected. The warm-up period should be continuously monitored throughout different experiments.

5.1.2 Simulation Run Time and Number of Replications

A suitable run time and number of replications needs to be decided on with care, to make sure the output data collected is sufficient enough to yield accurate results. A single long run, multiple replications or a mix of both can be performed to ensure the model performance measured is accurate and represents the real life model. To determine the number of replications needed, multiple methods can be used to determine the appropriate number of replications, whether by a graphical method or the confidence interval method.

The confidence interval method is a statistical method that shows how accurately the mean average of a value is being estimated, where the narrower the interval, the more accurate the estimate is deemed to be. A confidence interval of 95% is used and 20 runs were simulated with the warm up period of 39000 minutes that was decided upon earlier. The variations in the cycle time were not big, and figure 5-4 shows the plot of the cumulative mean. After analysing the plotting of the cumulative mean with confidence level of 95%, the output data interval started to narrow after 9 runs and that indicates the least number of runs needed for the more accurate and reliable data.

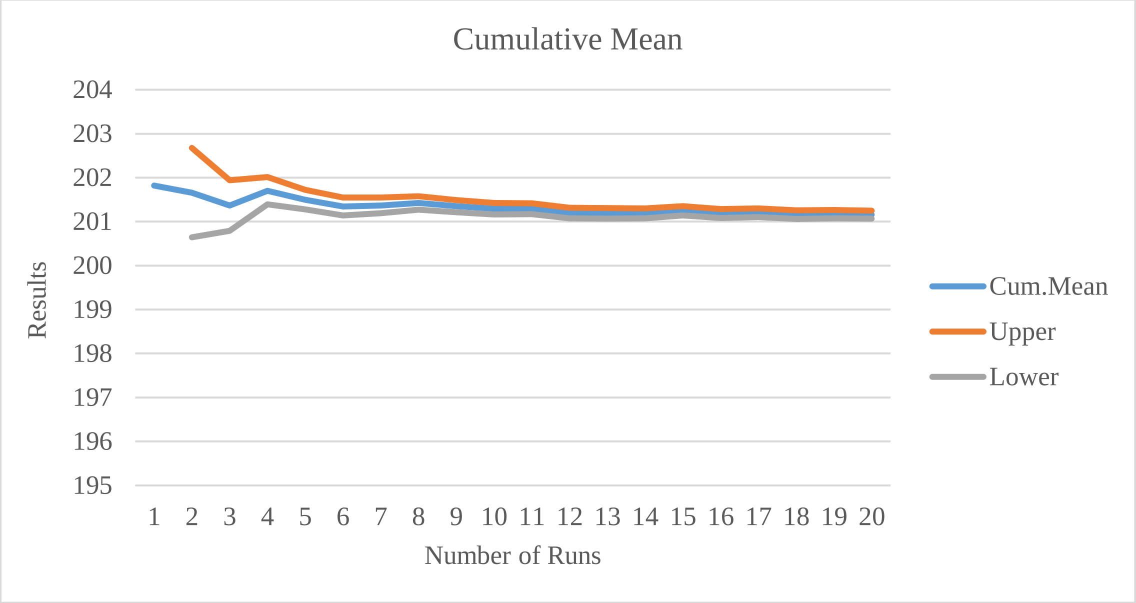


Figure 5-4: Cumulative mean plot

5.1.3 Experiments and Runs

Earlier, the base model was developed and run, and the results were analysed, verified and partially validated. Now after setting the warm-up period, run length and the number of replications, a number of different experiments will be developed and tested. Each experiment will have a different changeover schedule that will be run using the scenario manager block, and a solution space for all feasible combinations and scenarios will be analysed.

For the base scenario, six changeovers were scheduled each day, where every product gets 4 hours of production every 24 hours (excluding changeover times). Four different schedules were then tested, where the schedule period was varied, and the number of changeovers were changed. For each experiment, a minimum of 500 feasible scenarios were generated, and the most suitable scenario was identified. The results of each scenario from each experiment were exported to a spreadsheet and the responses outputs were analysed. Alternative solutions from each schedule were then compared, looking for the least energy-consuming scenario that satisfies all the constraints. After generating the scenarios for each experiment, these scenarios are exported to a spreadsheet and filtered. Any production scenario that lacked one of the four products was excluded, where each product type must be included in the plan at least once. This helped narrow down the solution space to feasible solutions. The filtered scenarios are then imported into the scenario manager again and tested.

5.2 RESULTS

5.2.1 Base Model

For the base scenario, six changeovers were performed during a 24 hour period. For this changeover schedule, there was 4096 different combination of production sequences. A balanced production mix must be achieved on the production line, and thus eliminating any scenarios neglecting any of the four products in the production plan, resulting in only 1560 scenarios where all four products are produced. These 1560 scenarios where run and tested, and the results of the specified performance measures were analysed. Given that the main priority is the electrical consumption during changeovers, the scenario with the lowest energy consumption was selected and tested once again. Results showed that the throughput of this scenario was on average 710 batches/month, which is less than the demand needed.

The production mix was not balanced, as product 2 is produced twice as many as any other product type. The energy consumption for this current scenario was 3.67 Kw.hr, and the total changeover time was around 11430 minutes per month. A new changeover schedule was needed to improve the throughput and also minimize both the energy consumption and the total time spent on changeovers. Table 5-1 shows a spreadsheet with the best changeover sequences and the data of the four responses. None of the scenarios satisfies the demand nor the production balance needed

Table 5-1: Base model results for different scenarios

Row#	Scenarios	Time-0	Time-4	Time-8	Time-12	Time-16	Time-20	Energy Consumption	Range	CT	Throughput
323	Scenario 0875	1	4	2	3	3	3	3.6525766	331	240.34684	710
389	Scenario 1015	1	4	4	4	2	3	3.6679021	354	221.63124	710
376	Scenario 0983	1	4	4	2	2	3	3.6730392	172	211.88827	708
49	Scenario 0219	1	1	4	2	3	3	3.6730392	182	216.11306	707
46	Scenario 0215	1	1	4	2	2	3	3.6781907	169	209.97453	708
59	Scenario 0247	1	1	4	4	2	3	3.6781907	189	218.54825	708
310	Scenario 0859	1	4	2	2	3	3	3.6833567	148	211.48137	705
5	Scenario 0055	1	1	1	4	2	3	3.6885373	344	233.66768	706
379	Scenario 0987	1	4	4	2	3	3	3.6885373	186	208.06518	704
307	Scenario 0855	1	4	2	2	2	3	3.7041667	302	222.96008	703
81	Scenario 0348	1	2	2	2	3	4	3.7072638	342	224.71035	704
1528	Scenario 3937	4	4	2	3	1	1	3.7081006	197	213.02295	709
1002	Scenario 2574	3	3	1	1	4	2	3.7102241	182	229.06046	710
616	Scenario 1668	2	3	3	1	1	4	3.7111166	177	221.51788	707
47	Scenario 0217	1	1	4	2	3	1	3.7132867	334	234.28488	710
521	Scenario 1380	2	2	2	3	1	4	3.7163361	301	219.63678	705
597	Scenario 1600	2	3	1	4	4	4	3.7163361	335	224.59778	702
9	Scenario 0092	1	1	2	2	3	4	3.7177511	169	206.40518	702
17	Scenario 0112	1	1	2	3	4	4	3.7177511	153	205.27003	700
1336	Scenario 3457	4	2	3	1	1	1	3.7184874	329	235.47596	706
798	Scenario 2110	3	1	1	4	4	2	3.7206461	193	217.33708	707
534	Scenario 1444	2	2	3	3	1	4	3.7215704	158	209.69192	705
525	Scenario 1412	2	2	3	1	1	4	3.7215704	160	215.60125	705
567	Scenario 1552	2	3	1	1	4	4	3.7215704	175	214.7694	704
1	Scenario 0028	1	1	1	2	3	4	3.723017	311	216.86683	701
113	Scenario 0428	1	2	3	3	3	4	3.723017	337	229.69771	701
13	Scenario 0108	1	1	2	3	3	4	3.723017	164	211.18769	700

5.2.2 Second Experiment

Results of the previous trial showed that less number of changeovers is needed in order to improve the energy consumptions and balance the production mix. For this trial, a new changeover schedule was proposed where only four changeovers occur every 24 hours, rather than 6, and see how the results will differ. For this trial, there was a total of 256 scenarios, with only 24 with an acceptable production mix. After running the 24 scenarios, a balanced production mix is achieved, but no other performance measures were improved and this trial yielded the same results as the previous one in most performance measures.

Table 5-2 shows that a changeover sequence of 1-2-3-4 achieved an acceptable range, 14, which indicates that all products were produced equally. The total time spent in changeovers and the number of changeovers decreased by nearly 22% and 26% respectively. No bottlenecks were created as the capacity of the line was not exceeded, however the monthly throughput was lower than the expected demand. The average energy consumed during changeover in a month was not affected.

Table 5-2: Second experiment results

1	Row#	Scenario	Time-0	Time-8	Time-16	Time-24	Energy Consumptiom	Range	CT	Throughput
2	55	Scenario 055	1	4	2	3	3.6833567	30	204.4976	705
3	142	Scenario 142	3	1	4	2	3.725879	34	201.8571	705
4	28	Scenario 028	1	2	3	4	3.7282979	14	200.8946	699
5	217	Scenario 217	4	2	3	1	3.7289326	33	205.7062	705
6	100	Scenario 100	2	3	1	4	3.7320833	19	204.9314	701
7	199	Scenario 199	4	1	2	3	3.7829659	19	202.1442	697
8	109	Scenario 109	2	3	4	1	3.7880682	33	202.4208	698
9	31	Scenario 031	1	2	4	3	3.7892603	29	199.9636	697
10	178	Scenario 178	3	4	1	2	3.7904558	22	198.2377	696
11	40	Scenario 040	1	3	2	4	3.8074101	17	195.0376	689
12	136	Scenario 136	3	1	2	4	3.8144381	19	201.6802	697
13	226	Scenario 226	4	3	1	2	3.8161702	21	204.6901	699
14	121	Scenario 121	2	4	3	1	3.8408832	22	200.8295	697
15	157	Scenario 157	3	2	4	1	3.8681556	27	203.0535	688
16	115	Scenario 115	2	4	1	3	3.8786087	16	197.7946	685
17	202	Scenario 202	4	1	3	2	3.882029	21	195.4255	684
18	46	Scenario 046	1	3	4	2	3.9943431	26	196.777	679
19	76	Scenario 076	2	1	3	4	4.0473827	23	196.3392	676
20	211	Scenario 211	4	2	1	3	4.0551686	21	196.2293	676
21	181	Scenario 181	3	4	2	1	4.0600293	27	198.5576	678
22	58	Scenario 058	1	4	3	2	4.104442	28	199.206	676
23	148	Scenario 148	3	2	1	4	4.1308651	26	200.1885	677
24	79	Scenario 079	2	1	4	3	4.1403812	37	200.0902	676
25	229	Scenario 229	4	3	2	1	4.1647059	39	199.4077	674

5.2.3 Third Experiment

A different approach was taken in this trial, where six changeovers were done over 32 hours rather than 24 hours. This was done in order to reach the required throughput. 1560 scenarios were run and the results showed a 30% decrease in the energy consumption to 2.51 kW.Hr and also a 25% decrease in total changeover time during a month, compared to the base scenario. A throughput of 771 batch/month was achieved which satisfy the demand, and the production mix was balanced.

5.2.4 Fourth experiment

Although the previous trial lowered the energy consumption by 25% while satisfying all constraints, another experiment was done to lower the energy consumption even more. 4 changeovers were scheduled every 32 hours in this trial. Results showed no change to the different trial, where the total changeover time was only reduced by 0.3%.

5.2.5 Fifth Experiment

A final experiment was done, where the schedule was expanded upon 48 hours rather than 32 hours. All performance measures improved dramatically, where the energy consumption was reduced by 40% compared to the fourth trial, and 60% compared to the base model. The cycle time, however increased dramatically due to the bottleneck that occurred in the primary packaging activity. This bottleneck occurred as the throughput rate exceeded the capacity of the production line. The bottleneck can be shown in table where the utilization of the primary packaging was 100%, as the line capacity was exceeded.

Table 5-3: Machines Utilization

Activity	Arrivals	Departures	Utilization
Kettle and mixer	9982	9982	46%
Mixer	9982	9981	42%
Mixer unloading	9981	9981	14%
Changeover	9982	9982	16%
Servo-lift fix	9981	9981	9%
Making	9981	9980	71%
Moving to Packaging	9980	9980	14%
Primary packaging	9428	9427	100%
Secondary packaging	9427	9426	59%

5.2.6 Sixth Experiment

After the conducting tests on five experiments, a sixth experiment was made to improve on the fifth experiment. The problem in experiment five was that a bottleneck rose when the capacity of the line was exceeded. The speed-scaling strategy is implemented on the previous scenario, where the processing time of the primary packaging process will be reduced by 10%, which means increasing the machine speed and thus increasing energy consumption.

Due to lack of sufficient data regarding the relationship between machine speed and energy consumption on the machine found on the production line, an assumption was made based on previous work that was reviewed that the relationship is exponential, and the energy consumption will increase by 7%. After adjusting the machine speeds, the total energy cost of the line increased by only 0.5%, but the throughout increased from 787 batches per month to 830 batches per month, which in turn increases the holding costs. Cycle time was reduced to 192 minutes as the utilization of the production line was increased by removing any bottlenecks.

5.3 ALTERNATIVE ANALYSIS AND COMPARING

After conducting several experiments and the best scenario from each schedule was chosen, alternative scenarios were compared in order to choose the best, least energy-consuming changeover schedule. Nearly 5000 different scenarios from different experiments were generated and tested, and the best scenario from each experiment was selected, resulting in five alternative scenarios to be evaluated and compared. Tables 5-4 and 5-5 shows the results of the key response from each of the five scenarios, and the total changeover time and energy spent per month.

Table 5-4: Performance measures comparison between different experiments

	Schedule	Mean Energy consumption per changeover	Range	Cycle Time (minutes)	Throughput (batches/month)
Experiment 1	6 slots 24 hrs	3.67	172	211.9	708
Experiment 2	4 slots 24 hrs	3.68	30	204.5	705
Experiment 3	4 slots 32 hrs	2.54	18	223.2	766
Experiment 4	6 slots 32 hrs	2.52	20	234.5	761
Experiment 5	4 slots 48 hrs	1.55	19	929.4	787
Experiment 6	4 slots 48 hrs	1.55	19	192	830

Table 5-5: Total changeover time and energy consumption in different experiments

	Schedule	Total Changeover time (mins)	Total changeover energy (Kwh/month)	Number of changeovers
Experiment 1	6 slots 24 hrs	11430	2622.55	79
Experiment 2	4 slots 24 hrs	8890	2548.8	77
Experiment 3	4 slots 32 hrs	6615	1951	59
Experiment 4	6 slots 32 hrs	6640	1958.8	59
Experiment 5	4 slots 48 hrs	4390	1295.05	39
Experiment 6	4 slots 48 hrs	4390	1295	39

To properly compare between all alternatives, graphical charts were illustrated to present the output of each key response in each of the five experiments. Figure 5-5 compares the energy consumed per month and the total time spent in changeovers. As expected, the total changeover energy consumed decreases as the schedules were improved and the total changeover time decreased. Based on these data, experiment 5 where 4 changeovers were done every 48 hours is the most energy-efficient schedule, where energy consumption decreased by 60% compared to experiment. However, this is a multi-objective problem, with three key responses that all need to be satisfied within the constraints.

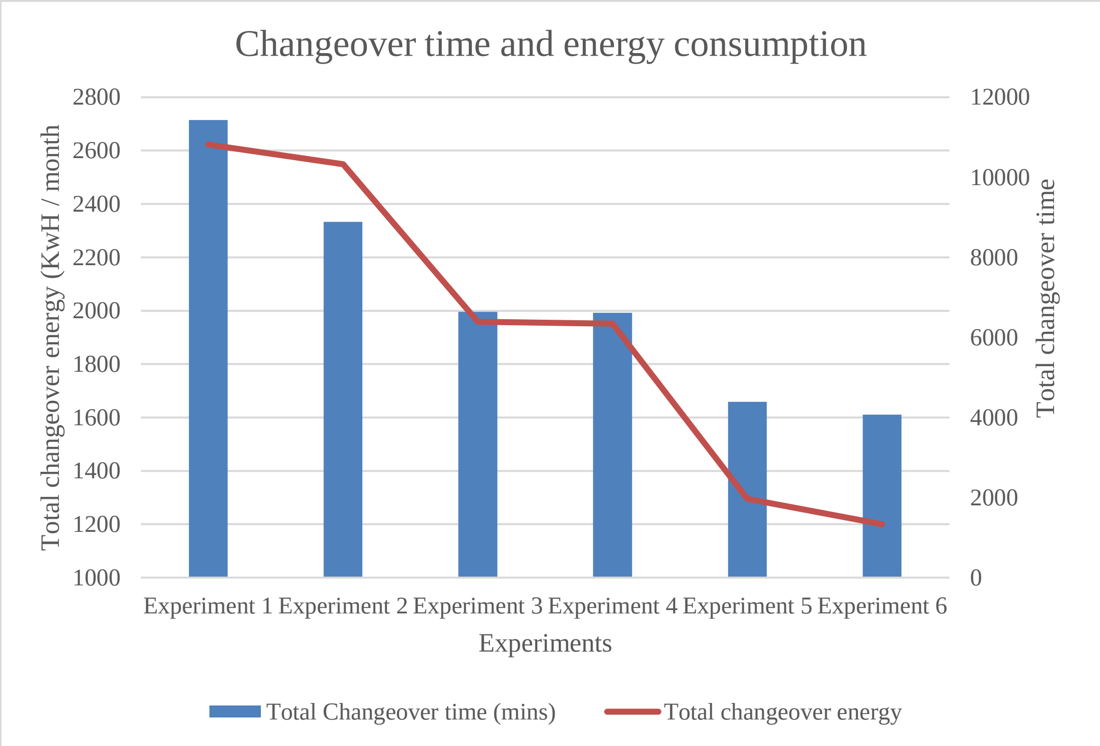


Figure 5-5: Energy comparison.

When comparing the scenarios based on Cycle time, as shown in figure 5-6, it is clear that experiment 5 had a very high cycle time compared to all other experiments in which the cycle time was relatively close to the real world. This spike in cycle time was due to overproduction, where the line did not have the capacity to produce. Based on these two responses, Experiment 5 is infeasible in current circumstances.

For the throughput data, the throughput efficiency was calculated for each scenario. Given that the demand per month is 747 batches, the following equation is used to calculate the throughput efficiency;$Throughput\ efficiency = \frac{Throughout}{Demand}$. The ideal situation is that the throughput efficiency close to 1. If the throughput efficiency is greater than 1, it is an indication of overproduction, which is not favoured in current circumstances. A maximum of 2.5% overproduction is allowed. Figure 5-7 shows the throughput for the different scenarios, where two scenarios, 1 and 2, did not meet the required throughput, while scenario 5 exceeded the demand needed, having an efficiency of 105%. Scenario 3 and 4 both met the demand required, having a throughput efficiency of 101%. Scenario 6 yielded 11% throughput efficiency, due to the increase in the line capacity.

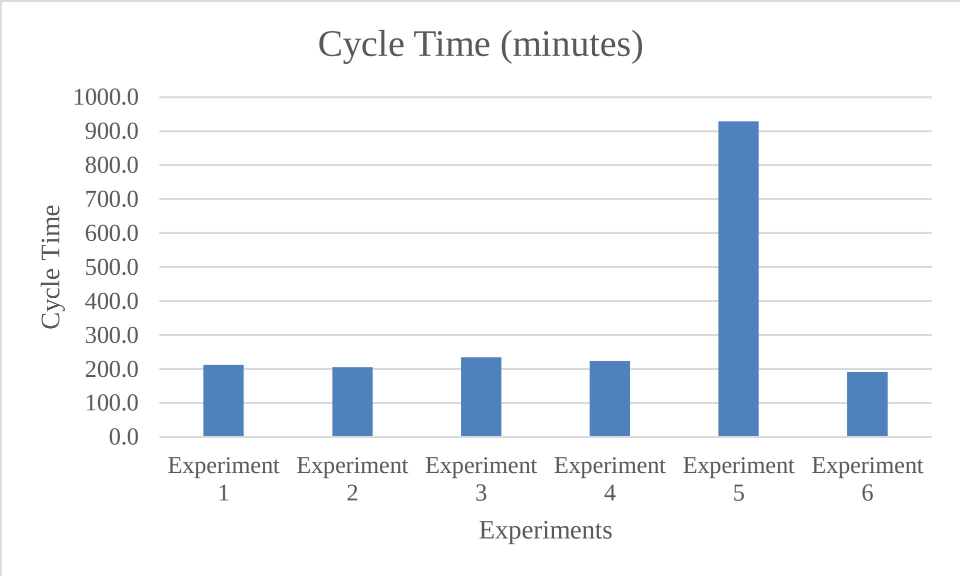


Figure 5-6: Cycle Time comparison between different experiments.

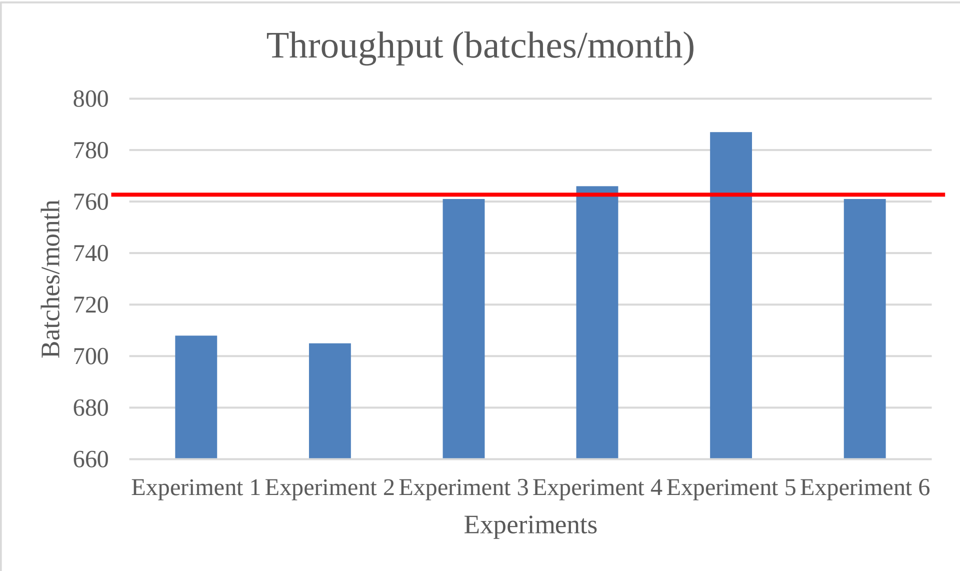


Figure 5-7: Throughput comparison between different experiments

For the final response, production balance needed to be checked to make sure that all products were produced equally. The difference between the most and least produced product in a month should not exceed 20, in order to maintain a balanced product mix. The base model and the second experiment should be excluded from comparison, as they did not meet the required criterion.

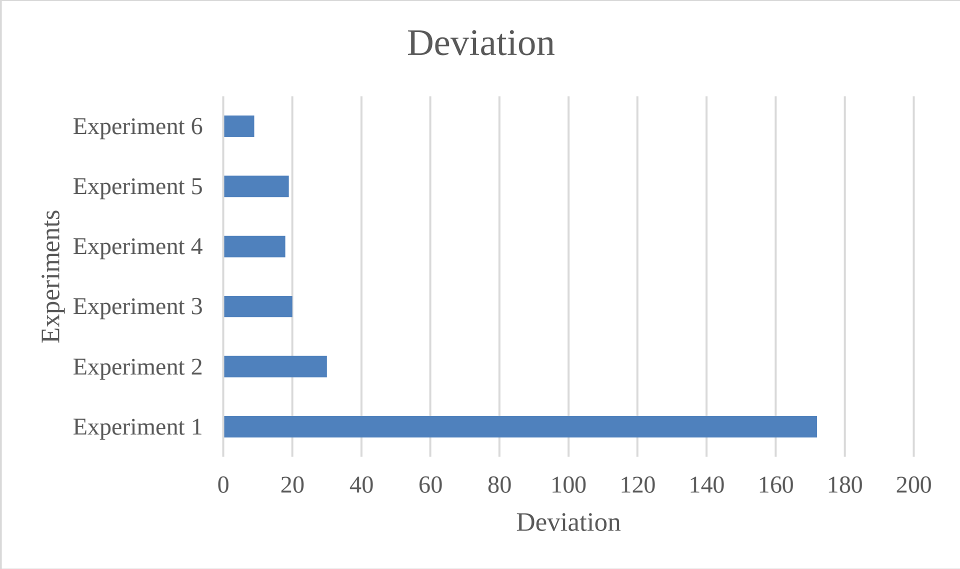


Figure 5-8: Production Mix

After analysing the results of five scenarios and all the corresponding key responses, Scenario 3 yielded the lowest energy consumption while maintaining the cycle time, fulfilling the demand and meeting the production balance required without changing the machines' speed. Table 5-6 shows the schedule that yielded the mentioned results.

Table 5-6 : Chosen Alternative

Schedule	1-4-2-3 repeated every 32 hours
Total changeover time	6615 minutes
Total changeover energy consumption	1951 kWh/month
Number of changeovers/month	59
Throughput/month	766 batches
Range	18
Cycle time	223.2 minutes
Mean Energy consumption	2.52 kWh
Changeover time reduction	42%
Energy costs saved	9582 EGP
Energy costs reduction	25%

Based on the base model, the total amount of money spent on energy consumed during changeovers is approximately 37450 EGP per year. By performing simulation runs on more than 5000 scenarios, the most suitable scenario saved nearly 10,000 EGP, which is a 25% reduction to the base scenario on changeover energy costs only. This results in a 7% reduction in total production line energy costs. These results fulfil the objective of the simulation model, where energy costs were cut by performing operations scheduling concepts. Besides reducing changeover energy costs by 25%, the total of 960 hours of changeover time have also been reduced, a 42% cut compared to the base model, which is equivalent to 40 production days.

Two approaches could be taken in experiment six, where the company can overproduce and keep high inventory levels, or switch off the production line when the demand orders are met. If the production line is switched off when 102% of the demand is produced, 1.5 working days can be saved every month which reduced the total annual energy cost by an amount of 71,000 EGP, a 7% reduction. Labour costs, holding costs and lighting costs will also be reduced. The total energy costs saved in this scenario is 86,000 EGP, and a total of nearly 7200 minutes of changeover time are reduced.

5.4 VERIFICATION AND VALIDATION

Verification is the process of ensuring that the model design has been transformed into a computer model with sufficient accuracy, while validation is ensuring that the model is sufficiently accurate to the real life model and the purpose at hand. No model can be 100% accuracy, so absolute validity is nearly impossible to achieve, so the aim is to make sure that the model is sufficiently accurate.

When the conceptual model was formed, and the data needed for the simulation study was gather, validation was needed to make sure the concepts, assumptions and the simplifications made to the model were sufficiently accurate. All data gathered for the study was validated by checking the source of the data and make sure these data represent the real world. Now that the concept of the changeover process was validated with the real world, it was translated into a computer model. The computer model needed to be verified in order to make sure that the changeover process is done correctly, only between product changes and the changeover time is read correctly from the database.

This was checked through visual checks by watching the products moving between different activities. The model was run for a year, and the throughput and the cycle time output data from the computer model were compared with the real life average output data. In the base model, the line throughput was 8378 batches/ year and the cycle time was on average 195 minutes, where the expected throughput from the line is 8400 batches/year and 185 minutes of cycle time. This means that the model was partially validated in terms of responses. To verify that the constraints set in the project plan are represented on the line, the arrival rate was reduced so that more products arrive every hour. This extreme change was done to verify that bottlenecks will rise as the capacity of the line was exceeded. Experimentation validation was also done where any initialization bias was removed by determining the warm-up period, run length and replications which assures that the results are as accurate as possible to the real world.

Chapter Six

6 CONCLUSIONS AND FUTURE WORK

Integrating sustainability aspects with operational production scheduling proved to yield significant results. Minimizing energy costs just by scheduling the operations on a production is significant on an environmental level, even more than on economical levels. Finding a suitable changeover schedule can make huge differences on the production level, whether minimizing energy costs, minimizing the number of stops and increasing the production line productivity. Going with the simulation approach lead to the testing of many scenarios in a very short time period, giving more time for result analysis and finding ways to reduce the energy consumption even more, whether by finding a more suitable changeover schedules, or discovering bottlenecks that would not have been discovered by other solution techniques. The speed-scaling strategy proved to have a far more important role than just reducing the energy consumptions on machines by slowing them. Utilizations of production lines can be increased if the position of bottlenecks can be identified and the machine speeds are increased slightly.

Most objectives that were set before the start of the project were achieved within the timescale. Implementation of the project and testing more strategies could not be completed within the timescale due to the COVID-19 crisis, which made visits and more in depth data collection not possible. Further research can be done where different energy-saving strategies can be used and discover the effect they have on the energy consumption and productivity of a production line. It is recommended that more accurate data regarding the effect of different machine speeds on their energy consumption can be collected to measure the full extent of changing machine speeds and how it effects the performance measures of the production line.

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