APPLICATION OF SYSTEMS SIMULATION FOR PREDICTING AND OPTIMIZING ENERGY REQUIREMENTS FOR A HDF MOULDED DOOR SKIN MANUFACTURING PRODUCTION PLANT

in One Volume

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DECLARATION

I hereby declare that the work reported here is my own and that it has not been used to obtain a degree in this University or elsewhere

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Executive Summary

In today's struggling economy, manufacturing companies make a great effort to maintain their competitive advantage. Daily they face challenges of improving efficiency and reducing cost. In order to survive in this rough environment, tough decisions need to be taken. The major challenge that most manufacturing companies face consists in reducing their energy consumption, as this represents one of their major costs. The highly automated production plants are usually equipped with the latest energy monitoring systems which capture the energy consumption throughout the entire company. These systems produce high quantities of data that most of the time is very difficult and costly to analyse. This is the first major challenge companies face. Looking at this data, the plants' engineers can get a rough understanding of where the major energy losses occur and they can come up with solutions. The next tough challenge consists in calculating the return on each project that can be implemented. This requires an in depth analysis that takes time and money to perform. Simulation is one of the technologies that can represent a solution to these problems.

Even though simulation has been used so far in manufacturing facilities for modelling supply chain management, production management and business processes, its applications in managing the energy consumption within manufacturing companies represents a new and innovative research domain. This prompted the research undertaken for the present thesis. The main focus of this research is to analyse production management in a manufacturing facility and correlate it with the energy consumption. The research initially concentrates on different simulation methodologies and their application in the current manufacturing space. Literature relating to the correlation of energy consumption with production management has also been reviewed. This review identified very few previous instances of where simulation tools where used to predict the energy consumption in a manufacturing facility. This research brings a novel approach to investigating the adaptability of industrial simulation processes and tools for modelling the energy consumption with respect to a variable production output. The end result of this process consists in a better understanding of the production system and the energy loses which were incorporated in the simulation model.

The simulation model was validated using real world data collected from Masonite – the case study company. This was closely followed by the creation of different scenarios that were analysed and which predicted a lowering in the energy consumption that could reach over 9%.

Published Work Associated with this Thesis

C M Luminea, D Tormey, '*Simulating Energy Requirements for an MDF Production Plant*', International Conference on Life System Modelling and Simulation & 2010 International Conference on Intelligent Computing for Sustainable Energy and Environment, Wuxi, China, September, 2010

PROLOGUE

The research described in this thesis was directed by a project entitled '*Application of Systems Simulation for Optimising Design and Implementation of Supply Chain Management Processes*' This project was founded by the Strand I program 2008 (Duration September 2008 – September 2010)

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CHAPTER 1: INTRODUCTION

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1.1. INTRODUCTION

The objective of this chapter is to provide an overview of the research that was undertaken for this thesis It initially presents the motivation and rational for undertaking this research The research objectives of this thesis are then outlined in order to provide the reader with a comprehensive understanding of what this study hopes to achieve The research methodology utilised for this study is then presented The chapter concludes with a thesis structure that outlines the content of each chapter

1.2. RESEARCH MOTIVATION AND RATIONAL

Modelling energy consumption with respect to production output is a relatively new and innovative research domain The majority of automated manufacturing plants consume large amounts of energy and they usually rely on sophisticated data management systems which monitor, record and control production resources These solutions are mostly based on real time energy monitoring systems These systems involve the installation of sensors and advanced metering technology to collect the information regarding an organization's energy and resource usage This results in large amounts of data being stored and presented to the user through internal websites or in Excel documents The down side to these systems is that they are not analyzing the data in any way and they are not being able to predict the energy consumption for a specified period of time Unfortunately the majority of engineers within manufacturing plants have neither the time, resources nor skills necessary to analyze and utilise the gathered data to its full extent

The novelty of this research lies in the application of traditional industrial simulation tools for modelling and optimising processing of raw material to include energy consumption for sustainable and cost efficient production in Masonite a High Density Fibre (HDF) moulded doors skin manufacturing plant

The process at Masonite requires large amounts of thermal energy and electricity for the extraction of fibre from wood chip and also for the drying and pressing of fibre Quantifying the energy consumption is important for managing energy supply and controlling production costs To the author's knowledge there is no published material available that is specific to energy demand/consumption models for door skin production However the author was able to source relevant research related to the wood fibre processing for Medium Density Fibreboard (MDF), which involves a similar process to that of door skin production

The author considered the study of Professor Jingge Ling and Professor Shusheng Pang from the years 2006 and 2007 on the modelling of energy demand in an MDF plant, along with the paper published by Carvalho et al (2003) which looked at the hot pressing of MDF

Li and Pang (2007) from the University of Canterbury, developed a computer model to quantify the energy demand in an MDF plant based on the commercial production process from wood chip preparation, refining, fibre drying, mat forming, batch pressing to product finishing The model was validated using plant data which demonstrated it was able to predict energy demand within a discrepancy of -5% to 7% for thermal energy and +/-4% for electricity Li and Pang (2007) state that according to their knowledge '*there has not been any energy demand models published for a commercial MDF plant*'

These studies demonstrate the effective use of simulation in predicting the energy demand and consumption in Medium Density Fiberboard production facilities, by looking at production management This encouraged the author to take the research to the next level and consider industrial simulation software tools for modelling the correlation between energy consumption and production process in Masonite

Given difficult market conditions, Masonite needs to rationalize all associated energy and production costs in order to remain competitive and viable

The primary focus of this project will be to model Masonite's production processes with a view to improving overall production and energy efficiency The manufacturing process of Masonite includes two main production lines and a cut and coat line, which combined, requires 85% of the company's energy needs

Testing and implementing proposed production and energy efficiency scenarios on such line set-ups, can be costly and in most instances just not feasible. Through developing simulation models that are representative of Masonite's actual production processes, the company will be able to conduct research on a wide range of production and energy efficiency scenarios without having to impact on any physical production process By defining and testing multiple production and energy consumption scenarios through the developed simulation models, Masonite's engineers will be better positioned to determine optimal production systems parameters that will be required to gain increased production and energy efficiencies

1.3. RESEARCH OBJECTIVES

From the author's perspective the primary aim of this project is to form an understanding of production management and energy monitoring within a manufacturing plant as well as comprehending simulation techniques that allows the author to research ways of applying simulation in the scope of reducing energy utilisation through production Consequently this research proposes to address the defined problem space in terms of the following primary research objectives

- Cary out comprehensive research in the area of production management and energy consumption, investigating information flows, new technologies and scenarios for management of energy consumption in relation to production output
- Investigate simulation techniques and their increasing role in today's world This involves the presentation of a number of case studies along with the selection of the optimum simulation software for this project together with its description
- Present a case study for Masonite, a large HDF moulded door skins manufacturing facility which includes the company background, data collection and the reason to use simulation
- Develop a simulation model of the production process and the energy consumption that would accurately predict the energy consumption and the production output
- Execute a number of experimental scenarios on the model that would help in identifying and implementing parameters that would be used to optimise and reduce energy utilisation for different production cycle configurations

- Provide recommendations to Masonite, regarding the optimum scenarios, from those which were executed on the simulation model that could be implemented and would result in the best energy savings

1.4. Research Methodology

The research methodology adopted by the author within this study is as follows

- An investigation into production management and energy consumption in Masonite and the correlation between the two This involved study of the company's AutoCad drawings and developing an understanding of PI and eSight, the two production and energy monitoring systems on site Additionally, time was spent with onsite engineers in order to understand Masonite's production process This resulted in a company case study
- A review of computer simulation This focused on understanding the concept of simulation, its advantages and limitations and learning when simulation should be used by reviewing a number of case studies This also involved a review of the different simulation types and software packages that would be favourable for this project
- A literature review of available books and papers that addressed the problem of correlating the energy consumption to the production management by using simulation in a similar manufacturing environment
- Carrying out the simulation project This included the development of the conceptual model, the data collection and analysis, the model coding, the validation of the model, the simulation run, the implementation of scenarios and the analysis of the output results The figure below shows the key stages and processes of a simulation model

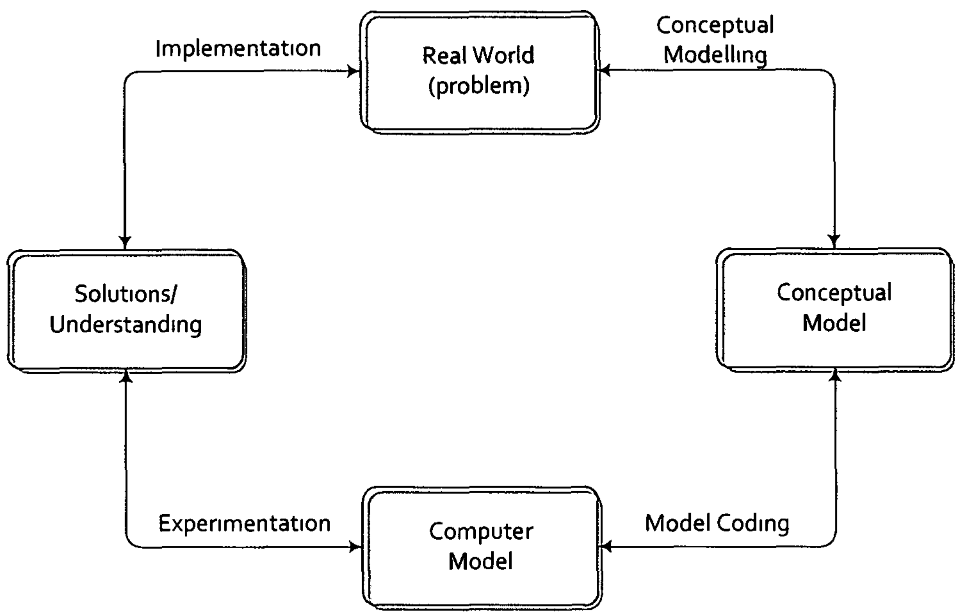

Figure 1.1 The Key Stages and Processes of Simulation Studies (Robinson, 2004)

According to Robinson (2004) "*the boxes are the key stages in a study and represent the important deliverables*"

- **A Conceptual Model** which represents a description of the model to be developed
- **A Computer Model** which represents the simulation model developed on a computer
- **The Solutions and/or Understanding** which comes about as a result of the experimentation
- **An Improvement in the Real World** which will be obtained from the implementation of the solutions and/or understanding gained

Robinson (2004) considers the arrows to be the processes that enable the movement between the four stages,

- **Conceptual Modelling** represents understanding of the problem, determining the modelling objectives, the inputs, the outputs, the model content and collection of and analysis of the data that is required to develop the model
- **Model Coding** which converts the conceptual model into a computer model

- **Experimentation** represents the implementation of scenarios in order to obtain a better understanding of the real world and to find solutions to the real world problems This phase represents a cyclical process that makes changes to the model's inputs, running the model, inspecting the results, learning from the results, making changes to the model, and so on (Figure 1 2)

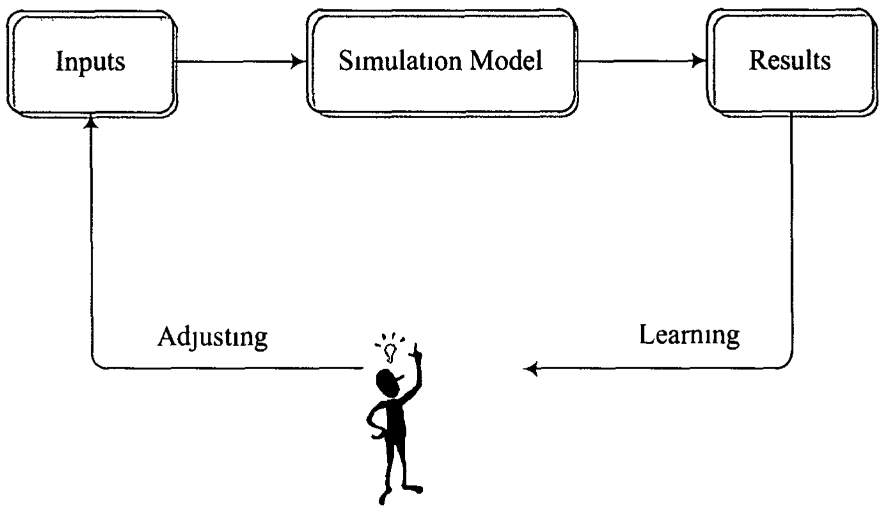

Figure 1.2 The Experimentation stage of Simulation (Robinson, 2004)

- **Implementation** which, according to Robinson (2004) can mean implementing the findings of the simulation model in the real world or implementing the learning which can help in future decision making

1.5. THESIS STRUCTURE

Chapter 1 Introduction This chapter presents the motivation and rational for this research and details the research objectives, methodology and structure

Chapter 2 Simulation This chapter originally concentrates on defining simulation, looking at its advantages and disadvantages and trying to determine the situations in which simulation should be used This theory is supported by a number of case studies The chapter will also describe different types of simulation software and different simulation approaches The last part of the chapter will look at software that can be adapted for energy modelling and will present a case study which demonstrates the efforts that have been made up to date in modelling the energy consumption in an MDF plant The process of choosing the simulation software that would represent the best fit for this project will be described at the end of the chapter followed by some information about the selected software

Chapter 3 Masonite This chapter reviews a short history of Medium Density Fibreboard (MDF) production and a description of the MDF production process which is very similar to door skin manufacturing carried out at Masonite The second part of the chapter looks at Masonite and its production process The two main production lines Line1 and Line 2 along with the Cut and Coat line are further explained in more detail as they are accountable for over 80% of the company's energy consumption

Chapter 4 The Model This chapter presents the simulation model that has been built with the purpose of managing and understanding the correlation between the energy consumption and the production schedule in Masonite In order to better understand the modelling environment the first section of this chapter is dedicated to ProModel The second part of the chapter concentrates on the steps that lead to the development of the final simulation project the conceptual model, the data gathering and analysis, the model coding and the testing of the model The last step is addressed in Chapter 5 as part of the model testing and validation

Chapter 5 Model Testing and Validation This chapter looks at the results obtained from the model, its testing and validation as well as the scenarios implemented The testing and validation section of the chapter will provide a base line This baseline is used in the final part of the chapter which looks at the implementation of six scenarios These scenarios are run a number of times and then the average results from each experiment are compared to the base line In the end the author looks at all six scenarios side by side with the scope of recommending the most efficient one

Chapter 6 Conclusions and Future Work The final chapter begins by summarising the work that was undertaken for this research General conclusions from the research are presented and discussed together with a synopsis of the significant research contributions and findings The chapter concludes by proposing future research in the simulation of energy consumption and production management

A detailed reference section is given at the end of the thesis Appendices are also provided These are as follows

- *Appendix A* presents the differences and similarities between the two simulation software Arena and ProModel
- *Appendix B* shows a schematic diagram of the Motor Control Centres network which monitors all the processes in Masonite
- *Appendix C* includes samples of the Interface xls document A copy of the original document can be found on the accompanying CD
- *Appendix D* contains the algorithm of the implementation of the Production Schedule for Line 1
- *Appendix E* shows the AutoCad plans of the production process for Line1, Line2 and Cut and Coat lines in Masonite
- *Appendix F* presents the correlation graph between production and energy consumption for the Cut and Coat Line

CHAPTER 2: SIMULATION

CONTENTS

2.1. INTRODUCTION

Simulation models have been used for a long time in day to day life. They can be represented by the daily weather forecast which shows us simulations of the weather system and the games that our children are playing which represent simulations of a variety of scenarios and situations; we can even refer to the smaller replica of the Eiffel tower from Las Vegas as being a simulation model of the real Parisian symbol.

This chapter concentrates on the definition of simulation, looking at its advantages, disadvantages and trying to determine the situations in which simulation should be used. Case studies describing the use of simulation in production planning, business process and supply chain management will be presented to support the theory. The chapter also describes different types of simulation software and different simulation approaches.

The last part of the chapter looks at software that can be adapted for energy modelling and will present a case study which demonstrates the efforts that have been made up to date in modelling the energy consumption in an MDF plant.

The process of choosing the simulation software that would represent the best fit for this project is described at the end of the chapter and includes information about the selected software.

2.2. SIMULATION: WHAT, WHY AND WHEN?

2.2.1. WHAT IS SIMULATION?

According to David Goldsman, Richard E. Nance and James R. Wilson (2009), the history of simulation starts in 1777 with the Buffon "needle experiment" which tried to estimate the value of π by throwing needles to a plane with equally spaced parallel lines. The next attempt at simulation was recorded in 1908 when Arthur Guinness allowed William Sealy Gosset to publish certain statistical results connected to the Guinness brewery, under the pseudonym "Student". Gosset used "*a crude form of manual simulation to verify his conjecture about the exact form of the probability* *density function for Student's t-distribution*" In 1945, the construction of the first general – purpose electronic computer sped up the growth of simulation which developed in today's modelling languages

In order to define Simulation most writers start with the concept of a system Schmidt and Taylor (1970) proposed *a system* to be defined as a collection of entities, e g people or machines that act and interact together toward the accomplishment of some logical end In practice a system can have different meanings, depending on the objectives of any particular study

According to Shannon (1975), simulation represents the "*process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behaviour of the system or of evaluating various strategies (within the limits imposed by a criterion or set of criteria) for the operation of the system* "

Checkland (1981) identified four main classes of systems, all of which presenting the capability of being simulated

- *Natural Systems* are systems whose origins lie in the origins of the Universe, like the atom and the Earth's weather system
- *Designed Physical Systems* are physical systems that are a result of human design like a house, a car or a production facility
- *Designed Abstract Systems* are abstract systems that are a result of human design like mathematics and literature
- *Human Activity Systems* are systems of human activity that are consciously or unconsciously ordered, like a family, a city or a political system

This thesis concentrates on the simulation of a manufacturing facility which represents a Designed Physical System There are many cases though, in which two or more classes of systems are joined together One of these cases can be modelling of private or public organisations where the human activity system and the designed physical system are of main concern According to Robinson (2004) these systems can be referred to as *operations systems* or *operating systems*

When defining Simulation a second aspect which should be considered is the *purpose* of simulation models Pidd (1998) identifies the purpose of models to be understanding, changing, managing and controlling reality He also emphasises the need for *simplification* It is almost impossible for a system to be simulated entirely as this would require an excessive amount of time for data collection, data analysis and for modelling every aspect of the system

According to Robinson (2004) there is a fourth aspect in defining simulation He sees simulation as being "*an experimental approach to modelling, that is, a 'what-if' analysis tool*"

Combining these four aspects operations systems, purpose, simplification and experimentation, Robinson (2004) defines Simulation as

"*Experimentation with a simplified imitation (on a computer) of an operations system as it progresses through time for the purpose of better understanding and/or improving that system* "

On another hand, Preston White and Ingalls (2009) start defining simulation, from the concept of a model They see a model as being "*an entity that is used to represent some other entity for some defined purpose*" and to study systems that exist only in concept They consider Simulation to be "*a particular approach to studying models, which is fundamentally experiential or experimental*"

The purpose of this research project is to analyse the production process and scheduling of a manufacturing facility and determine its correlation with the energy consumption which will result in the creation of energy efficient scenarios Based on the literature review and keeping in mind the case of this specific project, the author proposes to define simulation as a computer replication of a real life manufacturing system, with the scope of testing and comparing the data gathered from a series of scenarios In this case, simulation will represent the decision making tool for the implementation of the most energy efficient scenario

2.2.2. Why Simulate?

In Banks' (1998) book "Handbook of Simulation: Principles, Methodology, Advances, Applications and Practice", the contributor Matthew W. Rohrer, enumerates a few of the benefits of using simulation in Manufacturing. These include:

- The high level of automation applied to manufacturing;
- The need for motivation in order for manufacturers to stay competitive;
- The need for testing different trends such just – in – time manufacturing;
- Manufacturing systems are quite well defined;
- The complexity of manufacturing and material handling systems.

Three years later, Fishman (2001) looks at Discrete Event Simulation and identifies the following purposes that a simulation model serves:

- "*Enables an investigator to organise her/his theoretical beliefs and empirical observations about a system and to deduce the logical implications of this organisation*
- *Leads to improved system understanding*
- *Brings into perspective the need for detail and relevance*
- *Expedites the speed with which an analysis can be accomplished*
- *Provides a framework for testing the desirability of system modifications*
- *Is easier to manipulate than the system*
- *Permits control over more sources of variation than direct study of a system allows*
- *Is generally less costly than direct study of the system*".

At a broader level, Robinson (2004) identifies the nature of operations systems as being based on variability, interconnectedness and complexity.

Most of the systems that are simulated are subject to *variability* which can be seen as *predictable variations* and *unpredictable variations.* The predictable variations are, for example, the planned stoppages in a production facility, while an unpredictable variation could be the arrival rate of patients at a hospital emergency department.

In many operation systems the components of the system do not work in isolation but affect one another This explains the *interconnectedness* of the systems

Many systems are also *complex* and their complexity can be *combinatorial* or *dynamic* The combinatorial complexity is related to the number and the possible combinations of the system's components, while the dynamic complexity results from the interaction of components in a system over time

All of these lead to the conclusion that the behaviour of a system which is subject to one or all of variability, interconnectedness or complexity is difficult or even next to impossible to predict

Simulation models however are able to represent systems that are subject to all of the three characteristics above This is why they are able to predict the system's performance, compare different system designs and determine their performances

2 2 2 1 THE ADVANTAGES OF SIMULATION

There are a number of ways of analysing and improving operations systems Law and Kelton (2000) addressed the advantages of simulation over a number of different approaches, drawing the following conclusions

In the case of *Simulation versus Experimenting with the real system* they discovered that the *cost* is one of the biggest issues With simulation new ideas can be tried out by building different scenarios, without interrupting the day to day activities and without changing the real system

The concept of reducing costs through working out problems in the design phase rather than after a system has been implemented is best illustrated by the first graph in Figure 2 1 The second graph, illustrates how the cumulative cost resulting from systems designed using simulation can compare with the cost of designing and operating systems without the use of simulation In the short term the cost of using simulation can prove to be slightly higher, but in the long term the cost of using simulation proves to be significantly lower due to better efficiencies

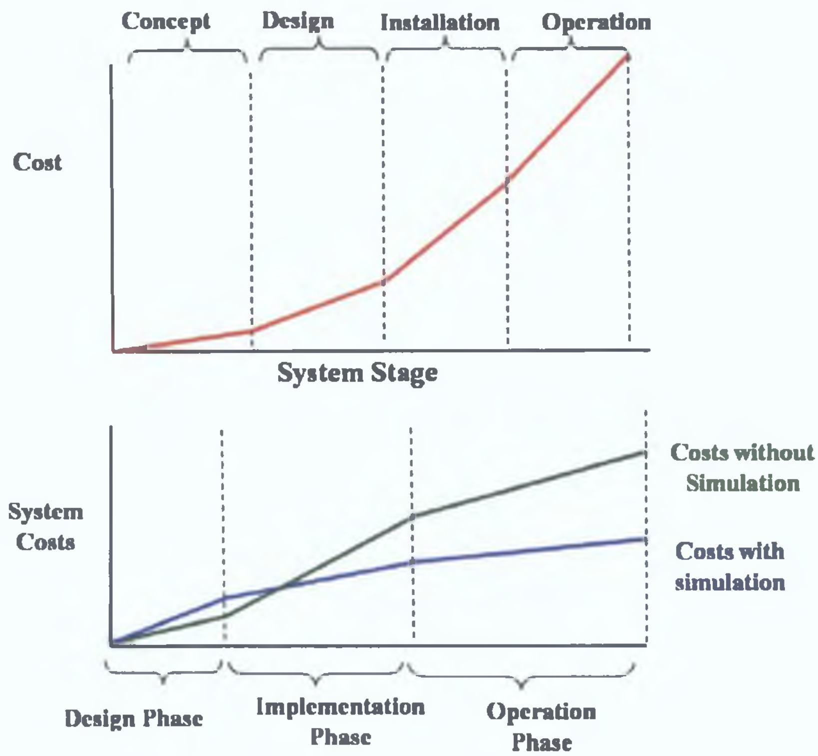

Figure 2.1 The Economic Justification of doing Simulation (Harrell 2004)

Time is another factor to be considered. It may take many weeks or months before obtaining relevant data regarding the performance of the new system which again can prove to be expensive.

At the same time, when comparing alternatives it is useful to have *control over the experimental conditions* under which the experiments are being performed so that direct comparison can be made. The simulation software provides the option of conducting experiments in the same environment, whereas with the real system one cannot be absolutely sure the conditions haven't changed in time.

The real challenge when it comes to experimenting with the real system is: when *the real system does not exist*. In this case the experimentation is impossible unless a series of alternative real systems are built. The only other option is to develop a simulation model.

Another possibility that Law and Kelton (2000) describe is *Simulation versus Other modelling approaches*. They believe that *restrictive assumptions* represent some of the major problems when looking at other modelling approaches, whereas simulation requires few, if any, assumptions to be made.

Modelling variability and its effect is also a problem that other modelling approaches are face while simulation, as stated above, is well able to deal with any kind of variability

A difference between simulation and other modelling approaches found by Robinson (2004) is *transparency* A manager facing a set of mathematical equations or a spreadsheet might struggle to understand the results of the model whereas with simulation the system can be represented as an animated display From a manager's point of view simulation also *fosters creativity* by trying ideas in an environment that is free of risk It can also help in *building consensus* between opposing parties, by sitting them around a model and testing all the different ideas From this point of view simulation also facilitates *visualisation and communication* Ideas will not be rejected anymore because the benefits could not be demonstrated

Sokolowski and Banks (2009) consider some other advantages of simulation to be

- *understanding why* by reconstructing and examining a scenario closely,
- *diagnosing problems* by understanding the interaction between the variables of a system,
- *identifying constraints* by reviewing delays on materials and process to determine if the constraint is the effect or cause
- providing *better training* which would be less expensive and with less disruption than on – the – job training

2 2 2 2 The Limitations of Simulation

El-Haik and Al-Aomar (2006) consider that like any other engineering tool, simulation has its own limitations They also give examples of issues that should be taken into account when considering simulation

One of these issues is *cost and time* which should be well planned The simulation study doesn't only refer to building the model Experimental design and data collection are parts of the simulation study that usually consume most cost and time Robinson (2004) adds to that the cost of the simulation software and the consultancy hours which are usually expensive This is why they both agree that other approaches should also be considered in addition to simulation

Simulation building also *requires expertise* El-Haik and Al-Aomar (2006) consider that employing an engineer is almost essential for simulation practitioners because the skills required are in the range of statistics, system analysis and validation In addition, the ability to work with people and project management skills would be beneficial

A disadvantage can also be *overconfidence* There are still people who strongly believe in the results generated by computers This is why, when interpreting the results, the validity of the model, the data inputs, the assumptions and the logical design should be kept in mind Simulation models are usually *data hungry,* requiring a significant amount of data which also needs to be further analysed and this can also be considered a limitation

Some other disadvantages described by El-Haik and Al-Aomar (2006) are

- over estimating the expectations of the simulation study,
- acknowledging that the validation and verification of the model determine the degree of model reliability,
- getting the support of upper management to make the simulation study fruitful and successful
- selecting the appropriate simulation tools

Apart from these, Sokolowski and Banks (2009) also mention

- the difficulty in interpreting results when the observation is a result of randomness and system inter-relationships
- the inappropriate use of modelling and simulation when an analytical solution can fit best

2.2 3. WHEN TO SIMULATE?

El-Haik and Al-Aomar (2006) believe that "*simulation is often the analysts' refuge when other solution tools, such as mathematical models, fail or become extremely difficult to approximate the solutions to a certain problem*" Simulation is usually used when the behaviour of a system is complex and dynamic They have also listed some of the situations which require simulation in manufacturing systems

- determining the throughput capabilities of an assembly line,
- determining the number of automated guided vehicles needed in a complex material-handling system,
- determining the best ordering policies for an inventory control system,
- validating the production plan in material requirement planning,
- planning the capacity of subassemblies feeding a production main line

Sokolowski and Banks (2009), in their book "Principles of Modelling and Simulation A Multidisciplinary Approach", see simulation as being used primarily for analysis, experimentation and training and they walk us through some of its applications, such as military, behavioural modelling, emergency management, game based learning, transportation, business, medical, engineering design and social science

In order to give some indication of the range of systems that can be modelled Banks *et al* (1996) suggests the following list

- Manufacturing systems
- Public systems like health care, military and natural resources
- Transportation systems
- Construction systems
- Restaurant and entertainment systems
- Business process reengineering/management
- Food processing
- Computer system performance

2 2.4 Simulation Case studies

This section of the thesis presents a number of case studies in order to demonstrate the applicability of simulation in different processes of a manufacturing company The chosen areas are production planning, business process modelling and supply chain management

2 2 4 1 Production Planning

Production planning stays at the base of any manufacturing process Its purpose is to minimise production time and costs, efficiently organise the use of resources and maximise efficiency in the workplace. The following are two case studies that demonstrate the use of simulation in production planning:

Case Study	ProModel enables Boeing to become more efficient. (Gilbert 2000)	A Simulation Case Study Of Production Planning And Control In Printed Wiring Board Manufacturing (Korhonen 2001)
Company Background	Boeing is well known as one of the biggest companies of airframe manufacturing in the world. The Seattle company branch produces between 300 and 600 commercial airplanes per year. One of Boeing's core engineering technologies is airplane wings, whose components have to go through a "shot peening" process. The shot peening operations are performed on the various parts of the wing by using five large machines, situated in an area called the Forming Corridor and interconnected through a rail network.	This case study looks at the production planning and control of PWB's (Printed Wiring Boards) in a multinational case company in order to achieve better customer satisfaction and cost efficiency. PWB's are physical bases on which electronic components are attached and provide the electrical interconnections between these components. There are two types of PWB's: the PTH boards have copper – plated holes that go through all the layers connecting them while the Blind boards have some of the holes connecting only part of the layers, by not going all the way through the board.
The Problem	Senior management considered the Forming Corridor to be a capacity limiting constraint in the skin and spar manufacturing process. The management set up the following two goals: shorter lead and cycle times and lower WIP inventories, in order to eliminate the excessively long flow times. Management also wanted to see if more capacity could be freed up for additional work.	The technology development of PWB's is strong and rapid and almost always they are product specific. This leads to the majority of orders being for new products which constitutes a difficulty in demand forecast and a risk in out of date stock grows. Factories need to reduce production lead times in order to adjust to rapid changes in both the amount of orders and the types of products ordered.
The Simulation Project	The most difficult task proved to be the process of defining and quantifying the system. The first part of the project consisted in breaking the system down into manageable pieces. Finding usable data also represented a challenge and it led to the necessity of adapting the	As there are no perfect methods for production planning and control, the simulation project needed to aim at presenting the results in such way so the company would gain better insight of the pros and cons of the principles under consideration. The main expected results

	modelling approach to fit the types of information that was readily available. In order to create the probability distributions for the downtime functions, data was collected from an electronic system which was monitoring the machine status in the area. A simulation model was built that was largely reflective of the actual performance and then it was used as a baseline for experimentation. After developing a model that area management agreed was valid, additional code was written in order to permit experimenting with the number of load bars in the system, prioritization of transfer bridge usage, machine operation schedules and how machine downtimes affect the system.	consisted in comparisons of more precise solution suggestions and it was envisioned that the simulation model would answer questions like: Which one of the alternative points should be chosen as the queue reorganising point? How well do the alternative scheduling and queuing logics work in this case? What is the effect of the proposed stock policies on production? What is the effect of smaller batch sizes or transfer batches and how small can the batches be? Did the proposed solution work and is anything else needed?
The Results	Analysis of the model output data showed that by cutting the number of load bars from 22 to 14 system performance improved: the average flow time was reduced by about 7% WIP inventory dropped by 1/3 delivery performance improved Increasing one machine's usage from two to three shifts per day also showed an increase in performance. Modelling also showed the impacts of machine failures on system performance. Simulating the production cycle resulted in: improved cycle time, improved delivery performance and reduced inventory holding costs.	In order to reach the goals set for the project the proposed remedies were: Reorganising the queue order in one control point after the initial queue arrangement at the beginning of production. Using the stock in order to level capacity need and provide fast service. Instead of the current practice of having lots of work in progress everywhere in production, stock should be kept as final stock or as buffer stock of half-made products just before the queue reorganizing point. Using smaller batches or transfer batches in order to level capacity need. Small transfer batches also allow concurrent processing and therefore shorten throughput time.

Table 2.1 Production Planning Case Studies

2.2.4.2. Business process

A business process is a collection of activities designed to produce a specific output for a particular customer or market. It implies a strong emphasis on how the work is done within an organization and contains a specific ordering of work activities across time and place, with a beginning, an end, and clearly defined inputs and outputs. The following case studies demonstrate the use of simulation in optimising the business process in two different companies:

Case Study	Selecting the Best Configuration for a Hospital Emergency Room Process (April et. al. 2006)	Predicting the Impact on Business Performance of Enhanced Information System Using Business Process Simulation (Tan and Takakuwa 2007)
Company Background	This case study considers the example of an emergency room in a hospital. The process begins with a patient arriving at the ER alone or in an ambulance. He signs in, is assessed into three levels (1, 2 or 3) based on his condition and transferred to an ER room where he will go through the registration and the treatment processes before being admitted in the hospital or released. 90% of all patients are being released from the ER while only 10% are admitted in the hospital for further treatment.	The company presented in this case study manufactures and sells toothpaste, toothbrushes and 50 other household products. It has a local headquarters (HQ) in Tokyo, six distribution centres (DC) across China and a factory in Quingdao. Each DC is sending a transportation request to the HQ, at the end of the month based on stock level and demand forecast. If the request is being approved the goods are carried to the DC by trucks based on the transportation plan. From there they will be delivered to their main consumers: the distributors.
The Problem	The ER is formed by nurses, physicians, patient care technicians (PCTs), administrative clerks and 20 ER rooms, one triage nurse and one charge nurse. The challenges are: finding the configuration of the above resources that minimizes the total asset cost which includes the staff hourly wages and the cost of each ER room used and Level 1 patients not spending more than 2.4 hours in the ER.	The company has difficulties in order management, demand forecast, production planning and standardizing the logistics at a company – wide level. As a response, the company developed and introduced an information system named Collaboration Inventory Portal (CIP) which interacts with all the existent information systems. Their goal is to evaluate the impact and benefits of introducing the CIP system.
The Simulation	The first step in the simulation process was to determine the base case with the Total Asset	The first step in the process of building the simulation model was detailing the definition and

Project	Cost of $ 36,840 and a Level 1 patient cycle time of 1.91 hours. The simulation model was created and run for 100 iteration with 5 runs for iteration. Each run simulated 5 days of the ER operation. The best solution found had the Total Asset cost of $ 25,250 and the average Level 1 patient cycle time of 2.17 hours and it consisted of: Nurses – 4 Physicians – 2 PCTs – 3 Administrative Clerks – 3 ER Rooms – 12 After obtaining the best solution with the existent configuration the following step was to redesign the model to improve the cycle time of Level 1 patients.	activities for each process step. This was followed by the data collection and analysis. After collecting the raw data some probability distribution analysis needed to be performed so this could be used as input into the simulation model. The next step consisted in the development of the "as – is" BPS Model, followed by the validation process which had to ensure that the model is an accurate representation of the real system. For the model validation the value of a key performance indicator (KPI) from the real world system was compared to the results of the simulation model which led to its acceptance as an adequate representation of the real world system. The last step consisted in building and validating the "to – be" BPS model which had a similar approach to the building and validation of the "as – is" model. Performances measures from running results of the "to – be" model were compared against those from sampling experiments or estimations.
The Results	The ER process configuration was redesigned and as a result, it lowered the Level 1 patient cycle time to 1.98 hours at implementation. After applying the optimisation process on this new model the following resource configuration was returned: Nurses – 4 Physicians – 2 PCTs – 2 Administrative Clerks – 2 ER Rooms – 9 This configuration resulted in a Total Asset Cost of $ 24,574 and an average Level 1 patient cycle time of 1.94 hours.	By comparing the "as – is" model with the "to – be" model the results suggested a significant reduction in the total lead times, in the case of the "to – be" model. Also by introducing the CIP system the processing time spent in the SD process and the utilisation of employees are decreased. Once built the BPS model allowed the possibility of analysing many new designs through its "what – if" capabilities and this will help in the future decision making process.

Table 2.2 Business Process Case Studies

2.2.4.3. Supply chain

Case Study	Discrete event simulation in supply chain planning and inventory control at Freescale Semiconductor, Inc. (Morrice et. al. 2005)	A Supply Chain Paradigm to Model Business Processes at the Y – 12 National Security Complex (Kress et. al. 2007)
Company Background	Freescale Semiconductor, Inc. is a global semiconductor company that provides embedded processing and connectivity products to large, high-growth markets like the automotive, networking and wireless communications industries. The supply chain in Freescale is divided in three main portions: front end (fabrication and wafer probe), back end (assembly and final test) and logistics. There are also two main inventories: the first one is situated between front end back end: the die change inventory and the second one between back end and logistics: the finished goods inventory.	The Y – 12 National Security Complex is a premier manufacturing facility which plays a vital role in the Department of Energy's Nuclear Weapons Complex. Y – 12 makes dozens of products which have hundreds of parts, each with many different process steps associated with manufacturing components, building sub – assemblies or assembling a final product. They also disassemble weapons to support stock pile reduction efforts and to retrieve high – value materials and components. These efforts must be coordinated within the Y-12 as well as the nationwide nuclear weapons complex.
The Problem	Considering the rapidly changing semiconductor industry on hand inventory loses value quickly and in contrast, not enough inventory can lead to stock outs and late deliveries. The challenge that Freescale encountered is keeping the balance between minimizing inventory and keeping on time service levels at an optimum point. At the same time the company had to be able to predict the result of changes in this balance and the impact on customer delivery.	The case study uses the analogy of a bicycle which requires two parts. When a retirement bicycle enters the process, it is placed into storage and it remains there until it is pulled through either the dismantlement (the process of taking apart a bicycle solely to obtain key materials) or the disassembly program (the process of taking apart a bicycle for obtaining reusable parts and key materials). The resulting key materials are pushed into interim or long term storage. They will be removed from the storage only for a customer demand.
The Simulation Project	The first step in the simulation process was to create an outline of the supply chain in order to quantify and visualize the links between each process and their corresponding amounts and impacts on customer delivery rates. The next step was to partition the supply chain in order	The most difficult step in building the simulation model was the data collection. During this phase it has been recognised the importance of keeping a record of the contributing expert as well as the time the information was collected. This provides

	to better understand how all the processes interact. Fereescale provided data from the past year which was used to create proper means and standard deviations for each process and then create distributions in the simulation model. After the implementation of the model, scenarios were defined by specific set of values for the parameters and ten simulation replications were made for each scenario in order to generate confidence intervals. Each replicate was simulated for 10 years after a 300 day warm-up period. It was determined by experimentation that the 10 years simulation replication was sufficient because statistics had stabilised indicating that they were approximating long-run steady state results.	confidence in the validity of the value. The simulation model of the company has been built by using the concept of a customer with an initial inventory of 100 bicycles and an estimated sales rate of one bicycle a day. When the inventory dropped under 100 bicycles, orders of new batches of bicycles would come in. Each batch would contain 5 bicycles. The Integrated Resource Planning Model (IRPM) is used to provide quick, rough ordered or magnitude answers to the manager's directives or requests. Often the simulation model would be run just a few times before a decision is being made. It was envisioned that the software would be extended to address questions regarding staffing levels, equipment needs and system availability.
The Results	The results of the simulation showed that the scenario considering the inventory levels to be exceeded by 400 units, achieved services levels greater than 90%. Further scenarios have been considered where the inventory levels were exceeded by more than 400 units but it was found that the increase in service level was not significant. In the case of Freescale, simulation analysis facilitated the prediction of the effect of internal on time delivery, inventory and WIP change on the customer order fulfilment service level. It allowed for the benefit of reducing front end lead times to be explored and also allowed the establishment of appropriate control levels at various stages in the supply chain based on inventory and service level metrics.	The simulation model was run for 70 days and the results included orders, shipments, sales, inventory at the customer's location as well as the maximum number of concurrent operations required to fulfil the customer's demands. The model also included reports of the utilisation of equipment, assuming that each operation requires one piece of equipment and that there are 30 pieces of equipment available in the pool. It was also found that the utilisation was a little greater than 50%. The simulation model was used to evaluate the schedule performance in Y – 12, to look at cost performance and production alternatives. Because of the model's speed, it enables a long term look at the business issues that the company could have.

Table 2.3 Supply Chain Case studies

The benefit of using simulation can be easily recognised in the case studies presented above. In the case of Boeing modelling showed the impact of machine downtimes on system performance and it resulted in improved cycle time, improved delivery performance and reduced inventory holding cost. In the case of a PWB manufacturer it showed how reorganising the queue order in the production planning and the use of smaller batches can improve performance.

In terms of business process, simulation helped in the selection of the best configuration for a hospital emergency room process in order to lower time and cost and was also used in predicting the impact of an Enhanced Information System on business performance in the case of a household products manufacturer.

Freescale, the semiconductor company, benefited from simulation by predicting the effect of internal on time delivery, inventory and WIP change on the customer order fulfilment service level. This facilitated the decision of reducing front end lead times and allowed the establishment of appropriate control levels at various stages in the supply chain based on inventory and service level metrics. The second case study of supply chain simulation looked at Y – 12 National Security Complex who managed to evaluate their schedule performance and to look at cost performance and production alternatives. This facilitated a long term overview of the business issues that the company could have.

All of these results encouraged the author to consider the use of simulation in trying to lower energy consumption by correlating it with production management in a manufacturing facility.

2.3. Modelling Approaches

In order to get an understanding of the algorithms used to build simulation software this section looks at three different approaches to modelling the progress of time: the time – slicing approach, the discrete simulation approach and the continuous simulation approach.

2.3.1. The Time – Slicing Approach

Deo (2006) describes the Time – Slicing Approach or the fixed time – step model as being based on a timer or "clock" that is simulated by the computer. "*This clock is updated by a fixed time interval and the system is examined to see if any event has taken place during this time interval. All events that take place during this period are treated as if they occurred simultaneously at the tail end of this interval.*"

Robinson (2004) considers the fixed time interval to be a constant of time for which he uses the notation Δt. He believes that the best way of describing the Time – Slicing Approach is by demonstrating it. The example that he chooses is of a telephone call centre, where calls arrive every 3 minutes and are passed to one of the two operators available. The operators take 5 minutes to deal with the customer. For this exercise he assumes that there would be no variation of any of the times described above.

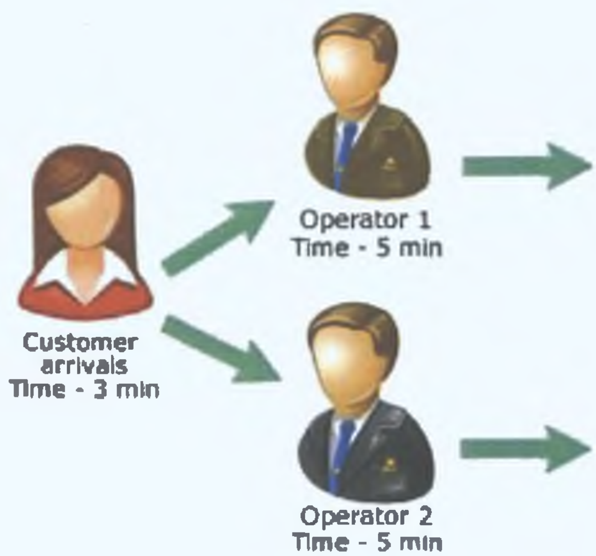

Figure 2.2 Time-Slicing Approach: Telephone Call Centre Simulation

For the purpose of this exercise Robinson (2004) considers the simulation to run for 24 minutes with $\Delta t = 1$ minute and represents graphically through Table 2.4. Column 2 shows the time remaining until a customer arrives and columns 3 and 4 show the time remaining until a customer service is complete. A customer arrives every 3 minutes. The first customer goes to Operator 1 who takes 5 minutes to complete the customer service. During this time the next customer arrives and goes to Operator 2 in order to be served and so on.

The two main problems identified with the time – slicing approach are inefficiency and determining the value of Δt. There are many time steps during which no change in the system is recorded. This results in unnecessary computations and inefficiency. Determining the value of Δt can be difficult in most simulations because the situations modelled would not be ideal and the activity duration may vary or could not be counted in whole numbers.

Time	Call Arrival	Operator 1	Operator 2
0	3		
1	2		
2	1		
3	3	5	
4	2	4	
5	1	3	
6	3	2	5
7	2	1	4
8	1		3
9	3	5	2
10	2	4	1
11	1	3	
12	3	2	5
13	2	1	4
14	1		3
15	3	5	2
16	2	4	1
17	1	3	
18	3	2	5
19	2	1	4
20	1		3
21	3	5	2
22	2	4	1
23	1	3	
24	3	2	5
Completed calls		3	3

Table 2.4 Time-Slicing Approach: Telephone Call Centre Simulation

2.3.2. The Discrete Event Simulation Approach

The Discrete – Event Simulation approach is another method for simulating the progress of time which has been explained by many writers.

Ingalls (2008), states that the power of Discrete Event Simulation stays in "*the ability to mimic the dynamics of a real system*".

According to El-Haik and Al-Aomar (2006) *discrete event simulation* is used to model production and business processes in both the manufacturing and service sectors. Discrete event systems are dynamic systems that evolve in time through the occurrence of events at possibly irregular time intervals. Given the fact that the majority of the real world production and business systems resemble this definition, *discrete event simulations* are used widely in real world applications.

Robinson (2004) points out that in *discrete event simulation* only the points in time at which the state of the system changes are simulated. This is why the system is modelled as a series of events that mark a state-change.

To better explain the *discrete event simulation* approach, Robinson (2004) goes back to the same example of a telephone call centre simulation, used in the *time slicing approach*.

Table 2.5 contains the results of a *discrete event simulation* approach which only consists in the events from Table 2.4.

Time	Event
3	Customer arrives
	Operator 1 starts service
6	Customer arrives
	Operator 2 starts service
8	Operator 1 completes service
9	Customer arrives
	Operator 1 starts service
11	Operator 2 completes service
12	Customer arrives
	Operator 2 starts service
14	Operator 1 completes service
15	Customer arrives
	Operator 1 starts service
17	Operator 2 completes service
18	Customer arrives
	Operator 2 starts service
20	Operator 1 completes service
21	Customer arrives
	Operator 1 starts service
23	Operator 2 completes service
24	Customer arrives
	Operator 2 starts service

Table 2.5 Discrete Event Simulation Approach: Telephone Call Centre Simulation

Figure 2.3 represents a flow chart inspired from the Discrete Event Simulation functionality model described by El-Haik and Al-Aomar (2006).

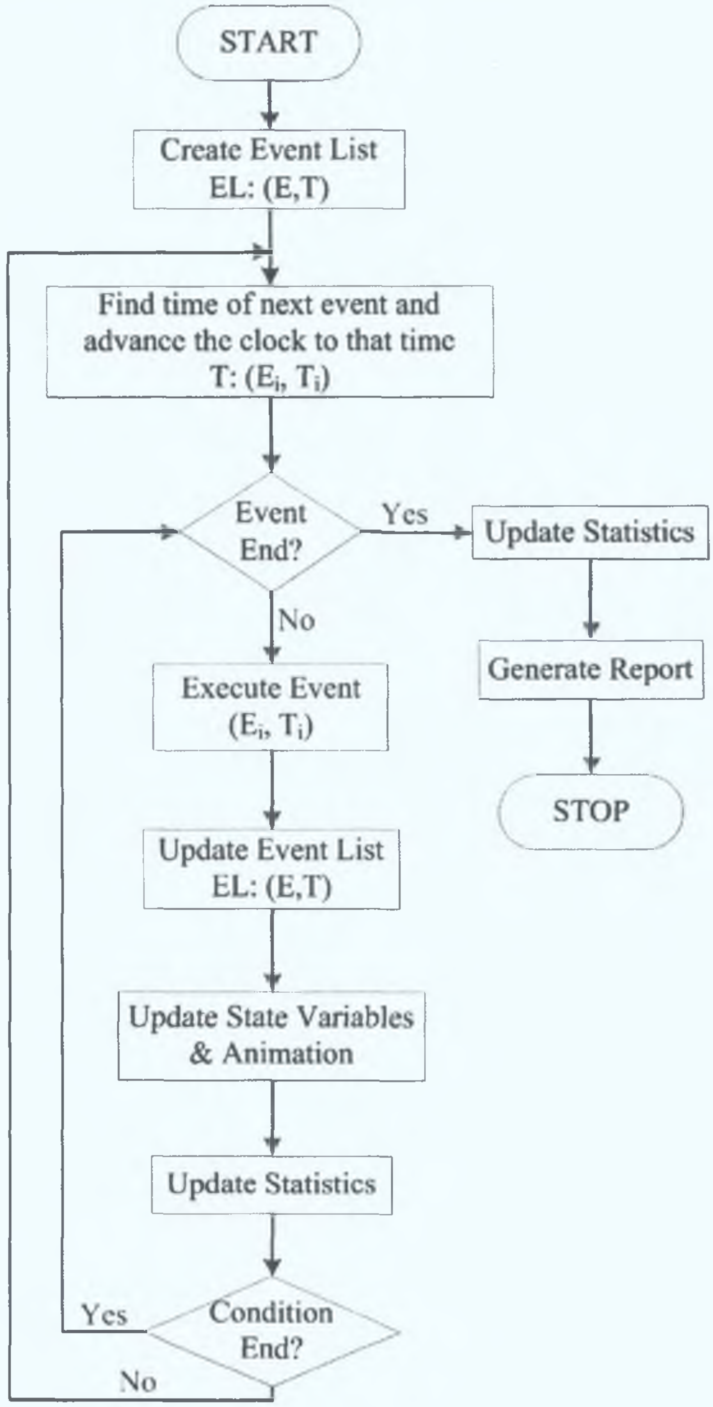

Figure 2.3 Discrete Event Simulation functionality

Discrete Event Simulations are dynamic, event – driven, discrete in time, computer animated, randomised and probabilistic. El-Haik and Al-Aomar (2006) have recognised some powerful mechanisms for establishing these characteristics. They believe that the backbone of Discrete Event Simulations is formed by the following mechanisms:

- the creation and updating of an event list,
- the time advancement mechanism,
- the capability of sampling from probability distributions with random number generation,
- the probability of accumulating statistics over run time
- the power of graphical representation with animation mechanism.

Most of the simulation software tools available at the moment vary in methods and algorithms but they all implement these mechanisms. The Discrete Event Simulation functionality usually includes the creation of an event list which advances the simulation clock, updating the event list, the permanent statistics and checks for termination.

2.3.3. The Continuous Simulation Approach

There are many times in which operations are not subject to discrete changes in state but the state of the system changes continuously through time. These situations can describe movement of fluids or systems that involve high volumes of fast moving items like food manufacturing, plants and communications systems.

According to Robinson (2004) the only thing that determines whether a system is seen as discrete or continuous is the level of granularity with which it needs to be analysed.

Currently, computers are not able to model continuous changes in state. This is why the continuous simulation approach approximates continuous changes by taking small discrete time steps Δt. Usually, the smaller the time step, the more accurate the approximation will be but, in the same time the slower the simulation will run.

2.4. SOFTWARE FOR SIMULATION

2.4.1. SPREADSHEETS

According to Ragsdale (2008) one of the most effective ways that businesses analysed and evaluated decision alternatives in the last decade was with spreadsheet models of the decision problems they faced. "*Using a Spreadsheet Model, a business person can analyse decision alternatives before having to choose a specific plan for implementation*".

Andrew F. Seila, in her paper: "Spreadsheet Simulation", presented in the 2006 Winter Simulation Conference explains why and when spreadsheets should be used for simulation. She considers that most spreadsheets have the following features which make them suitable for simulation:

- A way to represent mathematical and logical relationships among variables in the form of computations
- A way to generate random numbers and use them to sample observations from various distributions
- A way to implement replications
- A large number of functions to do mathematical, statistical, database, date/time, financial and other calculations
- Charting and graphing
- Automation through scripting languages such as VBA

At the same time she examines some limitations of spreadsheets for simulation which include:

- Spreadsheets can only store simple data structures as vectors and matrixes but in some simulation models more elaborate structures of data are needed, like lists or trees.
- Complex algorithms are difficult to implement as cells do not have the facility to implement 'for' and 'while' loops.
- Spreadsheets are slower than some alternatives as they use much more computer resources to support the user interface.

- Data storage is also limited in spreadsheet simulations by the length of the columns and rows.

Schriber (2009) lists the steps involved in building Spreadsheet – Based Simulations:

1. Building and testing the model capturing the logic and relationships from the problem at hand.
2. The model inputs that involve uncertain quantities must be represented using formulae that sample from probability distributions.
3. The model needs to be able to record the value of each output variable produced each time the workbook is recalculated.
4. The workbook must be able to recalculate repeatedly, in automated fashion, in order to create a set of values for each variable of interest, each time it iterates.
5. Each set of values must then be processed to produce information that will support the decision – making process.

Schriber (2009) also advises for the use of add-ins that provide support in the spreadsheet simulation process, like @RISK and Crystal Ball.

2.4.2. Programming Languages

Chung (2004) believes that any high-level programming language can be used to develop simulation models. These include programming languages such as Visual Basic, C++, Java, FORTRAN and Pascal. Programming languages usually give the modeller great flexibility but one of the inconveniences of using them is the lack of highly detailed animation graphics.

According to Robinson (2004) programming languages generally provide a greater range of application, modelling flexibility and are likely to run faster than equivalent models developed in other software. However they lack the time needed to obtain the software skills, the ease of use and the ease of model validation.

Pidd and Cassel (2000) look at Java and its use in developing discrete event simulations. They consider Java as being an attractive programming language for simulation and mention some of the following features that support their assessment:

- Java is fully object oriented
- it supports extensive packages which are defined as class libraries These provide useful classes that can be used directly or can be extended
- it has a familiar syntax which is based on the one of C++
- it supports multi – threading and it is highly portable

They also identify some of the downsides of using Java for simulation development, like the absence of pointers and the fact that it is slower than C and C++

2.4.3. Web – Based Simulation

Kuljis and Paul (2001) consider that, with the growing interest in the web as a new platform for applications, the simulation community was forced to migrate to the web in order to "remain alive" The first mention of web-based simulation was in 1996, at the Winter Simulation Conference and since then, in 1998, the importance of Java as a programming language for simulation was recognised Despite the great promise held by web – based simulation, in 2000 there was a big drop of interest and research in this domain

In 2010 Byrne, Heavey and Byrne list some of the advantages of web – based simulation, which include ease of use, cross – platform capability, model reuse, controlled access, wide availability, minimised version, customisation and maintenance This can be done through the server, integration, interoperability and collaboration which facilitate two of the most essential factors in a simulation project communication and interaction They also mention some of the disadvantages of web – based simulation

- loss in speed, due to downloading time and network traffic,
- graphical user interface limitations,
- security vulnerability
- difficulty in simplifying the simulation models

2.4.4. Simulation Software Packages

Kheir (1996) defines simulation packages as "*collection of routines [programs to be possibly compiled separately and then included as part of other programs]*" and he considers them to be some of the most powerful tools for simulation and modelling activities in an interactive mode.

Nikoukaran and Paul (1999) compare a simulation software package, or a simulator with a toolbox which contains a limited number of tools from which some can be flexible. They consider the main advantage of a simulator to be the fact that the user does not need to spend time and effort on building tools. However, on the other hand, its flexibility is not as great as the flexibility of a programming language.

Recent improvements in the facilities available in simulators make them more flexible and user friendly. Banks (1991) believes that "*the distinction between simulators and simulation languages is blurring. They are moving towards each other by offering special features.*"

Currently there are many specialist simulation software packages available. Law and Kelton (2000) classify simulation packages into two major types: *general purpose simulation packages* and *application-orientated simulation packages.* They describe the general purpose simulation packages as being intended for use on any type of applications. However, they may have special features for certain types like communications or process reengineering. On another hand the application-oriented simulation package is directed at a certain class of applications i.e. healthcare or manufacturing.

Robinson (2004) details some of the pros and cons of specialist simulation software. He states that the majority of simulation software allows a simulation to be built and run in a visual environment. Also, the modeller can usually choose from a predefined set of simulation objects provided by most software packages. As a result the modeller requires little programming skills although most visual interactive modelling systems provide an internal language of their own for more complex logic. At the same time specialist simulation software is likely to run slower as there are a lot of objects to be processed and displayed through the interactive interface. Other downsides of this type of software are the learning curve associated with it and the price which tends to be high compared to spreadsheets and programming languages.

2.4.5. Software for Energy Modelling

Many companies deliver software products which address energy efficiency. Their solutions are mostly based on real time energy monitoring systems. These systems involve the installation of sensors and advanced metering technology to collect the information about an organization's energy and resource usage. This information is stored in databases and presented to the user through internal websites or in Excel documents. The down side to these systems is that they do not analyze the data in any way and they are not able to predict the energy consumption for a specified period of time.

2.4.5.1. Current Knowledge on Energy Modelling

In 2006 Professor Jingge Ling and Professor Shusheng Pang from the University of Canterbury, New Zealand published the paper 'Modelling of Energy Demand in an MDF Plant'. This paper looks at taking inputs like MDF production, log moisture content and fibre drying method and predicting the energy demand for both heat and electricity.

Figure 2.4. presents the MDF production process. The logs are first debarked and fed to a chipper. The chips are screened, washed and fed to a hopper where they are heated using low pressure steam. They are then fed to the pre-heater/digester which further heats and softens the chips. These are then fed to a refiner where they are broken down into wood fibres. At the refiner entrance, a small quantity of paraffin wax is added as a moisture repellent.

From the refiner the steam and fibre mixture goes to the blownline where it is injected with resin solution. It will than fall into a tube drier and is brought to a target moisture content of 10 – 12%. From here the fibres are sent to storage bins before being conveyed to the vacuum forming station for the mat formation. This is where the mat thickness is reduced through a continuous cold press. The next step could either be cutting the mat and then compressing it in a batch press or feeding it directly to a continuous hot press in order to achieve the target board thickness and density.

After the hot pressing the pre cut boards are cooled in a star drier while those from the continuous press are first cut to length before going through the same cooling process. Before the panels are sanded, trimmed and cut into market sizes for packaging, they are stored for two up to three days.

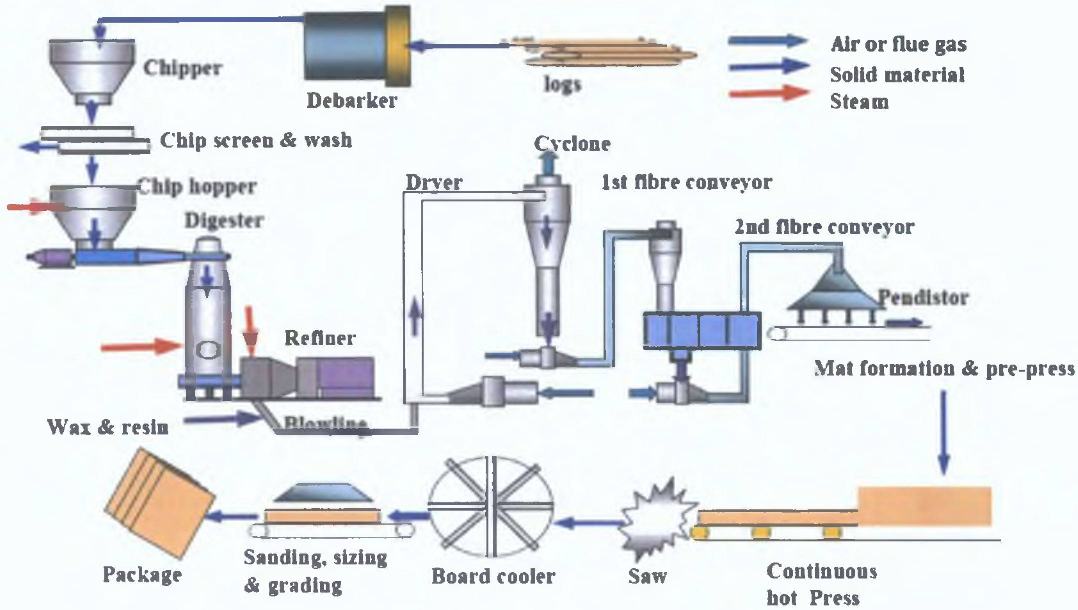

Figure 2.4 MDF Production Process

The authors developed a computer model in order to quantify the energy demand in the medium density fibreboard (MDF) plant '*based on the production process from chip preparation, refining, fibre drying, mat forming, hot pressing to product finishing*'.

In order to develop this model the process was divided into six unit operations:

- *Chip preparation* which included debarking chipping and screening;
- *Preheating and refining* which was formed by chip washing, plug screw feeding, preheating and refining;
- *Fibre drying* which included the blowline and the fibre drying;
- *Mat forming and pressing* formed by the mat forming, pre – pressing and hot pressing;
- *Finishing* which included cutting, sending, grading and packaging;
- *Miscellaneous* formed by thermal oil circulating, compressed air supply lighting and waste water treatment.

The model was than validated using energy audit results from three commercial plants. This showed that the model was able to 'simulate the energy demand with a discrepancy of -5 to +7% for thermal energy and ±4% for electricity'.

According to the authors' research, this is the first effort to predict both heat energy and electricity consumption in an MDF plant. A few years earlier though, in 2003, Carvalho et. al. published the paper 'A global model for the hot-pressing of MDF' in the Wood Science and Technology Journal.

Their model was used to 'predict the evolution of the variables relating to heat and mass transfer (temperature, moisture content, gas pressure and relative humidity), as well as the variables relating to mechanical behaviour (pressing pressure, strain, modulus of elasticity and density).' Also, they reached the conclusion that the model they developed is able to facilitate the scheduling of the press cycle 'to fulfil objectives of minimization of energy consumption, better quality of the board and increased process flexibility.'

In September 2007 Professors Ling and Pang published another paper: 'Modeling of thermal energy demand in MDF production'. Through their research they created a model which can be used to '*examine the effects of various production capacities, product grades, operation times and fibre drying methods on thermal energy demand and distribution.*' They also proved that the model is able to predict the energy demand with an accuracy of -17% to +6%.

The above cited research demonstrates the effective use of simulation in predicting the energy consumption in Medium Density Fiberboard production facilities, by looking at production management. Masonite, the case study company for this research project, is producing High Density Fibre (HDF) moulded doors which follow a process similar to the production of MDFs. The work of Ling and Pang in 2006 and 2007 and Carvalho et. al.(2003) proves that energy consumption can be modelled with an accuracy ranging between -17% to +6%, using spreadsheets for simulation. This encouraged the author to take the research to the next step and consider industrial simulation software tools for modelling the correlation between energy consumption and production process in Masonite.

2.4.6. Selection of Simulation Software

In all of the cases presented above the models were built using spreadsheets. For the purpose of this thesis a number of specialist simulation software packages were considered and reviewed.

Tewoldeberhan et. al. (2002) wrote about the methodology of performing an evaluation of discrete – event simulation packages. He recognizes the cost and the time involved in the process of evaluation and selection of a simulation software package unless an efficient methodology is used. In order for this task to be accomplished efficiently he proposes a two phase evaluation and selection methodology. The first phase includes the selection of simulation software, based on the most important features and criteria. The packages that satisfy the criteria and features in the first phase will be advanced in the second phase where they will be evaluated and analysed in detail.

2.4.6.1. Phase one in selecting the simulation software

For the completion of phase one in the selection of the simulation package suitable for this research, the author has created a list of required features. This list is presented below in Table 2.6.

Types of features for assessing the simulation software	Features for assessing the simulation software
General features	Primary market to which the software is applied *System Requirements:* • Ram • Operating System *Costs:* • License • Software installation • Training
Data Input/Output Criteria	*Data importing* • Electronic Spreadsheets • Autocad files Data Statistics Generation Ability to fit the data into a probability distribution *Input data mode:* • Batch

	• Interactive • Verification of data consistency *Reports* • Standard • Customized Data Export in Electronic Spreadsheets Data statistics generation Ability to fit the data into a probability distribution Statistic chart generation *Printing:* • Screen Layout • Generated Reports

Development Criteria	Support to theoretical and empirical probability distribution
	Random number generator
	Model—animation integration
	Icons:
	• Standard and user-defined library
	• Icon editor
	Background chart:
	• Image import
	• Screen layout editor
	Codification:
	• Codification assistants
	• Programming using supplier's language
	Built-in function and user-defined library
	Global variables
	Entity attributes
	Typical objects for model development in logistic systems
	• Material handling
	• Grouping and separation of entities
	• Schedule
	  ○ Resources and entities arrival
	  ○ Downtimes
	Conditional routing
	Animation
	• Enable/disable configuration
	• Speed control
	• Support to the different time and space units
	• Date/hour visualization
	• Instantaneous variable values and charts visualization

Efficiency and Testing Criteria	*Error depuration:* • Execution tracking • Inserting stop points • Inspection of instantaneous variable values • Stepwise execution Model validation

	Time required to construct models Model constraints
Execution Criteria	Multiple replications Batch mode Warm-up period
Technical Support / Modelling Assistance Criteria	*Documentation:* • User's manual • Tutorials • Application-based examples On-line help Technical support Required experience Easy learning Trainings Software updates

Table 2.6 Criteria for the evaluation of simulation software packages

In order to evaluate the simulation software packages on the market, according to these criteria, the author has used two of the simulation software surveys published by James Swain in 2007 and in 2009. Swain's 2009 survey is the ninth biannual survey of simulation software. Both the 2007 and the 2009 surveys include 48 products, making them some of the largest, to the author's knowledge. Swain (2007) states that his survey "*includes information about experimental run control (e.g., batch run or experimental design capabilities) and special viewing features, including the ability to produce animations or demonstration that can run independent of the simulation software itself.*" According to Swain (2009) "*the range and variety of these products continues to grow reflecting the robustness of the products and the increasing sophistication of the users*".

Considering the primary market to which the software is applied the author narrowed the list down to 10 software packages: @Risk, Arena, Any Logic, Decision Tools Suite, Micro Saint Sharp, Proof, ProModel, Simcad, Simio and Vanguard. All of these simulation packages address manufacturing and to a certain degree energy modelling. Out of the ten, the author narrowed the list down to three simulation packages which could be ideal for the project described in this thesis: @Risk, Arena and ProModel. The other packages were disregarded as they did not allow model building using programming or access to programmed modules (e.g. Proof), no input distribution fitting (e.g. Micro Saint Sharp), no code reuse like objects or templates (e.g. Decision Tools Suite), very expensive, even for a student version (e g Any Logic), no optimisation algorithms (e g Simio) and no real time viewing (e g Vanguard)

Apart from Swain's survey, the paper published by Verma et al (2009) "A Critical Evaluation and Comparison of Four Manufacturing Simulation Softwares" was also considered Within this paper there are four simulation software packages evaluated ProModel, AutoMod, HyperMesh and Process Model Adding these to the simulation software previously identified, the next step is to compare the six packages according to the criteria already presented and to find the ideal software for this project

Both Verma et al (2009) and da Silva and Botter (2009), considered the next steps in the selection process to be the attribution of weights to the criteria followed by the attribution of points to each software They all used a similar judgement scale in order to assign weight to each criterion and a similar list of criteria as the one defined in Table 2 3 above

Verma et al (2009) has put together a proposed rating for the four simulation software packages they evaluated ProModel, AutoMod, HyperMesh and ProcessModel According to their results, both ProModel and ProcessModel scored a total of 91 points, AutoMod scored a total of 84 points and HyperMesh recorded a total of 86 points All things considered, the two simulation software that qualified for the second phase were ProModel and ProcessModel

Da Silva and Botter's (2009) performed a similar evaluation of @Risk, Arena and ProModel According to their results, the two simulation tools that qualified for the second phase were Arena, with 248 points and ProModel with 235 points @Risk scored 166 points and therefore it did not qualify for the second phase of the selection process

2 4 6 2 PHASE TWO IN SELECTING THE SIMULATION SOFTWARE

In the first phase of the selection procedure the following six simulation software packages were chosen @Risk, Arena, ProModel, AutoMod, HyperMesh and Process Model, according to the essential criteria identified at the beginning of the project After a more rigorous assessment the three simulation software packages that qualified for the second phase of the selection process were: Arena, ProcessModel and ProModel.

The next step taken in the selection process was deciding the importance of each group of criteria for the project and comparing this to the points scored by each simulation software package.

The most important criteria deemed necessary for this project are: Coding and visual aspects, Technical Support or Modelling Assistance, Efficiency, The Execution Criteria or Experimentation, Testability and Input / Output criteria.

Below is a tabular representation of the comparison made by Verma et.al. (2009) between ProModel and ProcessModel, which contains only the essential criteria for this project. Arena has also been added to this comparison, considering the same criteria and its importance to this research project. The evaluation of each criterion for Arena was taken from da Silva and Botter's (2009) paper: "*Method for assessing and selecting discrete event simulation software applied to the analysis of logistic systems*".

Criteria	Arena	ProModel	Process Model
Coding and visual aspects	18	18	16
Modelling Assistance	10	10	8
Efficiency	8	8	7
Experimentation	6	6	5
Testability	7	7	7
Input / Output	5	7	7
Total	**54**	**56**	**50**

Table 2.7 Criteria ranking of simulation packages (Verma et. al. (2009) & da Silva and Botter (2009))

Looking at the table above a general better performance by ProModel can be noticed. In terms of Coding and Visual aspects, ProModel and Arena scored a total of 18 points while ProcessModel scored a total of 16 points. Even though ProModel's score of 9 points for coding aspects was just below ProcessModel's score of 10, ProcessModel lost points in terms of Visual aspects, which are very important to this project from a presentation and icon customization point of view.

Modelling Assistance is better ranked for ProModel and Arena than ProcessModel, as well as the efficiency and experimentation From the testability point of view all of the simulation models scored the same but looking at the Input / Output, ProModel and Process Model scored the same 7 points, while Arena only scored 5 points Arena lost points in Data Statistics Generation and the Verification of Data Consistency, which are two important parts in the validation and data analysis processes

Given the fact that Arena and ProModel scored similarly in most aspects of this comparison, a further detailed analysis between the two can be found in Appendix A For this detailed comparison, each criterion was assessed according to the features of the research project presented in this thesis and was assigned a certain weight by the author Next the two simulation tools were assessed according to the essential criteria determined above If the package fulfilled a criterion it was attributed 1 point If the criterion is not fulfilled the package was attributed 0 points At the end, the total points score was calculated by adding the product of the weight and the attributed point for each criterion that had been assessed While the author assigned the weight of each criterion according to its importance to the simulation project, the evaluation of each criterion was taken from da Silva and Botter's (2009) paper *"Method for assessing and selecting discrete event simulation software applied to the analysis of logistic systems"*

Considering all the facts presented above, and the total points scored by each of the simulation packages, the author considers that ProModel is the most appropriate simulation tool for modelling the production process and energy consumption of Masonite

2.5. CONCLUSION

This chapter presented an introduction in simulation, which looked at the definitions presented by various authors, the advantages and the limitations of simulation and also described the situations in which simulation should be used As a conclusion to the literature review presented in the first part of this chapter the author defined simulation, from the perspective of this project, as being a computer replication of a real life manufacturing system, with the scope of testing and comparing the data gathered from a series of scenarios. In the case of Masonite, simulation will represent the decision making tool for the implementation of the most energy efficient scenario.

In order to demonstrate the advantages of using simulation in production planning, business process and supply chain management, a number of case studies were presented. The chapter also described some of the modelling approaches and the software used for simulation which included: spreadsheet simulation, programming languages simulation, web - based simulation and specialised simulation software packages. The author has considered all the advantages and disadvantages of all the types of simulation software presented in this section and concluded that a simulation software package specialised on manufacturing is the best choice for this research project.

The final part of the chapter looked at the usage of simulation in the case of Energy management. For this purpose a case study has was presented which demonstrates the benefits of using energy modelling in an MDF plant. This case study was conducted using spreadsheet simulation and, to the author's knowledge it represents the first effort to predict both heat energy and electricity consumption in an MDF plant. Following this study the author has decided to consider a novel approach of using an industrial simulation tool to model energy consumption coupled with production process in a wooden door manufacturing facility. For this purpose the author has reviewed and compared a number of simulation tools considering the criteria identified at the beginning of the project as being essential for the purpose of modelling the production process and the energy consumption in a company like Masonite. The author also applied evaluation methodologies published in relevant research literature for simulation tool selection. At the end of this process the following six simulation software packages have been identified: @Risk, Arena, AutoMod, HyperMesh, ProcessModel and ProModel.

The selection process continued with the implementation of two phases: the first phase consisted in the selection of simulation software, based on the most important features and criteria while in the second phase the selected simulation software packages were evaluated and analysed in detail.

At the end of phase one the three simulation software packages that were advanced into phase two were Arena, ProcessModel and ProModel Based on a more rigorous selection process that took place in phase two of the evaluation, the author recommends the ProModel package for simulating the energy consumption coupled with Masonite's production processes The chosen simulation software presents an advantage in coding and visual aspects, modelling assistance, efficiency and experimentation against ProcessModel and an improved Input/Output process compared to Arena The definite advantage that ProModel presented was the Data Statistics Generation and the Verification of Data Consistency capabilities which are not incorporated in Arena and which represent an important part in the validation and result analysis process

CHAPTER 3: MASONITE

CONTENTS

3.1. INTRODUCTION

This chapter presents a short history of Medium Density Fibreboard (MDF) production and a description of the MDF production process which is very similar to HDF Moulded Door Skin manufacturing carried out at Masonite

The second part of the chapter looks at Masonite and its production process The two main production lines Line1 and Line 2 along with the Cut and Coat line are further explained in more detail as they account for over 80% of the company's energy consumption

An important part in the production process is defined by the production schedule This had to be transformed after a continuous decrease in demand When the company was functioning at full capacity all production lines were running 7 days per week, 24 hours per day Due to the economic downturn Masonite had to adapt its running time to a 10-4 cycle, where the company opened for 10 days and closed down for the following 4 days This had an impact on the company's efficiency as energy consumption remained the same despite a drop in production This represents a great challenge for Masonite as they need to find ways to lower energy consumption for each door produced

3.2. MDF PRODUCTION

In his paper, "*The Family of Wood Composite Materials*", Maloney (1996), defines wood composites as being "*materials that have the commonality of being glued or bonded together* " He also considers composites to include panels, molded products, lumbers, large timbers, components and products made through the combination of wood with other materials

In the same article Maloney (1996) groups plywood, variations of structural panels and glued laminated timber under the name of Engineered Wood Products (EWP) Later, Particleboard and Medium Density Fibreboard (MDF), have also been described as being Engineered Wood Products

Maloney (1996) defines Medium Density Fibreboard (MDF) as "*a dry – formed panel product manufactured from lignocellulosic fibres combined with a synthetic* *resin or other suitable binder.*" He also states that MDF production originated in Deposit, New York in 1966. At the same time he recognises the arguments which consider that the first MDF was manufactured in a plant in Oakridge, Oregon, or in Meridian, Mississippi.

As stated above, the base of the MDF production remains the softwood. A diagram of the MDF production process is presented in Figure 3.1. below.

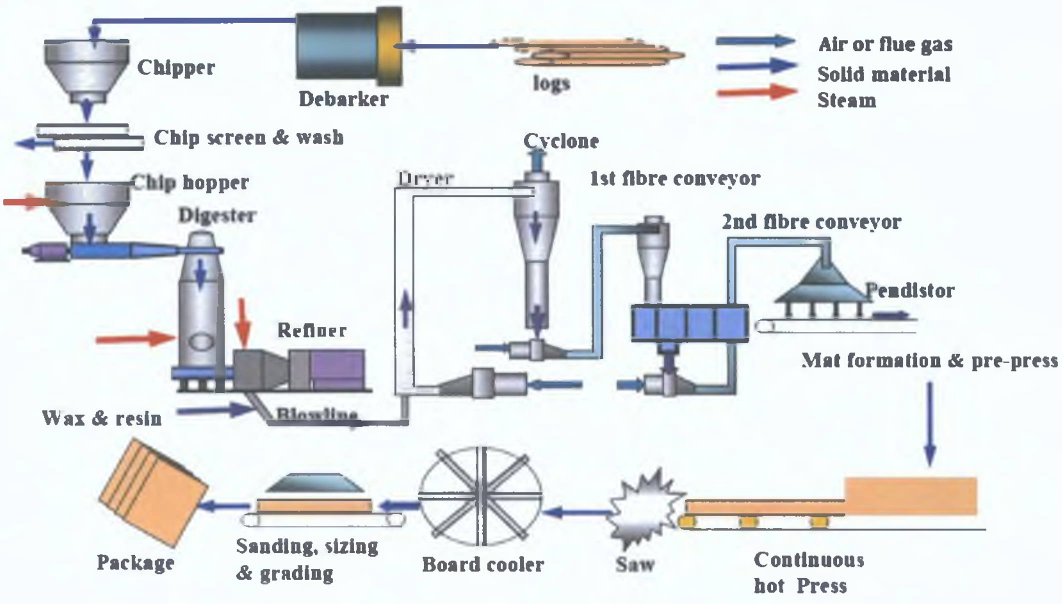

Figure 3.1 MDF Production Process – Li and Pang (2006)

The production process of an MDF manufacturing company, as described by Li and Pang (2006) starts with the logs of soft wood. These are first chipped and then transported to the manufacturing plant where they are stored in the chip yard. They are then washed and fed to a hopper. In the hopper they are heated using low pressure steam and then they are fed into the preheater or the digester where saturated steam further heats and softens the chips. These are then fed to a refiner which breaks them down into wood fibres at 180°C. At the refiner entrance a small quantity of paraffin wax is added as moisture repellent. The next step in the manufacturing process is the injection of resin solution when the fibres reach the blowline. From here they are directed into a tube drier where they are dried to a target moisture content of 10-12%. The dried fibres are then directed to storage bins before they are sent to the vacuum forming station for mat formation. A continuous cold press then reduces the mat's thickness, before being cut to size and compressed into a batch press. After the hot pressing the panels are cooled into a star drier and then stored for a few days before sandıng, trımmıng and cuttıng ınto market sızes for packagıng

3.3. Company Background

The case study company ıs the Irısh branch of Masonıte, a HDF Moulded Door Manufacturıng company wıth ıts headquarters ın Tampa, Florıda Masonıte was founded ın 1924 and employs over seven thousand people worldwıde

Masonıte Ireland ıs one of the largest productıon facılıtıes ın the country, comprısıng of 60,000m^2 under one roof and whıle thıs research was beıng conducted, ıt employed 200 people It ıs a fully automated door facıng manufacturıng facılıty and the 6th bıggest consumer of electrıcıty ın Ireland Rısıng energy costs coupled wıth reduced demand for product has had sıgnıficant ımplıcatıons on plant efficıencıes and competıtıveness

The manufacturıng process of HDF Moulded Door Skıns ıs hıghly sımılar to that of Medıum Densıty Fıbreboards The figure below presents the productıon process of Masonıte The raw materıal arrıves to the company under the form of wood chıps These are washed and then processed ınto a Refiner whıch transforms them ınto wood fibre From the refiner they go to the blownlıne where wax and resın solutıon ıs ınjected They then arrıve ınto a tube drıer where the moısture content ıs reduced to a target of 10 – 12% From here the fibres are sent to storage bıns before beıng transferred to the mat formıng statıon The next step ın the productıon process ıs reducıng the mat thıckness through a contınuous cold press, followed by cuttıng the mat and then compressıng ıt ın a batch press After hot pressıng the panels are dırected ınto the work ın progress (WIP) storage waıtıng area for the cut and coat process Through thıs process the panels are sanded, trımmed and cut to the standard sızes for packagıng

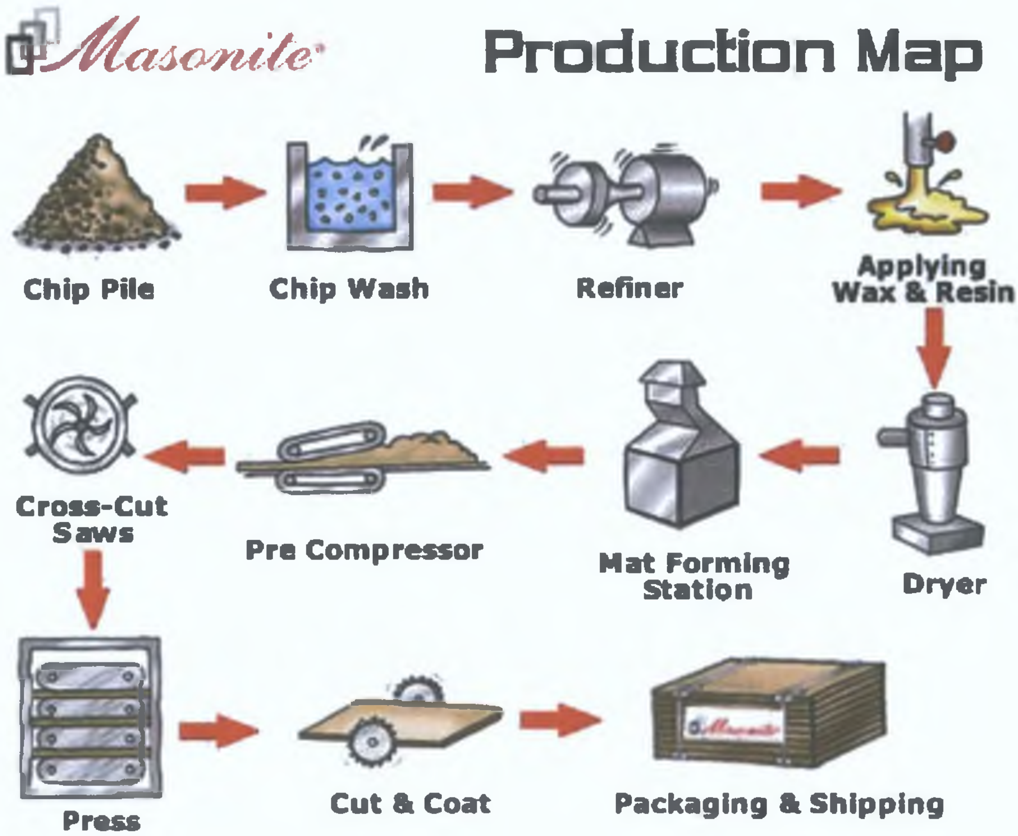

Figure 3.2 Masonite Production Process

Masonite has two highly automated production lines that when combined, measure 1.5km in length from raw material input to unit output. These lines account for 80% of the plant's energy needs.

The two main production lines are divided into three processes:

- The pre press processes
- The press
- The post press processes

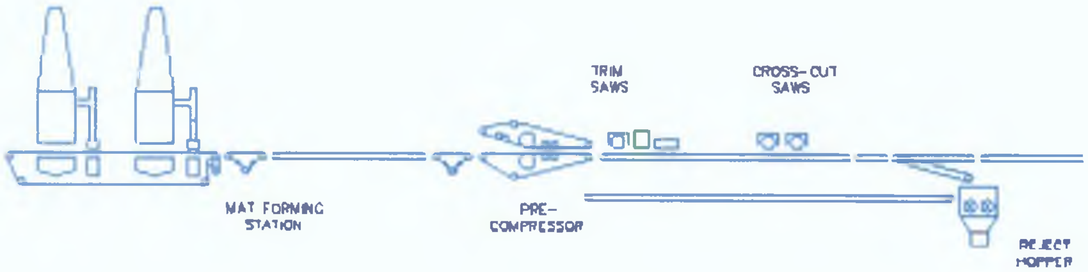

Figure 3.3 The Pre Press Process

The pre press processes include the mat forming station which lays the fibre on a conveyor belt, the pre compressor which compresses the mat in order to reduce its thickness, the trim saws which trim the edges of the mat and the cross-cut saws which cut the mat into the specific size.

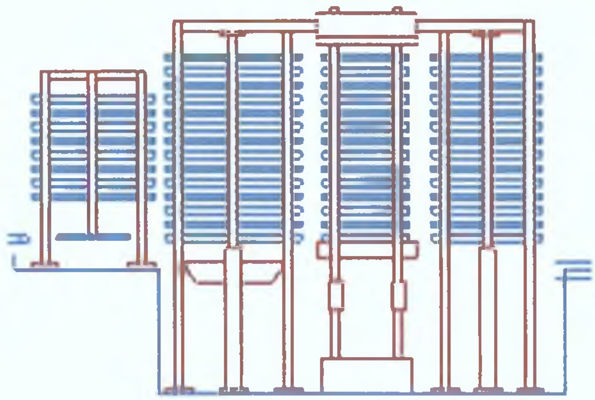

Figure 3.4 The Pressing Process

The pressing process consists of a pre-loader which stacks the mat pieces on 7 conveyor belts. When the seven conveyor belts are fully occupied, they transfer the mat pieces onto the loader. The loader is made up of 14 stacked conveyor belts. These transfer the 14 pieces of mat into the multi opening press. Here the mat pieces are hot pressed for 60 seconds and transformed into double HDF moulded panels. Each double HDF moulded panel is imprinted by two pairs of dies which results in two united door skins. Each die represents a door model. Masonite creates 13 models of doors, each of which is a different size. From the press the double panels are transferred to the un-loader which in turn directs them to the post press processes. This mainly comprises of conveyor belts, ending in a sort line. The sort line stacks the same types of double panels in batches of 220.

Figure 3.5 The Post Press Process

From the sort line the double panels are directed into the work in progress area where they are stored before the cut and coat process.

The Cut&Coat line is divided into two main processes: coating and cutting the panels. The coating process is made up of a dual feeder which directs the double panels through a preheat oven, a high velocity hot air (HVHA) oven and an infrared (IR) oven. The panels are than cooled and painted. This process is then repeated and after the second coating they are dried by passing through an HVHA and an IR oven. From here the double panels are directed towards the cutting process. This consists of a first pass saw that cuts the double panels into two single door skins. From here the two single door skins are directed on two different conveyor belts referred to as the second pass transfer and the third pass transfer. Here the single door panels go through the second pass saw and respectively the third pass saw where their edges will be trimmed. The next step in the process is a board sampler unit which checks the quality of the single door skins. These then pass through two humidifiers, before being stacked in batches of 440 single door skins and stored in the warehouse.

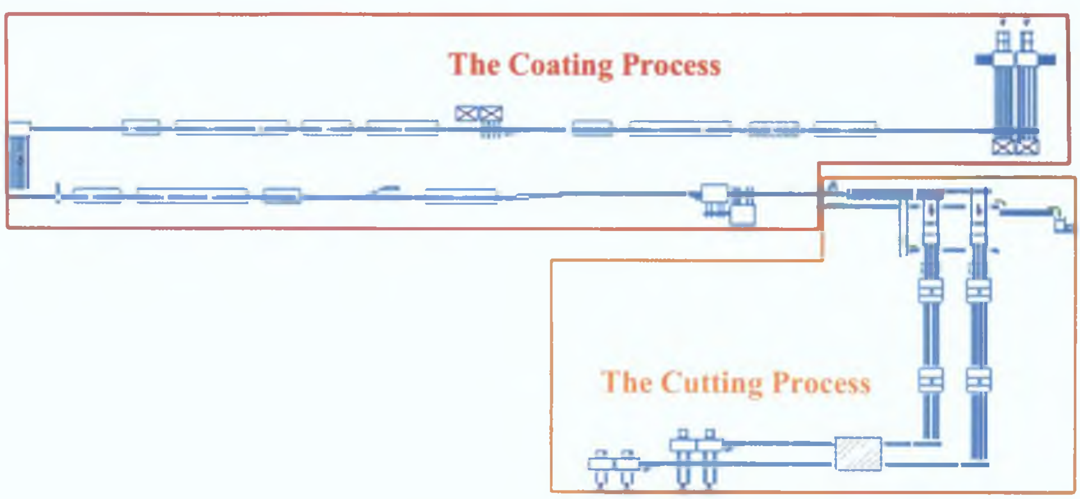

Figure 3.6 The Cut & Coat Process

All of these processes are monitored by Motor Control Centres (MCCs). The MCCs are part of a larger network, a schematic diagram of which can be found in Appendix B. A simplified graph of the system can be found in Figure 3.7 below.

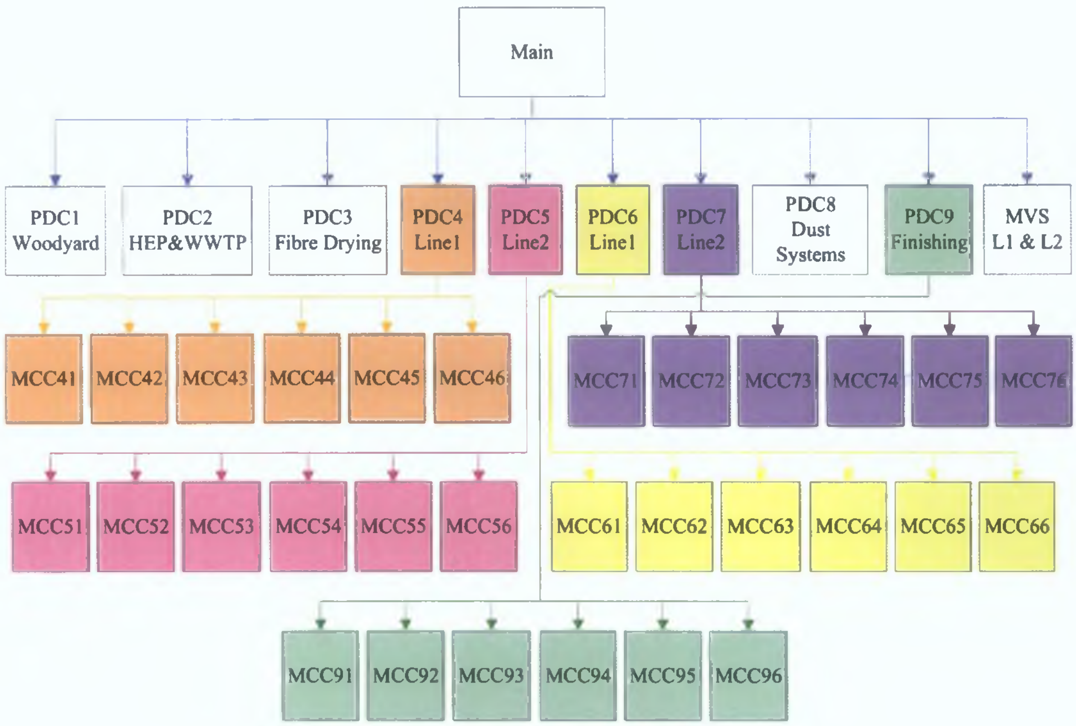

Figure 3.7 Meter Block Diagram

The network starts with the main power supply which directs the electricity to 9 Power Distribution Centres (PDCs) and a Medium Voltage Supply (MVS). In the figure above it can be seen that each PDC is responsible for supplying the energy to a specific part of the plant. The two main production lines: Line 1 and Line 2 are supplied with energy by PDC4, PDC5, PDC6 and PDC7, while the Cut and Coat line receives electricity from PDC9. These are the most important PDCs for this project and this is why they were the only ones expanded in the diagram above. The PDCs direct the power to the MCCs which in turn monitor the energy directed to each motor in the plant. Each PDC supplies energy to 6 MCCs.

The MCC energy data is collected by a system called PI, developed by OSIsoft. This system is an operational, event and real – time data management infrastructure, which brings together different types of data from a variety of sources such as: systems, equipment, solutions, applications, locations and networks.

PI gathers and archives large volumes of data on servers. It converts the real time data into actionable information offering access to real – time or historical data for the entire enterprise at any time. It provides notifications and it allows for anyone to view the data graphically, identify problems and take corrective actions.

The data is also recorded in another online system called eSight This is an intranet solution which provides energy analysis and reporting It enables the user to monitor standard utilities such as electricity, gas and water It also facilitates the presentation of data in a wide range of graphs, tables, reports and exports In addition, reports may be run on an ad hoc basis, saved as templates for later use or scheduled for automatic production and distribution by email

3.4. Production Schedules

Each production line runs according to its own production schedule While this research was being conducted the company was running based on a 10-4 production cycle This implies that the company is running for 10 days and it is closed for 4 continuous days The closing period is recorded as ***Shift Cycle Downtime*** During the 10 days when the company is operational the schedules can be

- ***Running*** when a line is running for a full day, without any scheduled downtimes
- ***Market Downtime*** when the line is not running for the day due to a decrease in demand The main difference between ***Shift Cycle Downtime*** and ***Market Downtime*** is that during the first one most of the motors within the plant are completely shut down while during the ***Market Downtime*** some of the motors within the production lines are still running This is justified by emergency orders which can be placed at any time In the case of an emergency order, the company has to be able to start production almost immediately which would not be possible if all the motors are shut down After a ***Shift Cycle Downtime*** it takes the plant around 6 hours to power up and be ready for production
- ***Market Downtime/Running*** when a line is coming from ***Market Downtime*** and is running only during the second part of the day
- ***Running/Market Downtime*** if a production line is preparing for ***Market Downtime*** and is running only through the first part of the day until it reaches the scheduled number of doors to be produced
- The two main production lines also have die changes scheduled according to the demand These are aimed to be performed when the lines are not running

If the die change needs to be performed during a running day, it is logged into the schedule as ***Running/Die Change*** or ***Die Change/Running***.

3.5. Why Use Simulation?

In an ideal situation Masonite would run all production lines for 24 hours, 7 days a week. Due to the economic downturn, at the beginning of this research project Masonite was running on a 10-4 shift cycle and considering reducing the running hours even further. Their main challenge is to maintain a constant energy consumption profile despite a drop in production. Rising energy costs coupled with reduced demand for product has had significant implications on plant efficiencies and competitiveness.

As the main production lines account for over 80% of all energy consumed by the plant, it became evident that Masonite would conduct process orientated research that would focus on improving production efficiency and couple this with the energy consumption across the production lines. The energy model Masonite used at the beginning of this project was becoming inaccurate because it was based on historical production data. This was suitable when production lines were operating at full capacity as they are more efficient from an energy utilization perspective. However, Masonite's product demand has become variable therefore production line schedules and associated energy loads had to be optimized to reflect the variability in demand and the new production run cycles and schedules. Production capacity, at the beginning of this study was running between 60-65%, however the energy that was utilised was not inline with lower capacity runs. The lower the capacity runs for production the less efficient the production lines became from an energy consumption perspective. Evidently this degree of inefficiency cannot be sustained long term and Masonite needed to research and test out new and potentially more efficient production cycles and scenarios, without interrupting the day-to-day production targets that the lines are responsible for meeting.

Through developing simulation models that are representative of Masonite's actual production processes, Masonite engineers will be able to conduct research on a wide range of production and energy efficiency scenarios without having to impact on any physical production process By defining and testing multiple production and energy consumption scenarios through the developed simulation model, the engineers will be better positioned to determine optimal production system parameters that will be required to gain increased production and energy efficiency Therefore, one of the desired outcomes of this project is to lower the energy consumption and more specifically, lower the amount of kilowatts hour consumed per every unit produced

Currently Line1 has a capacity of 1,150 press loads per running day which translates into 32,200 doors Line2 has a capacity of 1,200 press loads per running day which translates in 33,600 doors produced per running day The difference between the two lines comes from the fact that Line 1 has larger dies which slows down the process through the production of larger double door panels

The reduction of the energy consumed for every door produced implies either the improvement of energy efficiency in the same production conditions or an increase in the production while maintaining the energy consumption at the same levels This objective will later on result in a series of scenarios which will aim at improving the kW/unit ratio

3.6. Conclusion

This chapter looked at Masonite and its production process which is similar to the MDF production process Considering the fact that the main production lines account for over 80% of the company's energy consumption the emphasis was placed on detailing the process The author explained the pre press, press and post press processes of the two main production lines Line1 and Line2, and the coating and cutting processes of the Cut and Coat line A meter bloc diagram was also created in order to explain the energy monitoring system in Masonite

Due to economic decline Masonite was forced to change the shift patterns from working 24 hours a day, 7 days a week to working on a 10-4 shift cycle This had a great impact on the company's energy efficiency the energy consumption stayed the same despite a decrease in production This in turn had its own repercussions

- The system that Masonite employed to predict energy consumption and its cost became redundant as it was using past data which was not relevant in the new shift cycle conditions
- Masonite engineers were faced with the need to conduct research on a wide range of production and energy systems Unfortunately this would have a great impact on the physical production process and would not guarantee that the experiments would be successful
- Masonite recognised that their priority was to reduce the amount of kWh consumed per every unit produced This can be done by either increasing the production or decreasing the energy consumption The engineers had a number of scenarios in mind to achieve this but they could not decide on the ones that would make the most difference, to implement

In conclusion a simulation model should be created which would map out the production process in Masonite along with the energy consumption This would provide the engineers with an environment that will allow them to experiment on the simulated system and observe the results in real time, without having to disrupt the physical production process

CHAPTER 4: THE MODEL

CONTENTS

4.1. INTRODUCTION

This chapter aims to present the simulation model that has been built with the purpose of managing and understanding the correlation between the energy consumption and the production schedule in Masonite In order to better understand the modelling environment, the first section of this chapter is dedicated to ProModel This addresses some of the basic capabilities of the simulation software package, starting with a short description The author will then portray the modelling environment starting with the main window and ending with a description of the most important elements being used to put the basis to any simulation model

The second part of the chapter concentrates on the steps that lead to the development of the final simulation project The simulation of any production facility can take many forms It can be as simple as modelling only the amount of raw material going in the system, the end product exiting the production system and the customer demand To a model that is being expanded to include each piece of machinery, each engine and all the activity inside the office spaces in the manufacturing facility This is why there is a need to consider the scope and the level of detail at which the real world system needs to be modelled This process is known as conceptual modelling or designing the model and it includes the understanding of the problem, the model objectives and the determination of the inputs, outputs and the model content

After the development of the conceptual model the author concentrates on data gathering and analysis, which is central to the development and use of a simulation model Despite much effort being put into the design of the conceptual model and the coding of the simulation model, if the data used to populate the model is inaccurate then the model's results will also be inaccurate This chapter includes the description of the necessary data and the way it has been gathered and analysed

Model coding is another key process in the development of a simulation model It involves the conversion of the conceptual model into the computer simulation This process is described in the final part of the chapter It includes detailed information on key implementations of the production schedule, energy modelling, production downtimes and the work in process management

A final important piece of the simulation project development is the testing of the model. This however is addressed in Chapter 5 as part of the model testing and validation.

4.2. PROMODEL

4.2.1. WHAT IS PROMODEL?

ProModel defines its software as being *"a powerful simulation tool for simulating and analyzing production systems of all types and sizes."* Pro model focuses on modelling the resource utilisation, system capacity, productivity and the inventory levels, which gives engineers and managers the opportunity to test new ideas before investing time and resources in altering the actual system.

ProModel is a discrete event simulator designed to model systems where events occur at defined points in time. Its typical applications include: assembly lines, transfer lines and flexible manufacturing systems.

ProModel is an intuitive software package which doesn't require any programming skills. The models are built only by defining the way a system operates, mostly through part flow and operation logic. During the simulation ProModel displays an animated representation of the system on the screen. When the simulation is over performance measures are presented to the user in both tabular and graphed forms for evaluation.

4.2.2. OVERVIEW OF THE SOFTWARE

4.2.2.1. MODELLING ENVIRONMENT

The modelling environment of ProModel is contained in the main window of the software. One of the most important parts of the ProModel environment is the Menu Bar. This gives the user access to all of the tools necessary to build and run a model.

Figure 4.1 The ProModel Menu Bar

- The **File** Menu – allows the user to create a new model, open a new model, save the current model, view a text version of the model and print it, print the graphics layout and merge two or more models into one.
- The **Edit** Menu – provides the user the tools to edit the contents of edit tables and logic windows.
- The **View** Menu – allows the user to control the model's appearance, from controlling layout settings to operating the zoom controls and hiding or viewing paths.
- The **Build** Menu – provides the user with all the modules for creating and editing a model. These include Locations, Entities, Arrivals, Processing, Variables, Attributes, Arrays and Subroutines.
- The **Simulation** Menu – contains all the tools necessary for controlling the execution of a simulation: options for running a model, defining model parameters and running scenarios.
- The **Output** Menu – gives the user access to the ProModel Output Viewer 3DR for viewing model results.
- The **Tools** Menu – provides different utilities such as the Graphic Editor and the find and replace feature.
- The **Window** Menu – allows the user to arrange the windows currently displayed on the screen.
- The **Help** Menu – provides the user access to the ProMoodel Online Help system.

ProModel also offers quick access to the most used options in the Menu bar, through its toolbar.

Figure 4.2 The ProModel Toolbar

The toolbar contains options from the:

- *File menu*, allowing the user to create a new model, open it, save it, create and install a package;

- *View menu*, giving the user the options of zooming, showing the grid, hidden networks and routing paths;
- *Shortcuts to*: Play, Pause, Stop a simulation, Animation on/off and Simulation Options for an easier control of the execution of a simulation model;

4.2.2.2. General Elements

The Build menu is the place where the user finds the general elements needed for building and defining any model. This menu gives access to the locations, entities, arrival rates path networks, resources, downtimes, processing logic, variables and arrays which provide all that is needed for modelling a system.

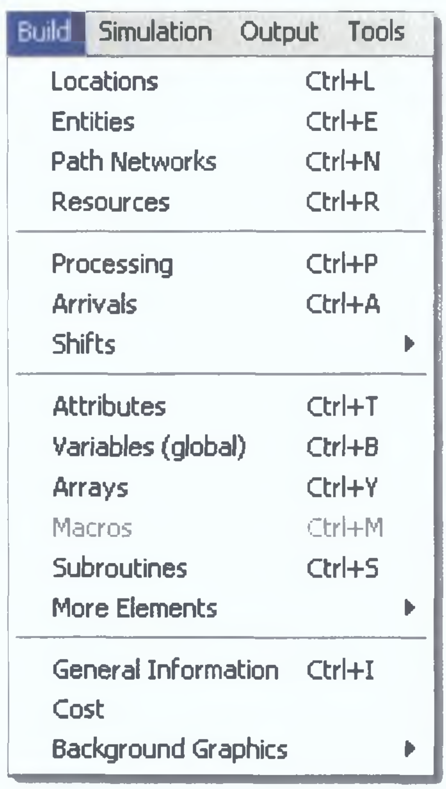

Figure 4.3 The Build Menu

Locations

Locations are the places in the system like warehouse locations, delivery locations and transaction processing centres where elements are routed for processing, storage or any other activity or decision making.

The Locations editor is formed by three windows that can be seen in Figure 4.4: the Location Graphics, the Location Edit Table and the Layout Window.

The Location Edit Table contains eight columns: the Icon column holds the graphic used to represent the location, the Name column represents the location's name, Cap. Stands for the capacity of the location which means the number of entities the location can hold and process at any one time, Units refers to the number of units of a location. A multi unit location stands for several locations with similar characteristics in the real system. DTs represents the location downtime, Stats refers to the level of statistical detail to be gathered for the location, with three levels of data collection available: None, Basic and Time Series. Rules defines the way a location selects the next entity from the ones waiting to enter it, the way multiple entities will queue for output and which unit from a multiple unit location will be selected by an entity. Notes represent any optional observations and notes for a location.

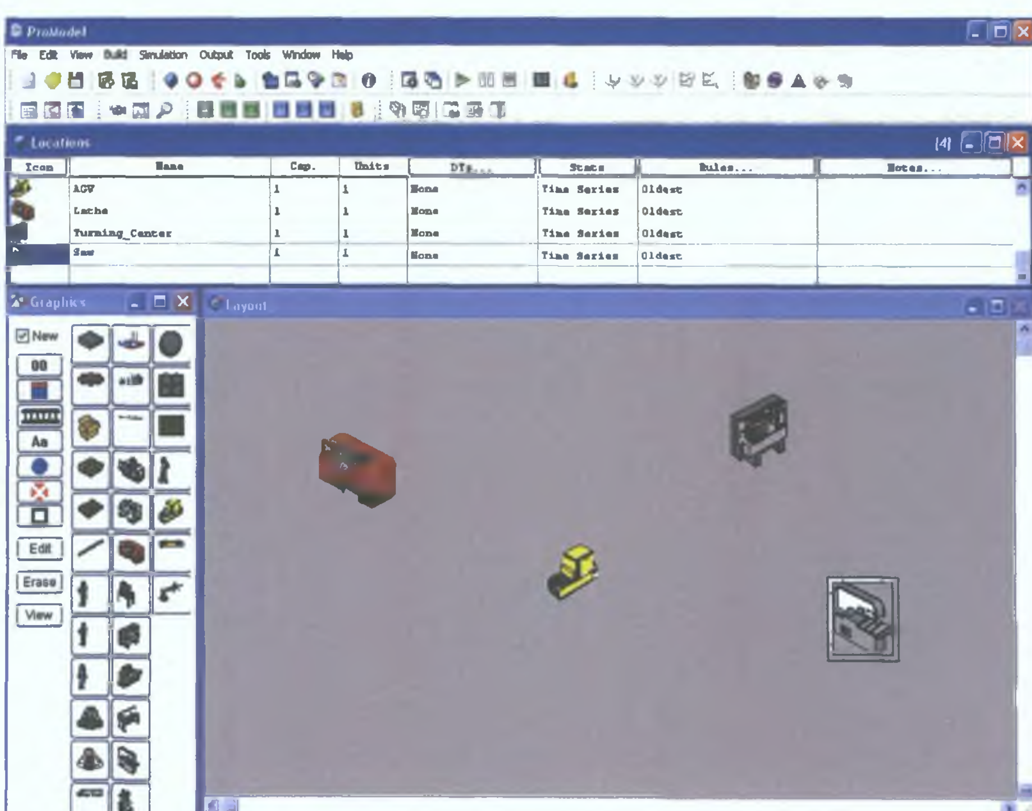

Figure 4.4 The Locations Editor

The Location Graphics Window includes, apart from the basic graphics provided by ProModel the New mode which, if checked, places a new location on the layout window, while unchecked, adds graphics to the current location. The Edit button allows the user to change the colour, dimension and orientation of a location, by showing it in the Library Graphic dialog box. The Erase button erases the graphic of the selected location, without deleting the corresponding record in the Location Edit table. The View button shows the location selected in the Layout table, on the Layout Window.

Entities

Entities are considered to be anything that a model is processing, like documents, people, and phone calls. In order to define an entity, the user has to click on a desired library graphic in the Entity Graphics Editor or by entering its name and characteristics in the Entity Edit Table. Entity graphics are optional.

Arrivals

An arrival represents the introductions of new entities into the system. When defining arrivals the user needs to specify the following information: the number of new entities per arrival, the frequency they arrive at, the location where the entities arrive, the time of the first arrival and the total occurrences of the arrival. The frequency of the arrival can be defined as a number or a distribution.

Processing

Processing defines the routes the entities are taking inside the system and the operations that take place at each location they move through. Once the entities enter the system in Arrivals table, the processing is what directs them through the system to the exit. Adding processing to the system is very simple, with the use of the ProModel interface, making use of the Process Edit Table, Routing Edit Table, Tools Window and the Layout Window.

The user chooses an entity from the Tools Window, clicks on the location that represents the starting point and an arrow appears. Next the user has to click on the location the entity moves to after leaving the previous location. Once the *from–to* relationship defined between all the locations and for all entities, the user will utilize the Process Edit Table and Routing Edit Table in order to fill in the details of operation and move logic for each location.

Variables

There are two types of variables in ProModel: local and global. The local variables are placeholders that are only available in the logic that declared them. Global variables are available anywhere numeric expressions are allowed in the model and represent changing numeric values. Variables are usually used for recording information and decision making.

Global variables are defined in the Variables Editor that can be accessed from the Build menu. When defining a global variable the user is asked to provide an ID which is the variable's name, its type: real or integer, its initial value and the level of detail on which ProModel should collect statistics about the variable: none, basic or time series.

Arrays

An array is a matrix of cells that contain real or integer values. Each of the cells contained in the array behaves like a variable. In order to reference a cell in an array the user needs to give the name of the array followed by each of its dimensions enclosed in square brackets. For example, referencing the third cell in an one-dimensional array would be made as follows: Name[3], referencing the cell on the fourth row and third column in a two–dimensional array would mean writing Name[4,3] (see table below), and so on. In ProModel the maximum dimension of an array is 20.

Rows \ Columns	1	2	3	4	5	6
1						
2						
3						
4			Name[4,3]			
5						
6						

Table 4.1 Graphical Representation of ProModel Arrays

Arrays can be used to import and export information from a spreadsheet. This is done through the Arrays Edit Table by specifying the path to the file and the location inside the spreadsheet where the data will be exported to or will be imported from.

User Defined Distributions

User Defined Distributions are used to define the data sets that cannot be represented by ProModel's built-in distributions. A user defined distribution is a table of data manually gathered and entered into the User Distribution Edit Table. The user can define both continuous and discrete distributions and these can also be cumulative or non – cumulative.

Apart from the general elements presented above the Build menu also contains advanced elements like: attributes, macros, subroutines, table functions, external files and streams. All of these help the user in the development of the model and in building a better understanding of the system that is being simulated.

4.3. Developing the Model

4.3.1. Conceptual Model

The first step in defining the conceptual model is: understanding the problem. As stated in the previous chapter, Masonite is a HDF Moulded Door Skin manufacturing company and it is one of the major energy consumers in Ireland. The production process which consists in the two main production lines and the Cut and Coat line accounts for over 80% of its total energy consumption. The main problem for them is that their energy consumption has remained constant despite a drop in their production.

Having identified the problem, the next step is to determine the modelling objectives. In Masonite's case the main objective is to lower the energy consumption, more specifically, lower the number of kilowatts consumed per every door skin unit produced. One of the major constraints of this project is the fact that the three lines are automated and are part of a continuous process, which makes it difficult to alter their layout. That is why the focus of the project is directed at the production schedule. Therefore the main objective is to try and reduce energy consumption by improving production management But even in this case there are a few constraints which revolve around Masonite's customer policy This policy states that any order that comes in should reach the customer within a two week timeframe This means that the company has to be able to predict some of the orders coming in and they cannot stop production for more than 4 days

With the problem and the objectives defined the next stage is to design the conceptual model which starts with the inputs and outputs These are described as the experimental factors and the responses A diagram of the conceptual model can be found in Figure 4 5

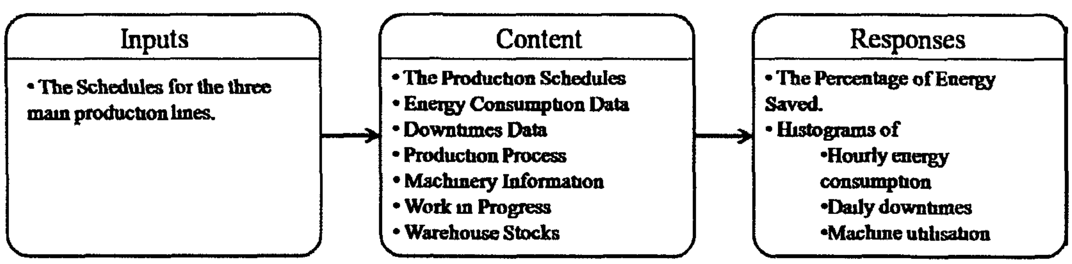

Figure 4.5 Conceptual model

In the case of this project the experimental factors (System Input) consist in the schedules for the three main production lines The response in terms of defining the achievement of the objective (System Output) will be the percentage of saved energy which translates into the amount of money being saved In terms of identifying the reasons to meet the objectives, the responses will be presented under the form of histograms of hourly energy consumption, of daily downtimes and of machine utilization These will be further discussed in Chapter 5

Having identified the model's inputs and outputs, the author proceeded to identify the content of the model itself The first thing the author recognized was that the model needs to be able to accept the experimental factors and to provide the required responses Therefore the model must be able to represent the schedules for the three mam production lines and to provide the relevant reports the hourly energy consumption, the daily downtimes and the machine utilization The model also needs to include the production process along with information on the conveyors, the downtimes, the energy consumption data, the work in progress and the warehouse stock information. All of these are presented in more detail in the next section of this chapter.

4.3.2. Data Collection and Analysis

The Conceptual Model presented above needed to be complemented with real data in order for the simulation model to have a solid base and be credible. From this point of view Data Collection is the most difficult and important part of the simulation model building process. Most of the simulation models run but the quality of the output data is heavily dependent on the quality of the input data. The type of data needed to be collected is usually dictated by the objectives of a project. In the case of this research project the input data includes, but is not limited to production schedule, conveyor speeds and length and historical energy data. This data was collected from the two monitoring systems available on the site.

PI, developed by OSIsoft, is one of the data collection systems installed in Masonite. It is an operational, event and real – time data management infrastructure, which brings together all the different types of data from a variety of sources like: systems, equipment, solutions, applications, locations, networks and suppliers. PI gathers and archives large volumes of data on servers. It converts the real time data into actionable information, offering access to real time or historical data for the entire enterprise at any time. It notifies people anywhere from plant to boardroom and it allows for anyone to view the data graphically, to identify problems and to take corrective actions.

The second monitoring system used by Masonite is an energy monitoring system called eSight. This is an intranet solution which provides energy reporting and analysis of demand and consumption. It enables the user to monitor standard utilities such as electricity, gas and water. It also facilitates the presentation of data to be presented in a wide range of graphs, tables, reports and exports. In addition, reports may be run on an ad hoc basis, saved as templates for later use or scheduled for automatic production and distribution by email. Reports can also be configured to monitor contracts, available capacity and maximum demand.

Since much of the raw data collected from the systems described above cannot be inserted into a simulation model directly, some input analyses such as probability distribution analysis were performed. All the data that was collected over the period of one month, was analysed and recorded in an Excel document called *Interface.xls*. A graphical representation of all the spreadsheets of this document can be found in Figure 4.6. This shows the connections between each sheet and the ProModel simulation model situated in the middle, as well as the connection between the spreadsheets themselves. A copy of the *Interface.xls* document can be found in Appendix C.

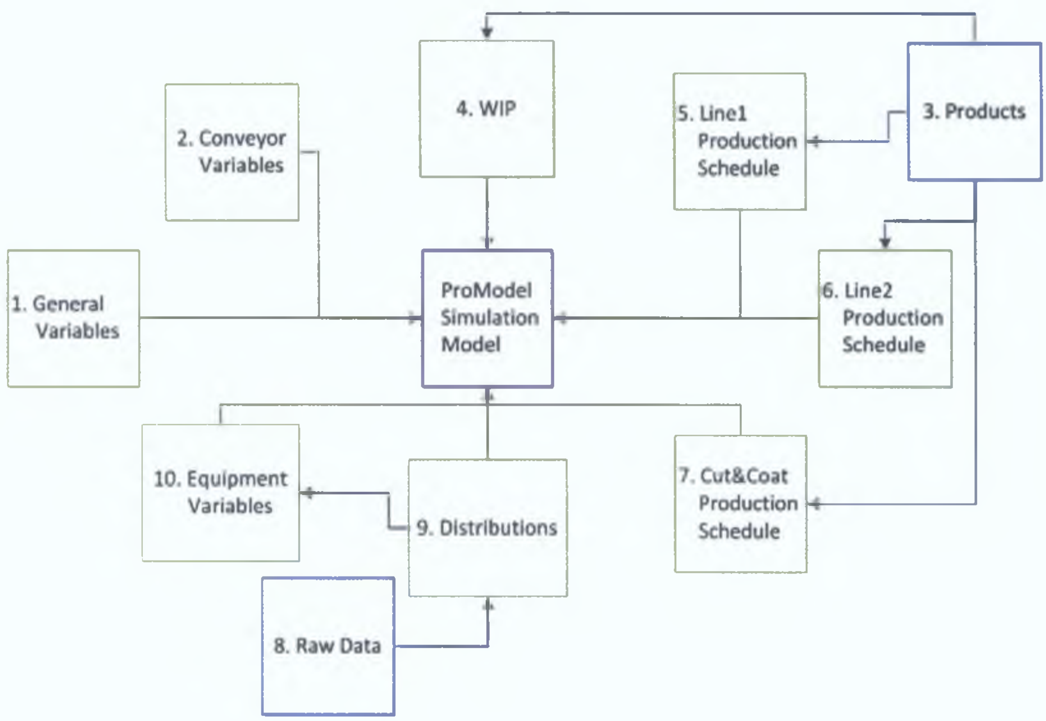

Figure 4.6 The Spreadsheets of the Interface document

The first sheet in the *Interface* document is called *General Variables* and holds the data that doesn't fit in any other sheets of the document. For the moment this sheet contains information on the necessary time for changing the dies in the press. A sample of the data presented in this sheet can be found in Table 4.2. Each column in this table has a capital letter in front of its name. This represents the corresponding letter of the column in the *General Variables* excel spreadsheet. Column B in this sheet is populated with the number of dies that are being changed. This influences the data in Column C which represents the average time needed for the specific number of dies to be changed. Column D holds the standard deviation in time that can be recorded during the dies' change. This data has been provided by the engineers in Masonite.

B - Dies	C - Average (min)	D - Std Dev (min)
1	60	3
2	90	6
3	120	8
4	150	11
5	180	14
6	210	16

Table 4.2 General Variables

The *Conveyor Variables* sheet contains the data for all the conveyors in the model. A sample of this document can be found in Table 4.3. A full copy of this table can be found in the Appendix section and on the attached CD. This includes each conveyor's length in meters and in feet, its speed in feet/hour, as well as an ID and a description for each conveyor.

ID	Description	Length (M)	Length (F)	Speed (F/H)
1	Unloader Conveyors	21.2	69.55	390
2	Incline Conveyors	10.5	34.45	360
3	Corner Transfer Infeed	10.6	34.78	360
4	Weigh Scale	0	0	360
5	90deg Transfer	3.2	10.50	240
6	Transfer Belt Conveyors	20.4	66.93	240
7	Lift Skid Systems	0	0	240
8	Saw Alignment Conveyors	14.4	47.24	300
9	First Pass Saw	0	0	300

Table 4.3 Conveyor Variables

The *Products* sheet holds information relating to the types of door skins produced by Masonite. The company produces ranges of product families and an example of these can be found under the *Description* column in Table 4.4. This data is further used in the sheets containing the work in progress (WIP) and the schedule of the three lines. It helps define the work in progress and the warehouse stock.

The *WIP* sheet contains the warehouse stock levels and the work in progress which represents the number of door skins that have been pressed and are waiting to be pushed into the cut and coat line. This sheet helps Masonite keep track of the type of doors produced and the stock levels during the simulation model. Ideally this sheet is populated with the latest data each time Masonite wants to run the simulation model. This will help in predicting the number and the types of doors Masonite needs to produce during the next period of time, so they can meet their customers' needs. The columns in this sheet along with sample data can be found in Table 4.4 and they hold the following data:

- column B contains a product ID,
- column C contains the name of each type of door that Masonite produces – this is taken from the *Product*'s page,
- column D contains the cutting buffer initial stock level which is the work in progress corresponding to each type of door Masonite is producing,
- column E contains the warehouse stock level at the time,
- column F contains the warehouse demand for each door,
- column G contains the frequency of the specific demand.

B - ID	C - Description	D - Cutting Buffer initial Stock Level	E - Warehouse Stock Level 01.01.2009	F - Warehouse Demand	G - Demand Frequency Days
1	2P ARCH TEXTURED	9430	297133	221878	28
2	3P TEXTURED	5225	76471	156695	12
3	6P TEXTURED	6130	130658	156518	15
4	4P TEXTURED	1125	43465	58434	3
5	4P ARCH TEXTURED	3225	39488	35671	13
6	2P ARCH SMOOTH	4625	21070	13755	13

Table 4.4 The WIP Sample Data

The next three sheets: *Line1ProductionSchedule*, *Line2ProductionSchedule* and *Cut&Coat Production Schedule* contain the same type of information: the production schedule. A graphical representation of the *Cut&Coat Production Schedule* spreadsheet can be found in Figure 4.7. This figure shows that the spreadsheet contains 4 tables:

- *Cut & Coat Production Schedule,*
- *ProModel Lookup,*

- *Run Schedule*
- *Door Type*

Each representation block contains the name of the table, together with the names of the columns that can be found in the table The names of each column are preceded by a capital letter B, C, D etc which represents the corresponding column in the excel spreadsheet

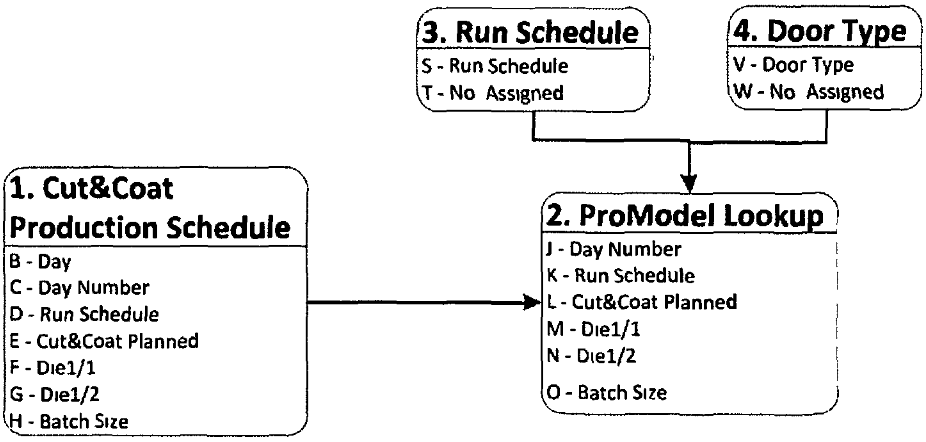

Figure 4.7 Graphical representation of the Cut & Coat Production Schedule Spreadsheet

In the first table *Cut & Coat Production Schedule*, the columns hold the following data

- **Column B** contains the day of the week
- **Column C** holds the day number in the simulation model
- **Column D** contains the run schedule data As explained in Chapter 3 the shift schedule can be
    - *Running*
    - *Shift Cycle Downtime*
    - *Market Downtime*
    - *Market Downtime/Running*
    - *Running/Market Downtime*
    - *Running/Die Change*
    - *Die Change/Running*

All of these conditions that apply to each line have been allocated a code number for the purpose of this project This information can be found on the same sheet in the table *Run Schedule*, **columns S and T** These code numbers are used in the simulation model for easier comparison and identification of each day's shift condition A more detailed description of their use is included in Section 3 3 of this chapter Model Coding, the actual algorithm is presented in Appendix D

- **Column E** in the *Production Schedule* sheets for the three main lines contains the number of press loads scheduled for each day, for the specific line
- **Columns F to AG** in the case of Line1 and Line2 contain the dies that are scheduled to be in the press for each day
- In the case of our example the *Cut&Coat Production Schedule* **columns F and G** contain information on the panels that are being cut and the door types resulting from this process This data is used in determining the work in progress and the warehouse stocks for each type of door

All of the above data is converted in a numeric format for the purpose of the simulation model Each type of door is allocated a number for easier identification in the model These numerical values can be found in the fourth table *Door Type*

The second table in the *Production Schedule* sheets *ProModel Lookup* contains the data presented above, transformed m numerical values This is done automatically in the excel sheet with the use of formulae

The *Raw Data* sheet contains raw data values of downtimes and energy consumption The first part of the *Raw Data* table holds *Downtime* information A graphical representation of this can be found in Figure 4 8 below and the actual spreadsheet can be found in Appendix C as well as on the attached CD

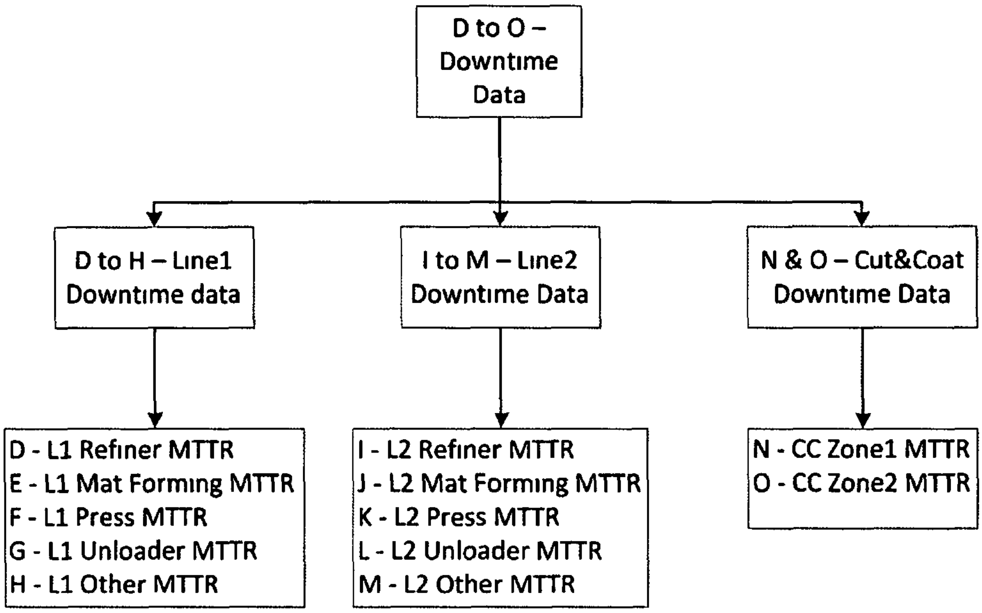

Figure 4.8 Graphical representation of the Raw Data Spreadsheet – Downtime Data

Columns D to O contain the downtime data for the two main production lines Line1and Line2 and for the Cut and Coat line This data represents the mean time to repair (MTTR) The data collected from Masonite in terms of downtimes is at a week's level This means the mean time between failures is weekly which translates to 168 hours As the downtimes can occur every day, in the simulation model the data pulled from this distribution is divided by 7 and because the measure unit within the simulation model is minutes this data is then multiplied by 60 This gives the daily downtime length in minutes

The production lines have also been divided into regions in terms of downtimes The two main production lines have been divided in 4 different regions the refiner, mat forming, press, and unloader downtimes which interfere with specific parts of the lines when downtimes occur Apart from these regions there is one additional category of downtimes that falls into 'Other' and which stops the whole line from running when they occur

The Cut and Coat line has only been divided into two zones zone1 and zone2 which split the line in two Whenever a downtime takes place in one of the zones, this will be the only one that will be stopped

Columns P to CR in the *Raw Data* sheet contain the energy data taken from *eSight*. This data also divides the lines into zones as it is collected by different energy meters. Line1 and Line2 have been divided in:

- Refiner Power
- Driers1
- Driers2
- Refining
- Preload Loader Press Pump A
- Press Pumps BC
- Press Pump D Filter Unloader
- Resin Wax Pumps
- Mat Forming Cleanup
- Precompressor Load Press
- Post Press

The Cut and Coat line has been divided into 5 zones which have been named after the energy meters that collect the data: MCC1, MCC2, MCC3, MCC4, MCC5. The author chose to keep the names allocated by Masonite for each zone so the model would be familiar to the people who operate it. This is the reason the zones' names do not follow a consistent notation.

The energy data collected from *eSight* has been analysed according to the production schedule and divided into three categories for each zone: *Running*, *Market Downtime* and *Shift Cycle Downtime*. This data is used by the simulation model according to the shift it is performing. If the line is *Running* then the data will be taken from the *Running* energy distribution for each zone, if the line is in *Market Downtime* the data will be taken from the *Market Downtime* energy distribution and during the *Shift Cycle Downtime* the data will be pulled from the *Shift Cycle Downtime* energy distribution for each zone.

In the case of *Market Downtime/Running, Running/Market Downtime, Die Change/Running* and *Running/Die Change*, during the period of the day that the line is running the data will be pulled from the *Running* energy distribution and when the line is stopped the data will be taken from the *Market Downtime* energy distribution.

The first two rows in the *Raw Data* sheet record the minimum and the maximum values within the data streams listed in the corresponding columns. The third row calculates the number of values introduced in each column. As stated above each of the columns records raw data of mean downtimes or energy consumption. This information is used for building the user distributions in the *Distribution* sheet.

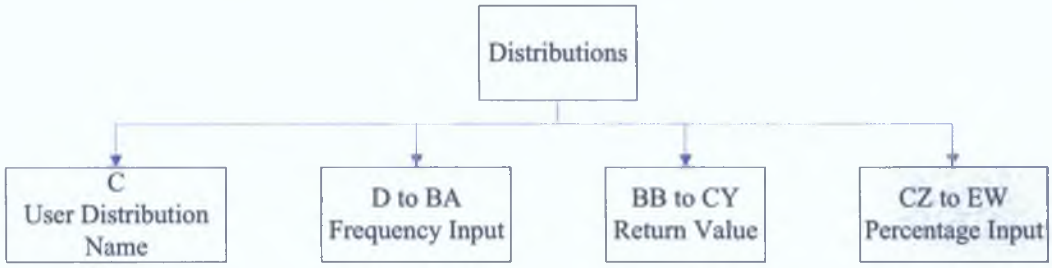

Figure 4.9 Graphical representation of the Distributions Spreadsheet

Figure 4.9 presents a graphical representation of the *Distributions* sheet which contains distributions for energy consumption for all the lines as well as the not scheduled downtimes. These distributions are created using the raw data from the *Raw Data* spreadsheet. They are very important in the development of a simulation model as they look at the raw data and determine the probability of each value to be recorded.

The *Distributions* spreadsheet contains a table that can be divided into 4 main sections. The first section corresponds to **column C** and contains the *User Distribution Names*. The second, third and fourth sections are all interdependent. They represent the *Frequency Input*, the *Return Value* and the *Percentage Input*.

- The ***Return Value*** section looks in the *Raw Data* spreadsheet and determines the minimum and maximum value within each column. The next step divides the interval between these two values into 50 equal intervals.
- The ***Frequency Input*** section of the table looks within the data recorded in the *Raw Data* table for the specific distribution and counts the number of values that are included within each of the 50 intervals recorded into the *Return Value* section
- The fourth section of the table is the ***Percentage Input***. This section looks at the data in the *Frequency Input* section and determines the percentage of each

frequency out of the total amount of frequencies. This gives the probability of each value to be recorded.

The *Distributions* spreadsheet also contains an *Update Distributions* button which updates the distributions in the simulation model, in case the data has been changed. This button can only be pressed when the model is opened in order for the changes to take effect.

B - ID	C - Description	D - MTBF Distribution	E - MTTR Distribution	F - Notes
1	L1 Refiner		L1RefinerMTTR()	
2	L1 MatForming		L1MatFormingMTTR()	0 cycletime as process completed while on conveyor
3	L1 Press		L1PressMTTR()	Time taken to press panels
4	L1 Unloader		L1UnloaderMTTR()	Time taken to press panels
5	L1 Other		L1OtherMTTR()	
6	L2 Refiner		L2RefinerMTTR()	
7	L2 MatForming		L2MatFormingMTTR()	

Table 4.5 The Equipment Variables

The *Equipment Variables* is the last page in the Interface document and a sample of the data included in this sheet can be found in Table 4.5 above. This sheet is used to import the names of the distributions from the Distributions sheet into column I.

- **Column I** of the *Equipment Variables* sheet represents an ancillary column which adds parenthesis '( )' at the end of each distribution's name. This is necessary as it represents the standard way of accessing a distribution in ProModel.
- **Column C** in this sheet contains a description of the distribution, introduced by the user.
- **Column E** is formed of Dropdown lists that contain the Distribution's name. This is being taken from column I which imports the data, as described above, from the *Distributions* sheet.

- **Column D** represents the mean time between events. The events can consist in downtimes, which represent failures or energy recordings. This column has not been used in this model so far because the mean time between downtimes is fixed: 168 hours and the mean time between the energy recordings is also fixed: 1 hour. This column has been kept in this sheet in the event that at a future point in time it may be needed.

Most of the analysis on the collected data has been performed already and the data has been introduced in the model. The author has decided to use an Excel document as an *Interface* for the purpose of familiarity. Most of the staff in Masonite who will work with this model is familiar with the Excel format. The Interface also replicates the look and feel of most of the documents currently generated in Masonite. From this point the data is imported in the simulation model and used to predict stocks and energy consumption as well as performing various scenarios with the purpose of lowering energy consumption.

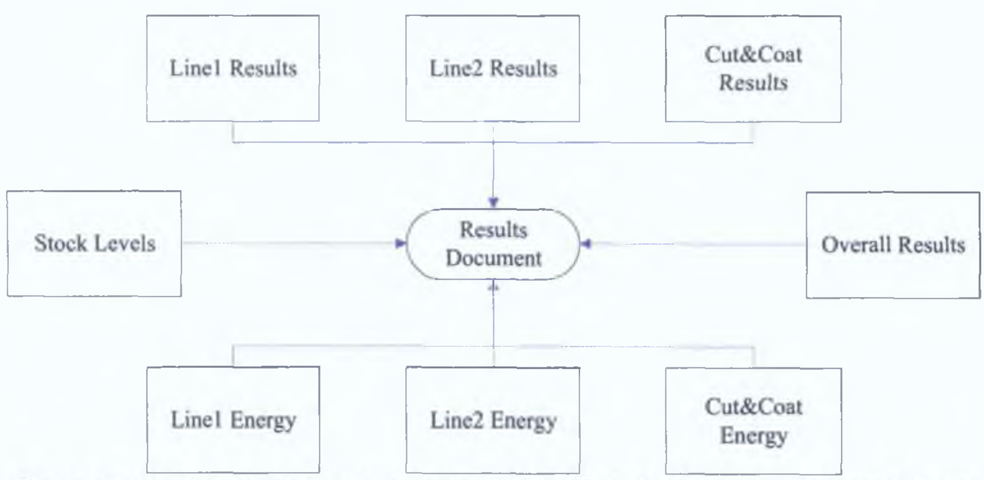

Figure 4.10 Graphical Representation of the Results Document Spreadsheets

The data generated by the model is exported in the *Results* excel document. A graphical representation of this document can be found in Figure 4.10 above.

The *Results* document contains the following spreadsheets:

- Three sheets for Line1, Line2 and Cut&Coat general results which include the schedule, the planned press loads and the actual press loads;
- Overall Results sheet which is being populated by summing up the data in the previous three sheets;

- Stock Levels Sheet which is populated with the number of doors of each type that can be found in WIP and in the Warehouse stock at the end of each simulation day;
- Three sheets that hold information on hourly energy consumption of the Cut and Coat line and the two main production lines: Line1 and Line2.

4.4. MODEL CODING

The model was coded in ProModel, based on the above conceptual model and the unit operation presented in the previous chapter.

The author started the development of the simulation model by mapping the Cut and Coat line along with the two main production lines. In order for the model to match reality and for the Masonite staff to be familiar with its layout, an AutoCad plan of the production unit has been imported as a background into ProModel and all the machinery has been added. This AutoCad plan can be found in Appendix E. A screen shot of Line1 from the model can be found in Figure 4.11.

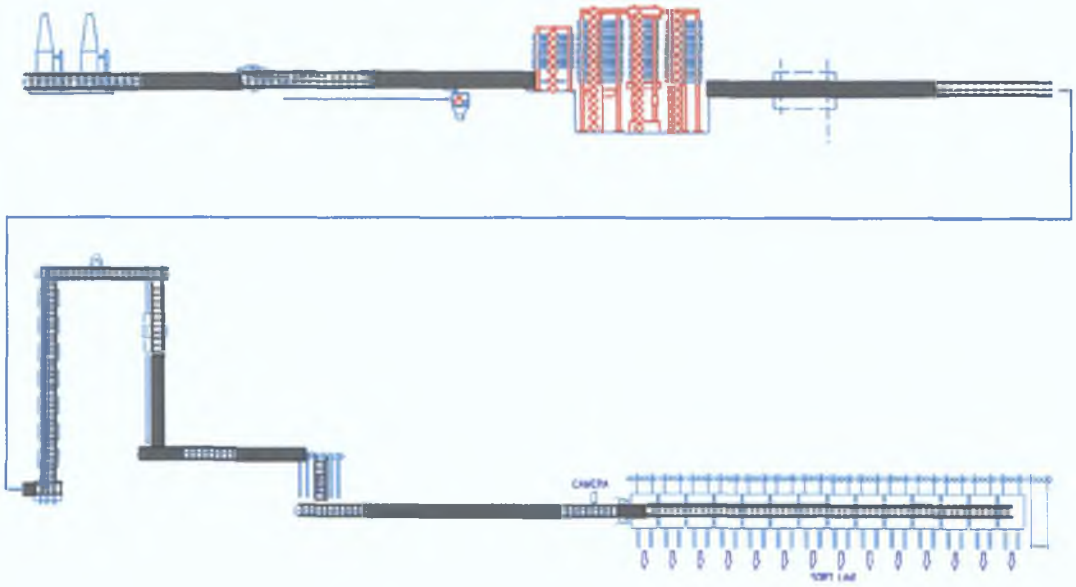

Figure 4.11 ProModel Model

During the process of adding the conveyors to the model, the information concerning their length and speed has been imported from the *Interface* excel document to the *arConveyorSpeeds* array. This array sets the length and speed of each conveyor at the beginning of the running model, allowing Masonite engineers to update this data in the *Conveyor Variables* sheet of the *Interface* Excel document in the event of any changes being made in the real world system, without having to interact with the simulation model

Having defined the locations the author proceeded also to define the entities of the simulation model representative of the wood fibre, the door panels, and the door skins Along with these entities, a control entity has been defined, which is used in modelling the energy consumption, the production schedules and the production downtimes The purpose of the control entity in the model development is explained later in the chapter

The next step in the simulation model development is the definition of the processes which the entities need to follow within the system This resulted in a basic representation of the production process in Masonite, which was followed by the implementation of the production schedules The data representing the three production schedules for Line1, Line2 and Cut and Coat was imported from the Line1 Production Schedule, Line2 Production Schedule and Cut&Coat Production Schedule spreadsheets of the Interface excel document to the following arrays

- *arLine1ProductionSchedule,*
- *arLine2ProductionSchedule*
- *arCutCoatProductionSchedule*

Apart from this, three locations have been created in the model, corresponding the three lines involved in production

- *L1_ProductionSchedule,*
- *L2_ProductionSchedule*
- *CutCoat_ProductionSchedule*

The control entity created above cycles inside each location every 24 hours, determining the beginning of each day within the production schedule

The following variables are also involved in the implementation of the production schedule

- *vL1ProductionScheduleRowRef*, *vL2ProductionScheduleRowRef* and *vCutCoatProductionScheduleRowRef* record the current row in the corresponding Production Schedule Spreadsheets form the Interface document, which also corresponds to the current position in the Production Schedule arrays
- *vL1DayNumber*, *vL2DayNumber* and *vCutCoatDayNumber* record the production day and it is obtained from the production schedule array through *arLine1ProductionSchedule[vL1ProductionScheduleRowRef,1]* The reason why the day number can differ from the current row in the corresponding production schedule spreadsheet of the Interface document and the current position in the production schedule array is due to the changing of the dies Considering an example of Line1 having to produce 1000 pressloads during day 5, out of which 600 should be with the current dies and 400 with a different configuration of dies The data will be introduced in the Line1 Production Schedule spreadsheet from the Interface document as follows
    - *The first row contains* day 5, **Running / Die Change**, the current configuration of dies and 600 pressloads to produce
    - *The next row contains* day 5 again, **Running**, the new configuration of dies and 400 pressloads to produce
- *MaxLineRunningSpeed* is a local variable which keeps in mind the maximum capacity of the line in a certain day As an example Line1 has a capacity of 1150 press loads per day which corresponds to 1150*14 = 16100 door panels as there are 14 pairs of dies in the press

The implementation of the production schedule starts by checking if there still are doors that should have been produced the previous day as they will have to be transferred to the current day Next the model checks the run schedule for the current day This opens seven possibilities

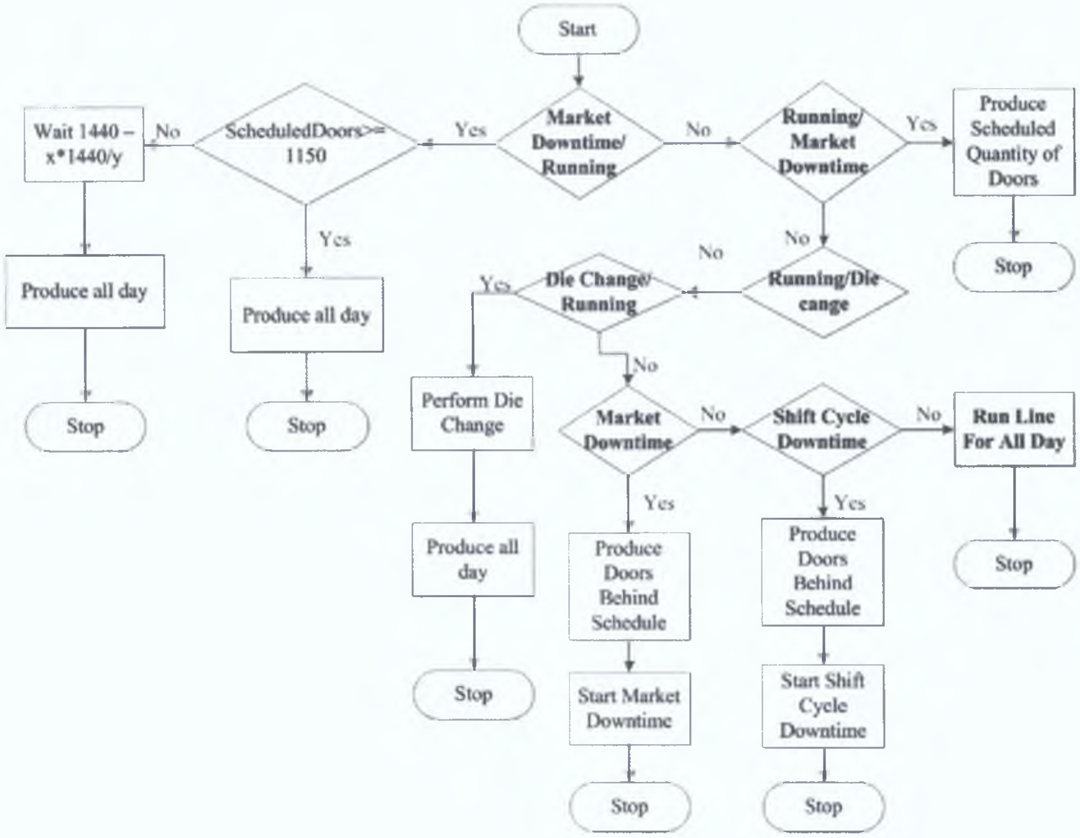

Figure 4.12 Flowchart of the Production Schedule Algorithm

1. If the schedule is **Market Downtime / Running** the model checks if the quantity of doors that are scheduled to be produced along with the quantity of doors that were transferred from the previous day is greater than the maximum capacity of the line. In this case the line will be running for the full day. Contrary, the line will have to wait a certain amount of time before starting production: **1440 – x*1440/y** minutes, where:
   - 1440=60min * 24h – the number of minutes in a day
   - **x** – represents the number of doors that need to be produced on the day
   - **y** – is the maximum capacity of the line
   - **x*1440/y** – represents the number of minutes required for the x amount of doors to be produced
2. If the schedule is **Running / Market Downtime** the line will be running until the scheduled amount of doors, cumulated with the remaining number of doors from the previous day are produced. When the production is over the line will enter *Market Downtime.*

3. In the case of **Running / Die Change**, the changing of the dies is performed after the line produced the quantity of doors that were scheduled. The model uses the data imported in the *arDieChangeTimes* array in order to determine the amount of time needed for the dies to be changed.
4. In the case of **Die change / Running**, the changing of the dies is performed before the line starts production.
5. In the case of **Market Downtime** and **Shift Cycle Downtime**, the model checks if there still are doors that should have been produced the previous day. If this is the case, the remained quantity of doors will be produced before stopping the production and preparing the lines for Market / Downtime or Shift Cycle Downtime.
6. If the schedule for the day is **Running,** the model adds the doors scheduled to be produced on the day with the doors remained to be produced the previous day and it starts production throughout the whole day. If the previous day the production exceeded the number of doors scheduled to be produced, the exceeding amount of doors is subtracted from the scheduled amount for the current day.

After the implementation of the production schedule for the three production lines, the author proceeded in the implementation of the production downtimes and the energy consumption. This part of the model uses the distributions created from the raw data provided by Masonite. The array *arDowntime* imports the names of the user distributions from the Distributions spreadsheet in the Excel Interface document, into the model. One of the assumptions that have been made for the purpose of this model is that the downtimes occur every 24 hours. This assumption was necessary due to the scarcity of data available on Production Downtimes which Masonite collected on a weekly basis. This led to, another array named *arRepairTime* populated with the formula *arRepairTime[i] = arDowntime[i]*60/7.*

In terms of the energy consumption, the model records the data every hour. For the data to reflect reality, the model samples three different user distributions. It first checks if the line is in *Market Downtime* schedule. Then it checks if it is in Shift *Cycle Downtime* schedule. If the model is in neither of these schedule modes it means it is *Running*. After checking the schedule of the line the model samples the corresponding user distribution.

The final part in the model coding is the implementation of the work in progress and the warehouse stock. The data corresponding to the number of door panels being stored between the two main production lines and the Cut and Coat line at the beginning of the simulation process is being imported in the array *arWIP*. This array changes its values each time door panels are produced and each time they are further processed in the Cut and Coat line. Therefore *arWIP* will always contain the amount of door panels that need to be further processed.

Another array: *arDemandFrequencyCount* has been created to keep track of the orders coming in. This array is also used to subtract the amount of doors that have been ordered from the warehouse stock. The new values are recorded in the *arWIPResults* array which will export the data into the *Results.xlsx* file at the end of the simulation process.

Apart from *arWIPResults*, the model populates another six arrays with results of the simulation as follows:

- *arLine1Results* is used to export the production results of Line 1.
- *arLine2Results* is used to export the production results of Line 2.
- *arCutCoatResults* is used to export the production results of the Cut and Coat Line.
- *arMCC9* is used to export the hourly energy consumption for the Cut and Coat Line.
- *arL1MCC* is used to export the hourly energy consumption for Line1.
- *arL2MCC* is used to export the hourly energy consumption for Line2.

All of these results are exported in the *Results.xlsx* file where, for a better understanding of them, reports, charts and diagrams are created. These are presented and explain in Chapter 5 of this thesis.

4.5. Conclusion

This chapter began by presenting a description of ProModel which was aimed at familiarizing the reader with the modelling environment and the general elements used to develop the simulation project.

The second part of the chapter concentrated on the most important aspects of developing a simulation model: the conceptual model, the data gathering and analysis and the coding of the project. It is very important for a conceptual model to be designed in order for the rest of the simulation project to succeed. The conceptual model presented in this chapter helped the author to define and understand the objectives and the main requirements of the project. It also identified the inputs and outputs, depicted as the experimental factors and the responses of the simulation project, along with the actual content of the model itself.

Defining the conceptual model proved to be highly beneficial for the next stages of the project through which the author had to collect and analyse the raw data necessary for the implementation of the simulation model. This process revealed that an assumption had to be made in terms of location Downtimes, as the collected data has been recorded weekly. This led to a compromise in the coding of the model, where the data sampled from the user Downtime distribution had to be divided by 7, in order to represent the daily location downtimes. The model coding also includes details of the production schedule implementation, the monitoring of the energy consumption and the development of the work in progress and customer demand which influences the warehouse stock. Appendix D provides the actual implementation of the Production Schedule described in the last section of this chapter.

Two of the major challenges that the author faced during the development of the project were the implementation of the production schedule and energy consumption.

Even though ProModel allows for production schedules to be implemented through its graphical interface, it was soon realised that this would be a very high level approach to the production schedules implemented by Masonite. The visual representation of production schedules available in ProModel only contains references to the production shifts. Figure 4.13 presents the Shift Editor window which contains a grid, representing the weekly shifts and breaks for locations and resources. This representation of the schedule assumes that the shift pattern is repetitive. The main problem with this is the 10 – 4 production cycles in Masonite which translates in 10 days *Running* and 4 days *Shift Cycle Downtime*. This type of schedule could not be represented in ProModel with the help of the Shift editor. At the same time the production schedule in Masonite contains extra information as the number of doors planned to be produced every day, the type of dies available in the press and one of the seven types of schedules: *Running, Running/Market Downtime, Market Downtime/ Running, Running/Die change, Die Change/Running, Market Downtime* and *Shift Cycle Downtime*. The Shift Editor Window presented below does not facilitate the documentation of all the variables listed above.

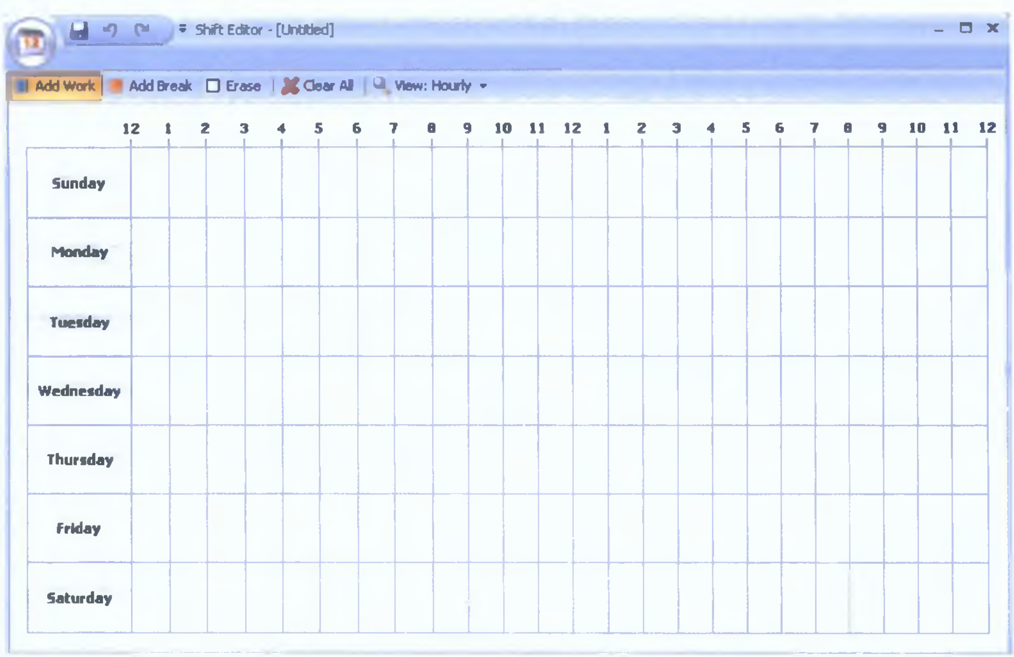

Figure 4.13 The ProModel Shift Editor Window

The solution to this problem is in the implementation of the production schedule as an array. The schedules for the three production lines have been recorded in three spreadsheets inside the Interface excel document. These contain each day's type of schedule along with the number of doors planned to be produced and the types of dies existent in the press. All this information is imported in the production schedule arrays inside the simulation model. A location responsible with the implementation of the production schedule was also created and the algorithm that allows for this production schedule to be employed has been described above.

The second challenge the author faced during the implementation of this simulation model was connected to energy consumption. ProModel is a simulation package mainly designed for manufacturing and supply chain modelling, thus it did not have a predefined method of implementation for energy consumption. The author's first approach to this problem was to implement energy consumption as a variable which would increase its value every hour This proved to be difficult to implement from the time point of view, the variable not being able to realise when an hour has passed in order for it to update its value This is why the author has decided to use dummy locations which represent the energy meters in Masonite A control entity is cycling each of these locations every hour, updating the value of the variable and recording this value in an array At the end of the simulation model this array is exported in the *Results* excel document where charts and diagrams are created

All the data from the model is exported in the *Results xlsx* document where reports are created, along with charts and diagrams of each line's production and energy consumption

The developed simulation model corresponds to an accurate representation of the production facility in Masonite, allowing the users to analyse the model in detail These analyses can be performed both during the simulation run and after the simulation run, through the reports and diagrams from the *Results* Excel document The user is also presented with an easy to use Excel *Interface* document for updating and changing the inputs of the model This document follows the Excel templates already in use by the Masonite engineers

A final issue that has not been discussed is the validation of the simulation project This will be covered in Chapter 5 as part of a more general discussion on the testing, validation and results of the model

CHAPTER 5: MODEL TESTING AND VALIDATION

CONTENTS

5.1. Introduction

This chapter looks at the results obtained from the model, its testing and validation as well as the scenarios implemented.

The first part of the chapter presents the data as it is recorded in the *Results* document. This gives the user a better understanding of the type of data collected by the model and the way this data can be used to create charts and graphs which provide a better understanding of the model's output. The next part of the chapter approaches the testing and the validation of the model which proves the accuracy of the model and provides a base line. This base line is important for the final part of the chapter which looks at the implementation of six scenarios which are as follows:

- 10% energy savings on refiners
- 10% energy savings on driers
- 15% energy savings on driers
- 58 second cycle time on the press
- 55 second cycle time on the press
- 4-3 shift cycle scenario

These scenarios are run a number of times and then the average results from each experiment are compared to the base line. In the end the author looks at all six scenarios side by side with the scope of recommending the most efficient one.

5.2. Model Results and Testing

5.2.1. Model Results

The model results are exported in the *Results.xlsx* document. A graphical representation of this document can be found in Figure 5.1. All the data recorded in this document is used for analysis through charts and diagrams. As the simulation model is run 5 times in order to improve its accuracy there are 5 sets of excel spreadsheets, each set containing the following sheets: *Line1 Results, Line 2 Results, Cut&Coat Results, Overall Results, Stock Levels, Line 1 Energy, Line 2 Energy* and *Cut&Coat Energy*.

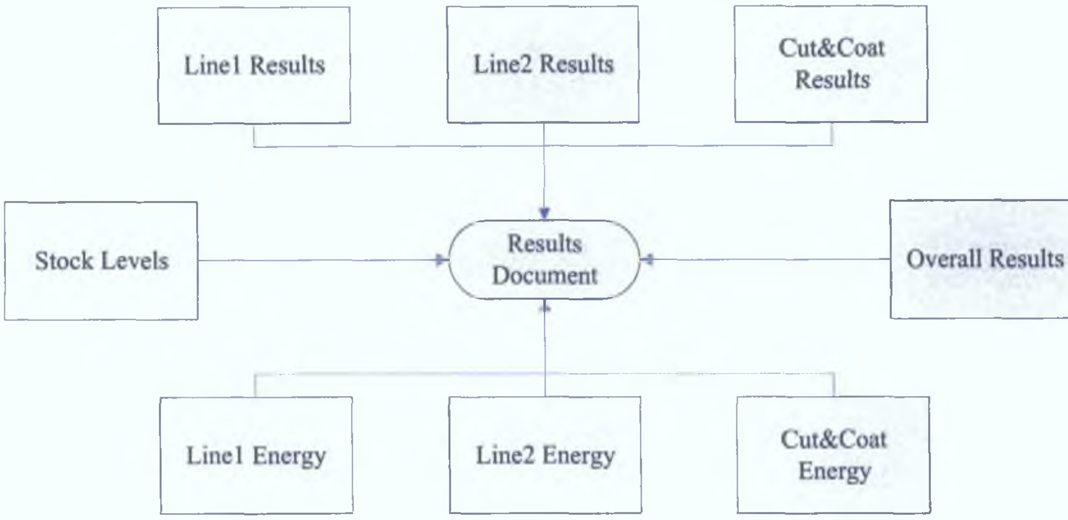

Figure 5.1 Graphical Representation of the Results Document Spreadsheets

Line1 Results, Line 2 Results and *Cut&Coat Results* contain the production schedules for the three production lines. These include: the day of the month, the run schedule for each day, the planned production and the production resulted from the simulation model. An example of this data can be found in Figure 5.2 below.

Line 1 Production Schedule

Day	Day	Run Schedule Line 1	Line 1 Pressloads Planned	Line 1 Pressloads Actual
Mon	1	Shift Cycle Downtime	0	0
Tue	2	Running	1,150	1306
Wed	3	Running	1,150	1005
Thu	4	Running	1,150	1255
Fri	5	Running	1,150	1139
Sat	6	Market Downtime	0	4
Sun	7	Market Downtime	0	0
Mon	8	Market Downtime / Running	750	755
Tue	9	Running	1,150	1112
Wed	10	Running	1,150	872
Thu	11	Running / Market Downtime	550	719
Fri	12	Shift Cycle Downtime	0	0
Sat	13	Shift Cycle Downtime	0	0
Sun	14	Shift Cycle Downtime	0	0
Mon	15	Shift Cycle Downtime	0	0
Tue	16	Market Downtime / Running	300	244
Wed	17	Running	1,150	1194

Figure 5.2 Line1 Production Schedule and Results

The *Overall Results* page records the total amount of door panels produced by each of the two main production lines and the total amount of doors cut by the Cut and Coat line.

The *Stock Levels* spreadsheet records the amount of door panels available in the work in process area (WIP) and the warehouse, before and after the simulation run. A sample of this data can be found in Figure 5.3.

Stock Levels

Product ID	Description	WIP initial stock levels	Warehouse Initial Stock Level	WIP stock levels	Warehouse Stock Level
1	Door Type 1	274462	297133	9430	707534
2	Door Type 2	424171	76471	6530	413444
3	Door Type 3	9430	130658	66070	2350
4	Door Type 4	34454	43465	7210	43514
5	Door Type 5	169230	39488	72834	250709
6	Door Type 6	9425	21070	163210	12530
7	Door Type 7	9425	20649	92253	218590

Figure 5.3 The Stock Levels Spreadsheet

The blue figures: *WIP initial stock levels* and *Warehouse Initial Stock Level* represent the amount of doors available in the WIP area and the warehouse before the simulation run while the orange figures: *WIP stock levels* and *Warehouse Stock Levels* represent the data collected after the simulation run. This sheet is meant to help Masonite to predict the types of doors they need to produce according to their demand.

The final three sheets *Line1 Energy*, *Line2 Energy* and *Cut&Coat Energy* record energy consumption throughout the simulation run. Both Line1 and Line2 record eleven values each for every hour within the simulation run while Cut&Coat records five values for every hour within the simulation run. All of these values form data streams corresponding to the energy meters in Masonite. After the data is exported in the corresponding excel spreadsheets it is analysed with the help of graphs and charts. An example of the Cut&Coat energy consumption graph throughout a month can be found in Figure 5.4.

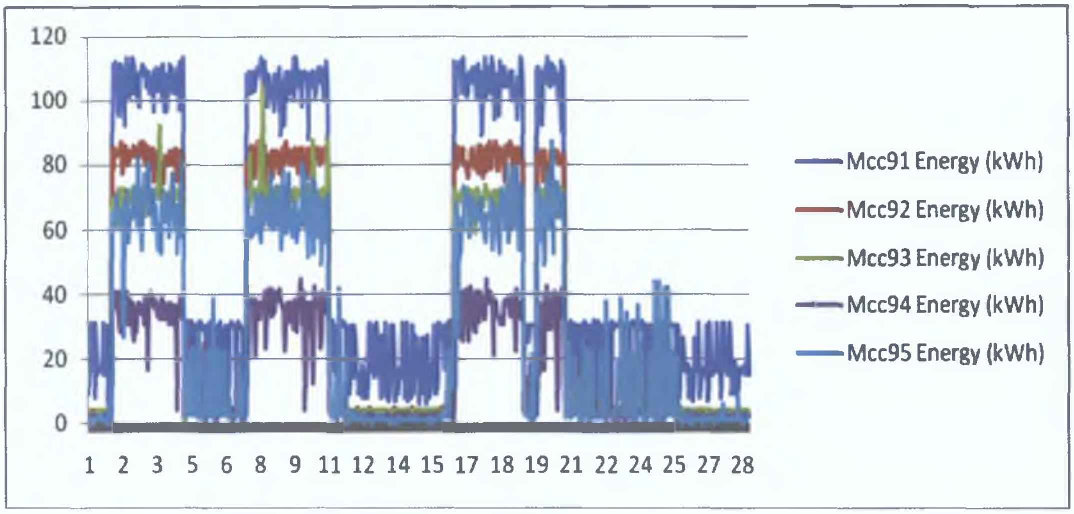

Figure 5.4 The Cut&Coat Energy Consumption Throughout a Month

The horizontal axis represents the days of the month while the vertical axis records the amount of energy in kilowatts per hour consumed. The five streams of data that can be observed through this graph represent energy consumption recorded by the five energy meters in Masonite that monitor the energy consumed within the Cut&Coat Line: MCC91, MCC92, MCC93, MCC94 and MCC95. Each of these meters records the energy consumed by different parts of the production line. The author chose this particular graph as an example for the fact that the energy consumption graphs for both of the other lines are too crowded.

From the graph above it is easy to mote the times when the line was *Running* and when it was in Shift Cycle Downtime. Looking at the graph at a larger scale one can also observe the downtimes in the line and the part of the line that corresponds to these downtimes. Further analysis can allow Masonite engineers to avoid certain unpredicted events, if the simulation is being run on a longer period of time. As an example they may notice the repeated or prolonged occurrence of certain downtimes within the energy consumption recorded by a certain meter. This could give them enough time to investigate that specific part of the production line and prevent the downtime from happening.

Another way of looking at the data exported by the simulation model shows that out of the three production lines Cut&Coat consumes the least amount of energy per month while Line1 and Line2 are the main consumers with roughly the same amount of energy consumed per month. This can be noticed in Figure 5.5 below which looks at the energy results within a month of simulation run. The horizontal axis records the days of the month while the vertical axis presents the amount of energy in kWh consumed. The three streams of data that are being graphed represent the total energy consumed by each production line, recorded on an hourly basis within the simulation run.

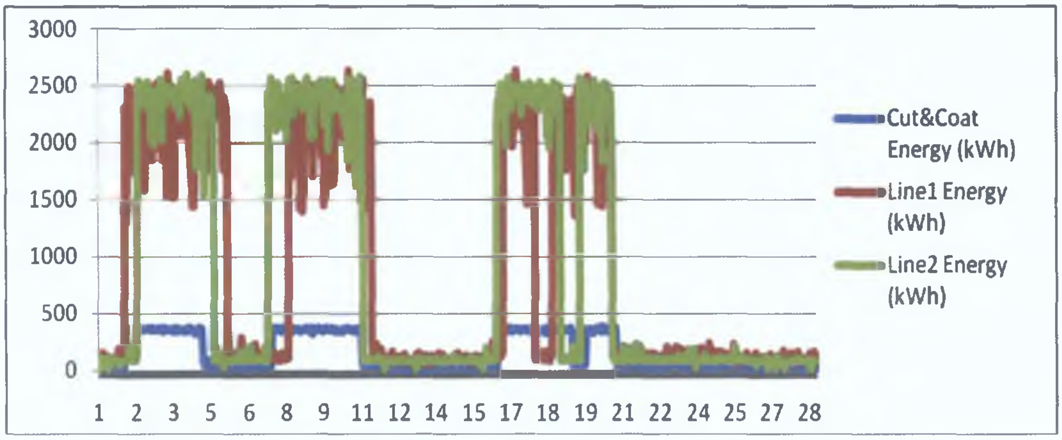

Figure 5.5 The Total Energy Consumption for the Three Production Lines

As stated at the beginning of the chapter, apart from energy consumption, the simulation model also exports data related to production for each of the three lines. These two sets of data can be helpful in understanding the correlation between energy consumption and production. Figure 5.6 shows this correlation for the two main production lines: Line1 and Line2. The Cut&Coat line is not presented on the same graph because of the big difference in both the energy it consumes as well as its production levels compared to the other two lines. As it can be observed from the graph above the Cut&Coat line consumes much less energy consumption compared to Line1 and Line2. At the same time the Cut&Coat line cuts on average 65000 panels per *Running* day which is a greater compared to the 1150 - 1200 press loads produced by Line1 and Line2 within a *Running* day. For these reasons the correlation between production and energy consumption for the Cut&Coat Line has been charted in a separate graph which is included in Appendix F.

From the graph below it can be observed again that the two main production lines follow roughly the same linear trend when it comes to production and energy consumption. The more the lines produce, the more energy they consume.

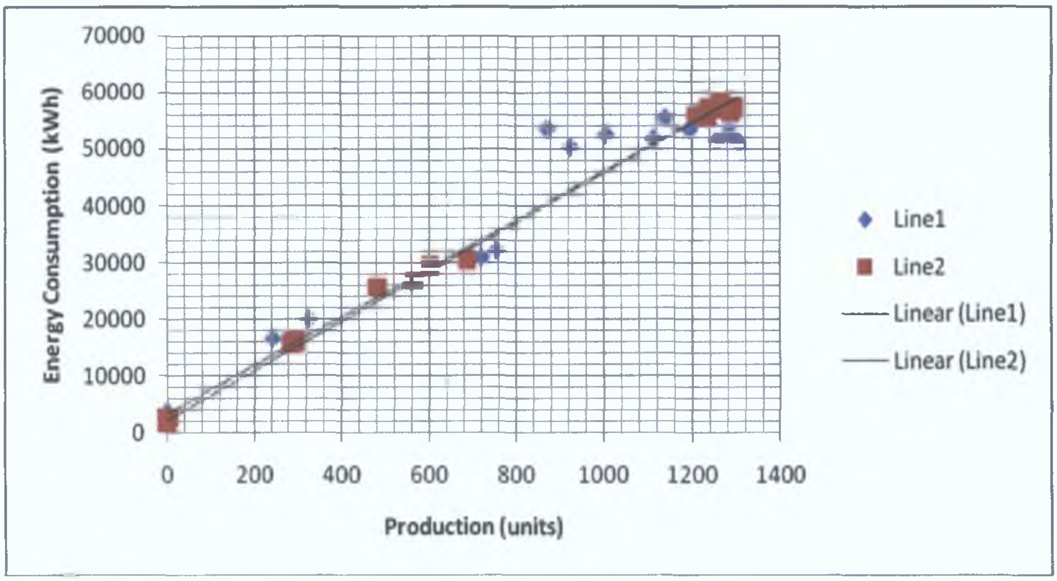

Figure 5.6 The Correlation between Production and Energy Consumption for Line1 and Line2

5.2.2. Model Testing

The author started the model testing by looking at the real world data gathered from Masonite. In order to prove that the model is valid the author took one month of actual data which included the production schedules for the three lines and the actual energy data. The author compared side by side the production schedule and the actual energy data. This resulted in three main data streams: the first one contained the actual energy data for only the periods when the line was *Running*, the second one for only the periods when the line was in *Market Downtime* and the third stream recorded the actual energy data for only the periods when the line was in *Shift Cycle Downtime*. This process was repeated for each production line. At the end of this process the actual data was recorded in the *Interface* document. For more information on data gathering refer to Chapter 4.

The next step in the testing process involved running the simulation model five times. At the end of the simulation the results were exported in the *Results* document. Here the average monthly energy consumption was calculated for each production line. As already stated in Chapter 3 each production line is monitored by multiple energy meters. The author decided to compare the monthly energy consumption resulted from the simulation model for each meter as well as the overall energy consumption of each of the production lines with the actual data gathered from Masonite. This process was executed in a new document called *Validation*. This document contains the actual monthly energy data taken directly from Masonite's PI and eSight systems, as well as the monthly data from the five runs of the simulation model. For greater accuracy the actual data was compared to the average data of the five simulation runs and the comparison was made based on common inputs of the production schedule.

Figure 5.7 presents a graph of the actual energy consumption data and the average energy consumption data of the five simulation runs for the meters that monitor the energy consumption for Line1. It is clear that the difference between the two sets of data is quite small. The results show that the model is able to simulate the functionality and the energy consumption of Line1 with an average accuracy of 96.53%. This has been calculated by dividing the total *Average Simulation Run Energy Consumption* to the total *Actual Energy Consumption* for Line1. The margin of error within which the simulation model predicts the energy consumption for Line1 is -4.77% to -2.71%. This is achieved by examining the five simulation runs, choosing the minimum and the maximum total energy value that has been recorded between them and comparing it with the actual energy consumption recorded in Masonite for the selected month. The margin of error is expected as the model uses probability distributions to simulate the production and energy consumption of Line1.

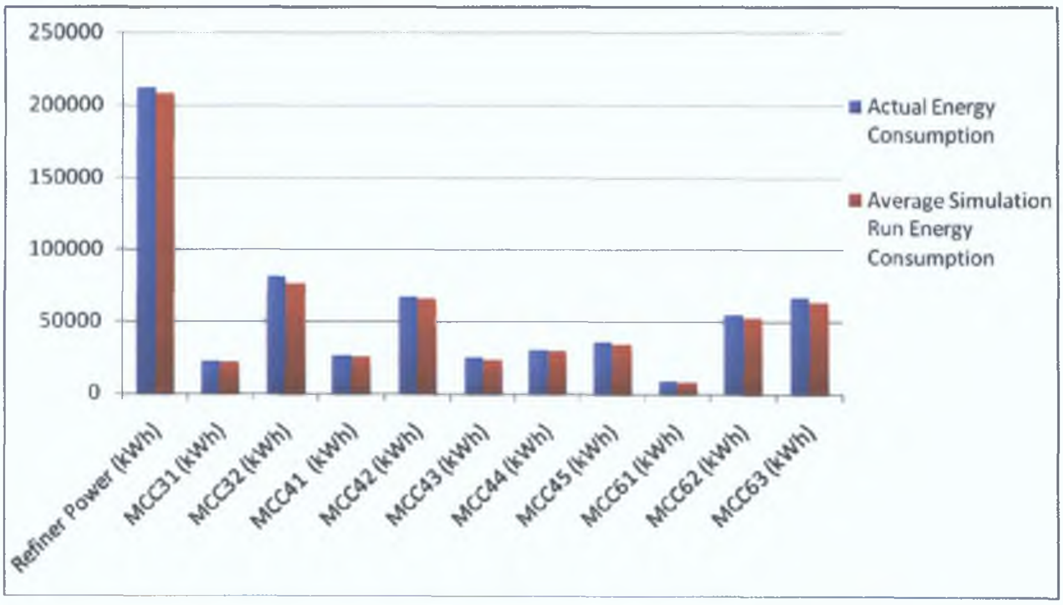

Figure 5.7 Line1Energy Data Comparison between the Actual Data and the Simulation Results

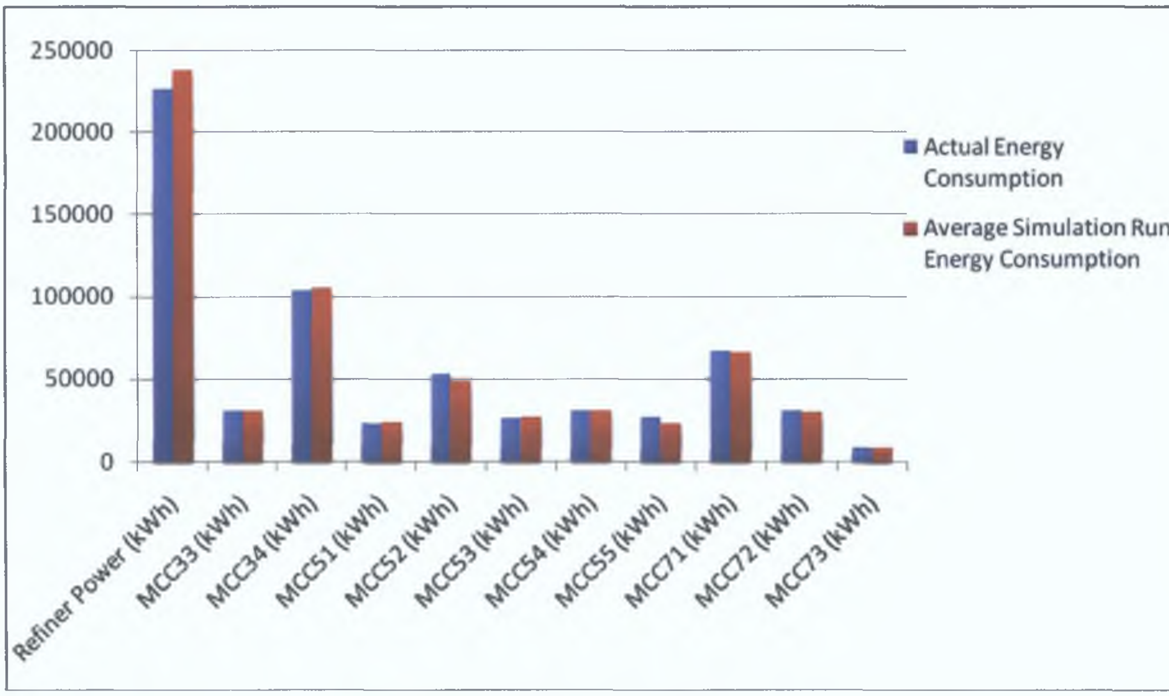

Figure 5.8 Line 2 Energy Data

Figure 5.8 presents the average results of the five simulation runs for Line2, along with the actual data recorded in Masonite. It is clear that apart from the *Refiner Power,* the rest of the simulated meters produced a very small difference to the actual energy meters in Masonite. The results show the model is able to simulate the functionality and the energy consumption of production Line2 with an average accuracy of 100.71%. This result was obtained by dividing the total *Average Simulation Run Energy Consumption* to the *Actual Energy Consumption* for Line2. The margin of error within which the model predicts the energy consumption of Line2 is -0.04% to 1.62%. This resulted from calculating the minimum and the maximum values from the range figures of the five simulation runs. The margin of error was expected as the model uses probability distributions to simulate the production and energy consumption of Line2.

Figure 5.9 below presents the average results of the five simulation runs for the Cut and Coat line along with the actual data recorded in Masonite. This data shows the accuracy of the simulation model which is able to predict the energy consumption of the Cut and Coat line within an average of 94.94%. This result was obtained by dividing the total *Average Simulation Run Energy Consumption* to the *Actual Energy Consumption* for the Cut and Coat Line. The margin of error within which the simulation model predicts the energy consumption of the Cut and Coat line is

-5.71% to -4.19%. This is achieved by looking at the five simulation runs, choosing the minimum and the maximum total energy value recorded between them and comparing it with the actual energy consumption recorded in Masonite for the selected month. The margin of error was expected as the model uses probability distributions to simulate the production and energy consumption of the Cut & Coat Line.

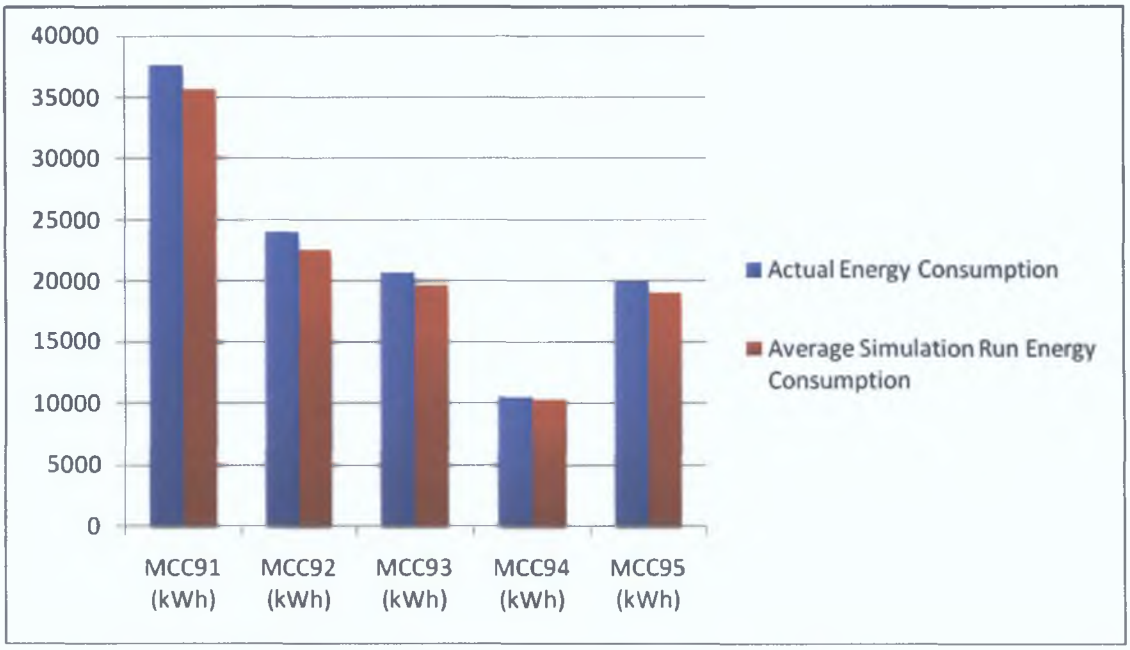

Figure 5.9 Cut and Coat Energy Data

Table 5.1 presents the data collected from Masonite as well as the data from the simulation model in terms of production. Column two presents the production data for Line1, column three presents the production data for Line2 and column four shows the production data for the Cut and Coat line. The first row in this table looks at the actual data recorded by Masonite while the next rows look at the data recorded in each of the five simulation runs for the three main production lines. The final two lines of the table record the average of the production data recorded in the five simulation runs as well as the percentage of the this average out of the actual data recorded by Masonite. This data shows the simulation model is able to predict Masonite's production within an average of 3.06% for Line1, 1.59% for Line2 and 0.86% for Cut and Coat.

	Line1 Production (press loads)	Line2 Production (press loads)	Cut&Coat Production (doors)
Actual Totals	11741	12391	643870
Simulation Totals			
Run 1	12144	12969	649120
Run2	12264	12789	639540
Run3	12085	12214	635040
Run4	12127	12401	663560
Run5	11880	12565	659690
Average	12100	12588	649390
Average/Actual (%)	103.06%	101.59%	100.86%

Table 5.1 Production data for the three main production lines

For a better comparison with the real data the author decided to calculate the amount of energy consumed for each door skin processed within the three production lines. In order to accomplish this, the total amount of energy consumed by each line has been divided by the total amount of doors produced by that line. The total amount of doors produced by each line was obtained by multiplying the number of press loads by 14, as there are 14 dies in the press. The results can be found in Table 5.2 below.

	Line1	Line2	Cut&Coat
Simulated	3.61	3.60	0.17
Actual	3.85	3.63	0.18
Simulated/Actual%	93.67%	99.14%	95.32%

Table 5.2 The kWh/unit door panel data for the three production lines

From the table above can be determined that the accuracy of the simulation model in terms of kilowatt hours per unit (where 1 unit corresponds to 1 door) for Line1 is 93.67%, for Line2 is 99.14% and for the Cut and Coat line is 95.32%.

The author, along with Masonite agreed that this is an acceptable margin of error as long as this data acts as a base for future variations of the model to be compared against. This would give a more realistic view of improvements made by future experiments conducted on the three production lines.

5.3. CONDUCTED EXPERIMENTS

After the validation of the model the author proceeded to implement a number of scenarios which look at varying the model inputs to try to optimise the model outputs with the scope of lowering energy consumption and in the end lowering the kilowatt hours per unit value for each line. Masonite has also been involved in this process as they already have proposed a number of scenarios. They identified a number of projects they could implement to lower the energy consumption and decided to use the simulation model in order to prioritise between them. The first three experiments chosen to represent scenarios in the simulation model look at what the impact the reduction of energy consumption of the refiners and driers will have on the kilowatt hour per unit output and overall energy consumed. The following two scenarios look at lowering the press cycle time for both main production lines and how this impacts on production and energy consumption output in terms of kilowatt hour per unit. The last scenario looks at the impact that a change in the shift cycle might have on the production and energy consumption outputs. With this in mind the six chosen scenarios are as follows:

- 10% energy savings on refiners
- 10% energy savings on driers
- 15% energy savings on driers
- 58 second cycle time on the press
- 55 second cycle time on the press
- 4-3 shift cycle scenario

The above scenarios have been implemented and run 5 times in order to determine a realistic average energy saving.

The first scenario looked at the effects of lowering the refiners' energy consumption by 10% on the overall energy consumption and the kilowatt hours per unit. Masonite engineers are planning to achieve this target by redesigning the refiner plates and by making sure they maintain low energy consumption through changing used refiner plates sooner. This experiment resulted in an overall drop in energy consumption of the two main production lines by 3.58% which would save Masonite approximately €320,800 per year. This cost has been calculated with the following formula:

Cost = ((L1BaseEnergyConsummed –L1ScenarioEnergyConsummed)+ (L2BaseEnergyConsummed –L2ScenarioEnergyConsummed)) * 12 * €0.6

Table 5.3 Cost Formula

Within the above formula:

- *L1BaseEnergyConsummed* represents the Line1 energy consumption resulted from the run of the base simulation model for a duration of one month;
- *L1ScenarioEnergyConsummed* represents the Line1 energy consumption resulted from the run of the simulation model within the current scenario for a duration of one month;
- *L2BaseEnergyConsummed* represents the Line2 energy consumption resulted from the run of the base simulation model for a duration of one month;
- *L2ScenarioEnergyConsummed* represents the Line2 energy consumption resulted from the run of the simulation model within the current scenario for a duration of one month;
- *12* represents the number of months in order to find the approximate cost per year;
- *0.6* represents the approximation in euro, of the cost of one kW of energy consumed at the time of this study. This figure has been provided by the Masonite engineers as the approximate figure that they are using within their estimations of the cost of energy consumption.

In terms of kWh/unit the implementation of this scenario would decrease the amount of kWh/unit by 3.60% for Line1 and by 3.89% for Line2. As the Refiner performance does not affect the Cut and Coat line, this has been left out of the calculations. In terms of cost, the implementation of this scenario would decrease the amount of €/unit by 3.24% for Line1 and 3.70% for Line2.

	Line1	Line2	Line1+Line2
Base simulation model			
Production (units)	169,400	176,232	345,632
Energy Consumption (kWh)	610,737	634,238	1,244,975
Cost (€)	366,442	380,543	746,985
kWh/unit	3.61	3.60	3.60
€/unit	2.16	2.16	2.16

10% energy savings on refiners scenario			
Production (units)	169,400	176,232	345,632
Energy Consumption (kWh)	589,972	610,443	1,200,415
Cost (€)	353,983	366,266	720,249
kWh/unit	3.48	3.46	3.47
€/unit	2.09	2.08	2.08
Overall savings			
kWh saved/month	20,765	23,795	44,560
€ saved/month	12,459	14,277	26,736
kWh saved/year	249,180	285,540	534,720
€ saved/year	149,508	171,324	320,832
%kWh saved	3.40%	3.75%	3.58%
% kWh/unit saved	3.60%	3.89%	3.61%
% €/unit saved	3.24%	3.70%	3.70%

Table 5.4 The data for the 10% energy savings on the refiner scenario

The second and third scenarios looked at the effects of lowering the energy consumption of the driers by 10% and by 15%. This can be achievable by analysing the design of the driers and reducing airflows through the system where possible. Typically, during the design of the dryers, the designers build in safety margins. This design will then be taken by an engineer who will add his own safety margins. This results in large safety margins which cause waste of energy.

When the 10% energy savings on driers scenario was run the overall results showed a decrease of only 1.62% in the energy consumption for Line1 and 2.15% for Line2. This translated in a total of approximately €170,000 savings per year. This can be calculated by using the cost formula presented in Table 5.3 and the data in the table below, by adding the Line1 and Line2 € saved/month and multiplying this sum by 12. In terms of the amount of energy consumed for each door produced, the implementation of this scenario resulted in a 1.94% decrease in the amount of kWh/unit for Line1 and 2.22% decrease for Line2. Apart from this, the implementation of this scenario would decrease the cost per unit by 1.39% for Line1 and 2.31% for Line2.

The 15% energy savings on the driers scenario also resulted in fairly low energy savings of 2.43% for Line1 and 3.23% for Line2. By using the cost formula presented in Table 5.3, the cost of these energy savings can be calculated at approximately €254.000 per year, or 2.31% of cost savings for each unit produced by Line1 and 3.24% cost savings per unit produced by Line2. This scenario also decreased the amount of kW/unit by 2.49 % for Line1 and 3.33% for Line2 as it can be seen in the table below.

	Line1	Line2	Line1+ Line2	Line1	Line2	Line1+ Line2
Base simulation model						
Production (units)	169,400	176,232	345,632	169,400	176,232	345,632
Energy Consumption (kWh)	610,737	634,238	1,244,975	610,737	634,238	1,244,975
Cost (€)	366,442	380,543	746,985	366,442	380,543	746,985
kWh/unit	3.61	3.60	3.60	3.61	3.60	3.60
€/unit	2.16	2.16	2.16	2.16	2.16	2.16
Scenarios simulation data						
Production (units)	169,400	176,232	345,632	169,400	176,232	345,632
Energy Consumption (kWh)	600,838	620,579	1,221,417	595,887	613,721	1,209,608
Cost (€)	360,502	372,347	732,849	357,532	368,232	725,764
kWh/unit	3.54	3.52	3.53	3.52	3.48	3.50
€/unit	2.13	2.11	2.12	2.11	2.09	2.10
Overall savings						
kWh saved/month	9,899	13,659	23,558	14,850	20,517	35,367
€ saved/month	5,940	8,196	14,136	8,910	12,311	21,221
kWh saved/year	118,788	163,908	282,696	178,200	246,204	424,404
€ saved/year	71,280	98,352	169,632	106,920	147,732	254,652
%kWh saved	1.62%	2.15%	1.89%	2.43%	3.23%	2.84%
% kWh/unit saved	1.94%	2.22%	1.94%	2.49%	3.33%	2.77%
% €/unit saved	1.39%	2.31%	1.85%	2.31%	3.24%	2.77%

Table 5.5 The kWh/unit data for the 15% energy savings on the driers scenario

The next two scenarios looked at the press cycle time for the main two production lines. The current cycle time for the presses of both Line 1 and Line 2 is 60 seconds. Masonite is considering lowering this time to 58 seconds or even to an ideal 55 seconds per press cycle. The simulation model provided a better understanding of the impact the implementation of these two projects could have on the amount of kWh/unit consumed.

The fourth considered scenario is the lowering of the press cycle of both production lines to 58 seconds. This resulted in a reduction of energy consumption for Line1 from 610,737 kWh per month to 607,175 kWh per month which represents a 0.58% decrease in energy consumption. For Line2 the monthly energy consumption dropped from 634238 kWh to 632,014 kWh which represents a 0.35% decrease in energy consumption. The overall decrease in energy consumption for the two Lines would save Masonite approximately €40,000 per year. This cost is calculated from the data presented in Table5.6 by adding the Line1 and Line2 € saved/month and multiplying this sum by 12. Apart from this saving an increase in production can be noticed: from 169,400 units to 175,784 units for Line1, which represents a 3.77% increase and from 176,232 units to 182,938 units for Line2, which represents a 3.80% increase. This implies a decrease of the kWh/unit by 4.43% for Line1 and 4.17% for Line2.

	Line1	Line2	Line1+Line2
Base simulation model (60 seconds cycle time on press)			
Production (units)	169,400	176,232	345,632
Energy Consumption (kWh)	610,737	634,238	1,244,975
Cost (€)	366,442	380,543	746,985
kWh/unit	3.61	3.60	3.60
€/unit	2.16	2.16	2.16
58 second cycle time on press			
Production (units)	175,784	182,938	358,722
Energy Consumption (kWh)	607,175	632,014	1,239,189
Cost (€)	364,305	379,208	743,513
kWh/unit	3.45	3.45	3.45
€/unit	2.07	2.07	2.07
Overall savings			
kWh saved/month	3,562	2,224	5,786
€ saved/month	2,137	1,335	3,472
kWh saved/year	42,744	26,688	69,432
€ saved/year	25,644	16,020	41,664
%kWh saved	0.58%	0.35%	0.46%
% kWh/unit saved	4.43%	4.17%	4.17%
% €/unit saved	4.17%	4.17%	4.17%

Table 5.6 The data for the 58 second press cycle scenario

The next scenario considered was the ideal 55 second press cycle for both of the production lines. This resulted in a decrease in energy consumption form 610,737 kWh to 603,403 kWh for Line1, which represents a decrease of 1.20% and from 634,238 kWh to 627,577 kWh for Line2 which represents a decrease of 1.05%. This would save Masonite approximately €100,700 per year, cost calculated by adding the € saved/month for both Line1 and Line2 and multiplying the result by 12. Similarly to the previous scenario an increase in production was noticed from 169,400 units to 184,212 units for Line1, which represents a 8.74% increase and from 176,232 units to 192,052 units for Line2 which represents a 8.98% increase. This decreased the kWh/unit value by 9.41% for Line1 and 9.44% for Line2. So far this was the most productive scenario encountered and the data can be found in Table 5.6 below.

	Line1	Line2	Line1+Line2
Base simulation model			
Production (units)	169,400	176,232	345,632
Energy Consumption (kWh)	610,737	634,238	1,244,975
Cost (€)	366,442	380,543	746,985
kWh/unit	3.61	3.60	3.60
€/unit	2.16	2.16	2.16
55 second cycle time on press			
Production (units)	184,212	192,052	376,264
Energy Consumption (kWh)	603,403	627,577	1,230,980
Cost (€)	362,041	376,546	738,588
kWh/unit	3.27	3.26	3.26
€/unit	1.96	1.96	1.96
Overall savings			
kWh saved/month	7,334	6,661	13,995
€ saved/month	4,401	3,997	8,398
kWh saved/year	88,008	79,932	167,940
€ saved/year	52,812	47,964	100,776
%kWh saved	1.20%	1.05%	1.12%
% kWh/unit saved	9.41%	9.44%	9.44%
% €/unit saved	9.26%	9.26%	9.26%

Table 5.7 The data for the 55 second press cycle scenario

The final scenario considered was the change in the production cycle from 10–4 to 4–3, meaning that instead of 10 days running and 4 days shift cycle downtime, the factory would be running 4 days with 3 days shift cycle downtime After running the scenario five times, the author compared the average results to the base line simulation results As it can be observed in the Figure 5 10 below, the data resulted after the run of the last scenario is similar to the data from the base line simulation run

Table 5 8 shows the results in more detail In the case of the 4-3 Shift Cycle scenario the energy consumption for each line changed as follows

- From 610,737 kWh to 633,720 kWh for Line1, which represents an increase in energy consumption of 3 95%
- From 634,238 kWh to 623,672 kWh for Line2, which represents a decrease in energy consumption by 1 83%
- From 107,227 kWh to 107,643 kWh for Cut and Coat, which represents an increase in energy consumption of 0 4%

In terms of kWh/unit the implementation of this scenario, would result in

- 0 27% decrease in kWh/unit for Line1,
- No change for Line2,
- 6 25% decrease in kWh/unit in the case of Cut and Coat

The results also show that Masonite would pay approximately €92,000 more per year on energy consumption This cost has been calculated by adding the amounts listed in the *€ saved/month* row from Table 5 8 and multiplying the result by 12 At the same time the cost/unit would decrease by 0 46% for Line1 and 10% for Cut and Coat, remaining the same for Line2 This is possible because of the production increase from 169,400 units to 176,094 units for Line1 and from 648,702 units to 673,174 units for Cut and Coat

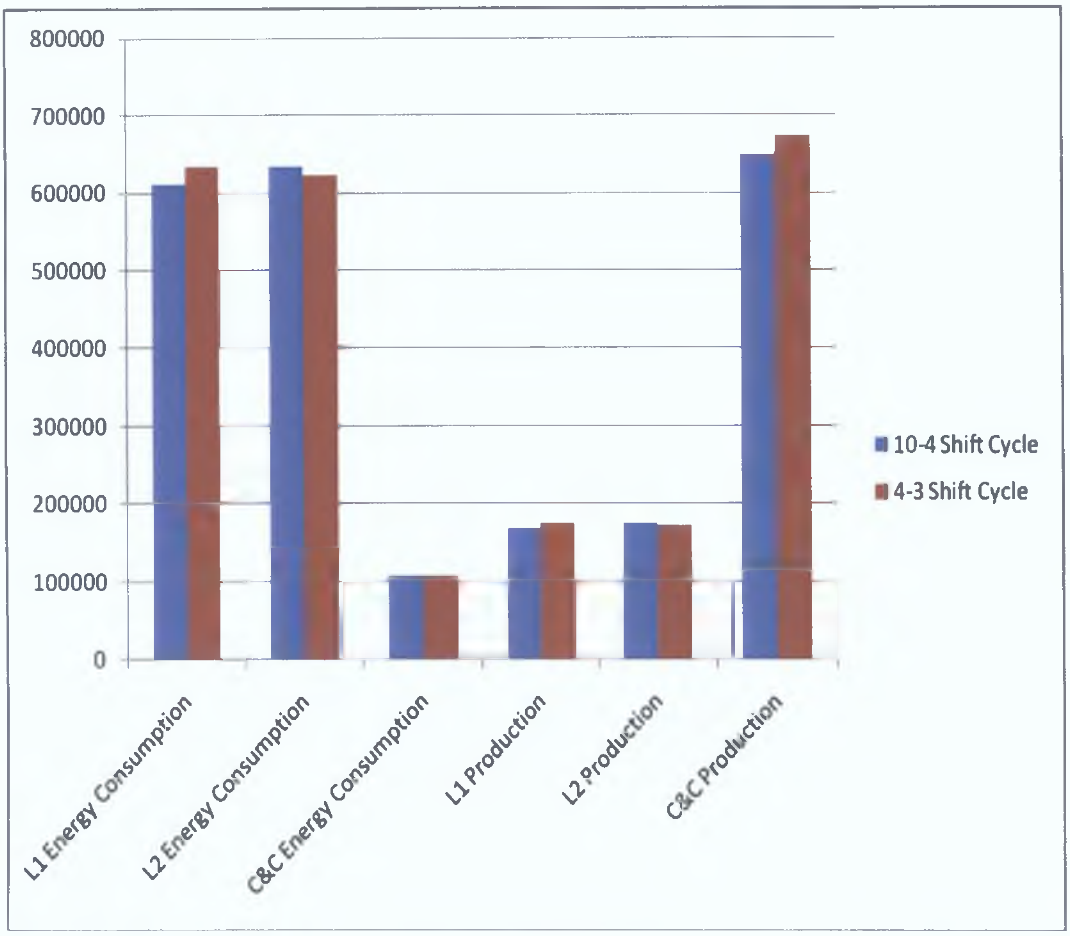

Figure 5.10 The data for the 4-3 Shift Cycle scenario against the data for the base line (10-4 Shift Cycle)

	10-4 Shift Cycle (Base Line)			4-3 Shift Cycle scenario		
	Line1	Line2	C&C	Line1	Line2	C&C
Production (units)	169,400	176,232	648,702	176,094	173,005	673,174
Energy Consumption (kWh)	610,737	634,238	107,227	633,720	623,672	107,643
Cost (€)	366,442	380,543	64,336	380,232	374,203	64,585
kWh/unit	3.61	3.60	0.16	3.60	3.60	0.15
€/unit	2.16	2.16	0.10	2.15	2.16	0.09
Overall savings						
kWh saved/month				-6,694	3,227	-416
€ saved/month				-13,790	6,340	-249
% Energy saved				-3.95%	1.83%	-0.4%
% kWh/unit saved				0.27%	0%	6.25%
% €/unit saved				0.46 %	0%	10%

Table 5.8 The data for the 4-3 shift cycle scenario compared to the 10-4 shift cycle scenario

5.4. CONCLUSION

Thıs chapter analysed the results of the sımulatıon model and detaıled ıts testıng and valıdatıon The valıdatıon process looked at one month of actual data collected from Masonıte Thıs data represented the ınput data for the sımulatıon model whıch was then run five tımes The next step calculated the average of the results from the five runs of the sımulatıon model and compared thıs to the actual data Thıs showed that the sımulatıon model predıcts the energy consumptıon wıth an average accuracy of 96 53% for Lıne1, 100 71% for Lıne2 and 94 94% for Cut and Coat The margın of error wıthın whıch the model predıcts the energy consumptıon for Lıne1 ıs -4 77% to -2 71%, for Lıne 2 ıs -0 04% to 1 62% and for Cut and Coat ıs -5 71% to -4 19% At the same tıme, the analysıs of the data also showed that the sımulatıon model ıs able to predıct Masonıte's productıon wıthın an average of 3 06% for Lıne1, 1 59% for Lıne2 and 0 86% for Cut and Coat

The testıng and valıdatıon process resulted ın a stream of data whıch represented a baselıne for further experıments and scenarıos ımplemented on the sımulatıon model

The second part of the chapter looked at the followıng sıx scenarıos Masonıte ıs consıderıng to ımplement, wıth the scope of lowerıng the amount of energy consumed for each door produced (kWh/Unıt)

- 10% energy savıngs on refiners
- 10% energy savıngs on drıers
- 15% energy savıngs on drıers
- 58 second cycle tıme on the press
- 55 second cycle tıme on the press
- 4-3 shıft cycle scenarıo

After the sıx scenarıos were ımplemented wıthın the model and the sımulatıon was run five tımes for the perıod of one month, the data was collected and analysed Table 5 9 below presents all the data gathered from the 6 scenarıos

ID	Scenario	kWh/Unit	Energy Consumption	Approximate Savings/Year
1	**10% energy savings on refiners**	**3.74%**	**3.58%**	**€320,800**
2	10% energy savings on driers	2.08%	1.89%	€170,000
3	**15% energy savings on driers**	**2.91%**	**2.84%**	**€254,000**
4	58 second cycle time on the press	4.30%	0.46%	€40,000
5	**55 second cycle time on the press**	**9.42%**	**1.12%**	**€100,700**
6	4-3 shift cycle scenario	3.14%	-0.84%	€-92,000
	Maximum Total	**25.59%**	**9.05%**	**€675,500**

Table 5.9 The data collected from the 6 scenarios simulated

After running all the scenarios and analysing the data presented above it can be observed that Masonite could save up to €675,500 per year if they were to implement the best case scenarios: scenario 1, scenario 3 and scenario 5. Scenario 2 and scenario 3 are mutually exclusive as well as scenario 4 and scenario 5. However the author recommends the implementation of scenario 4 or 5 which assume a decrease in the cycle time of the two main production lines presses to 58 or 55 seconds respectively. Even though this doesn't result in a major reduction in energy consumption, it represents a substantial boost in productivity which increases the savings in kWh/Unit to up to 9.44%. This means Masonite would consume almost the same amount of energy but produce almost 10% more doors.

Another scenario that shouldn't be disregarded is the 10% decrease in energy consumption on the refiners. This would bring the energy consumption as well as the kWh/Unit down by over 3.5% which would save the company approximately €320,800 per year.

The author considers that the scenarios mentioned above can be seen as the best ones to implement in terms of long-term investment with a steady return for the company.

CHAPTER 6: CONCLUSIONS AND FUTURE WORK

CONTENTS

6.1. THESIS OVERVIEW

The purpose of this thesis was to identify how to improve productivity and energy efficiency at Masonite, a HDF Moulded Door Skin manufacturing company

The project began with a review of simulation and its applications in industry and continued with a case study of Masonite It looked at the production management and energy consumption in the company together with an economic decline which forced Masonite to change its shift patterns, therefore becoming less effective This required that a simulation model be created which would map out the production process in Masonite along with energy consumption in order to provide engineers with an environment that will allow for experiment on the simulated system and observation of the results in real time, without having to disrupt the physical production process

The development of the simulation model began with the creation of the Conceptual Model and the determination of the inputs, the model contents and the outputs This was followed by data collection and analysis, model coding, validation of the model, the simulation run, implementation of scenarios and analysis of the output results

6.2. THESIS CONCLUSIONS

The following are the main conclusions that have been reached as a result of the research carried out in this thesis

- It has been stated that due to the continuous change in the economic environment manufacturing companies need to be smart when it comes to energy consumption as this may constitute a competitive advantage
- It has been shown that using off the shelf products which address energy efficiency is not always a solution for the future Their software is mostly based on real time energy monitoring systems which collect information and present it to the user in Excel documents or internal company websites The downside to these is the amounts of data being stored but not analysed

- It has been proven that computer simulation is an efficient tool which enables the analysis of the stored data and its utilisation in predicting the energy consumption for a specific period of time.
- The author has shown that ProModel is a very flexible simulation software package which can be adapted to modelling energy consumption and correlating it with the production outcome. ProModel allows for the creation of a simulation model by using drag and drop objects and changing their custom settings to the ones in the real life, through a very intuitive interface. Apart from this, ProModel allows for the hard coding customisation of the simulation model which proved to be very useful for this project. The ProModel software also facilitates the end user with rich animation which helps to visualize and understand how processes work during the simulation run and it provides Masonite engineers with a visual representation of the real world system.
- Masonite has been analysed in detail and a large amount of data has been collected for this research project. In particular this refers to the production schedule for the three main production lines, the energy consumption data, the downtimes data, the machinery information, the work in progress and the warehouse stocks.
- The simulation model has been developed with the user in mind and has been customised for Masonite. At the same time it can easily be adapted to any manufacturing company as all of the inputs have not been hard coded into the simulation model but are being imported into it from an Excel document called Interface.xls at the beginning of each simulation run.
- It has been noted however that the Shift defining operation in ProModel is too basic to be able to implement the Shift Cycles in Masonite. The visual representation of production schedules available in ProModel only contains references to the production shifts, which assumes that the shift pattern is repetitive. The main problem with this is the 10–4 production cycles in Masonite which translates in 10 days *Running* and 4 days *Shift Cycle Downtime*. This type of schedule could not be represented in ProModel with the help of the Shift editor. At the same time the production schedule in Masonite contains extra information as the number of doors planned to be

produced every day, the type of dies available in the press and one of the seven types of schedules Running, Running/Market Downtime, Market Downtime/ Running, Running/Die change, Die Change/Running, Market Downtime and Shift Cycle Downtime The solution to this problem lies in the hard coded implementation of the production schedule within the simulation model

- The results of the simulation model were exported into an Excel document where they can be easily read The output confirmed that the model is able to predict energy consumption with an average accuracy of 96 53% for Line1, 100 71% for Line2 and 94 94% for Cut and Coat The margin of error within which the model predicts energy consumption for Line1 is -4 77% to -2 71%, for Line 2 is -0 04% to 1 62% and for Cut and Coat is -5 71% to -4 19% At the same time, the analysis of the data also showed that the simulation model is able to predict Masonite's production within an average of 3 06% for Line1, 1 59% for Line2 and 0 86% for Cut and Coat
- The author has independently introduced a number of changes to the model inputs with the scope of lowering energy consumed for each door produced (kWs/Unit) The scenarios considered were 10% energy savings on refiners, 10% energy savings on driers, 15% energy savings on driers, 58 second cycle time on the press, 55 second cycle time on the press, 4-3 shift cycle scenario However the author recommends the implementation of scenario 5 which assumes a decrease in the cycle time of the two main production lines presses to 55 seconds Even though this doesn't result in a major decrease of energy consumption, it represents a substantial boost in productivity which increases the savings of kWh/Unit to up to 9 44% This means that Masonite would be consuming almost the same amount of energy but producing almost 10% more doors Another scenario that shouldn't be disregarded is the 10% decrease in energy consumption on the refiners This would bring the energy consumption as well as the kWh/Unit down by over 3 5% which would save the company approximately €320,800 per year The author considers that these two scenarios can be seen as best to implement with regard to long-term investment with a steady return for the company

- This thesis, proves that the developed simulation model can be used as a tool to illustrate the effects of various production scenarios and concepts It also proves the benefit of not having to tamper with the real world system which could result in additional costs At the same time the model can be used in the long term decision making process in Masonite

6.3. Recommendations

The simulation model presented in this thesis can be further extended to cover the whole operation and further developed to cover other forms of energy consumption This would require further research in the area of thermal energy consumption as well as production management, however this is outside the scope of this document The primary role of the developed simulation model is to help Masonite understand the implications of the different scenarios they would like to implement on the real world system and to give them an idea around the returns that those scenarios could bring The following are some recommendations for future work in this area

- This model was developed for a wooden door skins manufacturing company The same modelling and development approach can also be applied to other manufacturing companies which rely on highly automated processes
- Although the model already implements most of Masonite's processes, it is limited to the three production lines which consume the most electrical energy As a future implementation the model should include the representation of the entire factory operation to include all production processes This will allow for a better understanding of the entire manufacturing system and may uncover different implications of the implemented scenarios
- A further development of the simulation model should also include the modelling of thermal energy (heat and steam) This could have a great impact on identifying where expended thermal energy output from critical production resources may be captured and re-used It should also investigate multiple closed loop scenarios that could be deployed to convert captured energy back into electrical energy which could be reutilised

- The current simulation model does not take into account Masonite's supply chain The author sees as a future development the implementation of the supply chain management as well as distribution management within the simulation model This could help Masonite make decisions regarding their needs for raw material and regarding production schedules If the company can simulate the demand it would be able to adapt its production schedule to suit it This could result in major savings in energy consumption
- The simulation model could also facilitate the user with cost reports At the moment all the cost calculations are done in the excel document where the results are exported At the same time these cost calculations represent an approximation of real energy costs and do not keep track of the difference between day and night or summer and winter tariffs This could be a major addition to the simulation model as the costs could be implemented to keep track of different energy prices at different times of the day This will provide Masonite with an extra level of accuracy that will help in the decision making process regarding production schedules

A final addition to the simulation software could be the implementation of an alternative energy source, such as a wind turbine or solar panels The simulation of these resources could help Masonite realise the return on a major investment like this and also facilitate the decision making process by backing it up with simulation data

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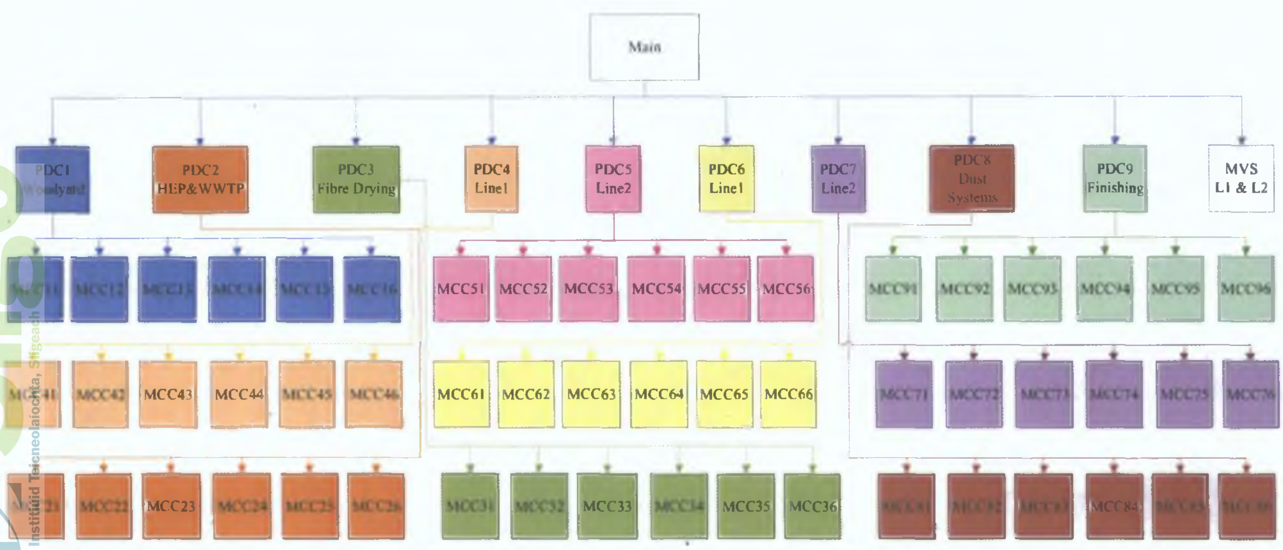
APPENDIX A

The table below shows the differences and similarities between Arena and ProModel in terms of the criteria that is essential to this research project. Both of the simulation packages score the same in Coding and Visual Aspects, Technical Support, Experimentation, Efficiency and Testability. The only area in which ProModel scored better than Arena was in Data Input and Output. ProModel facilitates Data Statistics Generation and the Verification of Data Consistency, which are two important parts in the validation and data analysis processes.

Criteria	Weight	Arena	ProModel
Coding and Visual Aspects			
Support to theoretical and empirical probability distribution	4	1	1
Random number generator	3	1	1
Model—animation integration	2	1	1
Icons: • **Standard and user-defined library**	2	1	1
• **Icon editor**	2	1	1
Background chart: • **Image import**	2	1	1
• **Screen layout editor**	2	1	1
Codification: • **Codification assistants**	4	1	1
• **Programming using supplier's language**	3	1	1
Built-in function and user-defined library	2	1	1
Global variables	4	1	1
Entity attributes	3	1	1
Typical objects for model development in logistic systems • **Material handling**	3	1	1
• **Grouping and separation of entities**	3	1	1
• **Schedule** ○ **Resources and entities arrival**	3	1	1
○ **Downtimes**	3	1	1
Conditional routing	4	1	1
Animation • **Enable/disable configuration**	4	1	1
• **Speed control**	4	1	1
• **Support to the different time and space units**	4	1	1
• **Date/hour visualization**	4	1	1
• **Instantaneous variable values and charts visualization**	4	1	1

Technical Support			
Documentation: **User's manual**	2	1	1
• **Tutorials**	2	1	1
• **Application-based examples**	3	1	1
On-line help	2	1	1
Technical support	3	1	1
Required experience	3	1	1
Easy learning	3	1	1
Trainings	3	1	1
Software updates	3	1	1
Efficiency and Testability			
Error depuration: • **Execution tracking**	3	1	1
• **Inserting stop points**	3	1	1
• **Inspection of instantaneous variable values**	3	1	1
• **Stepwise execution**	3	1	1
Model validation	3	1	1
Time required to construct models	4	1	1
Model constraints	2	1	1
Experimentation			
Multiple replications	4	1	1
Batch mode	2	1	1
Warm-up period	3	1	1
Data Input / Output			
Data importing • **Electronic Spreadsheets**	3	1	1
• **Autocad files**	3		1
Data Statistics Generation	4	0	1
Ability to fit the data into a probability distribution	3	1	1
Input data mode: • **Batch**	3	1	1
• **Interactive**	3	1	1
Verification of data consistency	4	0	1
Reports • **Standard**	4	1	1
• **Customized**	3	1	1
Data Export in Electronic Spreadsheets	3	1	1
Data statistics generation	4	1	1
Ability to fit the data into a probability distribution	2	1	1
Statistic chart generation	3	1	1
Printing: • **Screen Layout**	1	1	1
• **Generated Reports**	1	1	1
Total		**159**	**167**

APPENDIX B


Main
PDC1
PDC2
HEP&WWTP
PDC3
Fibre Drying
PDC4
Line1
PDC5
Line2
PDC6
Line1
PDC7
Line2
PDC8
Dust
Systems
PDC9
Finishing
MVS
L1 & L2
MCC12
MCC16
MCC51
MCC52
MCC53
MCC54
MCC55
MCC56
MCC91
MCC92
MCC93
MCC94
MCC95
MCC96
MCC42
MCC43
MCC44
MCC45
MCC46
MCC61
MCC62
MCC63
MCC64
MCC65
MCC66
MCC71
MCC72
MCC73
MCC74
MCC75
MCC76
MCC22
MCC23
MCC24
MCC25
MCC26
MCC31
MCC32
MCC33
MCC34
MCC35
MCC36

APPENDIX C

The General Variables spreadsheet of the Interface.xls document:

TIMES TO CHANGE DIES

Dies	Average	Standard Deviation
1	60	3
2	90	6
3	120	8
4	150	11
5	180	14
6	210	16
7	240	19
8	270	22
9	300	25
10	330	27
11	360	29
12	390	30
13	420	31
14	450	32
15	480	37
16	510	40
17	540	42
18	570	44
19	600	47
20	630	49
21	660	51
22	690	54
23	720	56
24	750	58
25	780	61
26	810	63
27	840	65
28	870	68

THE CONVEYOR VARIABLES SHEET

ID	Description	Length (m)	Length (f)	Speed (f/hr)
1	Unloader conveyors	21.2	69.55	390
2	Incline Conveyors	10.5	34.45	360
3	Corner Transfer Infeed	10.6	34.78	360
4	90deg transfer	3.2	10.50	240
5	Transfer Belt conveyors	20.4	66.93	240
6	Saw alignment conveyors	14.4	47.24	300
7	Second pass saws	6.9	22.64	270
8	Saw Outfeed Belts	11	36.09	270
9	90deg transfer	5.1	16.73	300
10	Belt conveyor1	1.3	4.27	300
11	Lift Table Assy	8.1	26.57	300
12	Kiln Outfeeds	5	16.40	270
13	90deg transfer	8.5	27.89	300
14	Belt conveyor2	2.75	9.02	200
15	Dwell Conveyors	19.15	62.83	180
16	Inspection Conveyors	7.15	23.46	300
17	Sort Lines	2.85	9.35	300
18	Spacing Conveyors	4.4	14.44	300
19	Left Feeder Belt	3.5	11.48	480
20	Right Feeder Belt	3.5	11.48	480
21	Left Feeder Decline	10.1	33.14	310
22	Right Feeder Decline	10.1	33.14	310
23	Transfer Rolls	3.2	10.50	450
24	Elect Cleaner Conv	6.6	21.65	315
25	Preheat Oven Conv	13.5	44.29	315
26	Paint Coater 1 Conv	8	26.25	315
27	HVHA Oven 1 Conv	23	75.46	255
28	IR Oven 1 Conv CHN	15.5	50.85	300
29	Accumulator Infeed	3.6	11.81	335
30	Accumulator OutFeed	4.2	13.78	360
31	Cooler 1 Conv Chain	15.3	50.20	315
32	Paint Coater 2 Conv	7.8	25.59	285
33	HVHA Oven 2 Conv	23.2	76.11	270
34	IR Oven 2 Conv CHN	8.6	28.21	285
35	Future IR Conv CHN	7	22.97	285
36	Speed Up Conv Belts	4.8	15.75	600
37	Coater 3 Xfer belts	3.2	10.50	350
38	Coater 3 Xfer Rolls	13.2	43.31	380
39	Paint Coater 3 Infd	9	29.53	280

40	Paint Coater 3 Conv	10.6	34.78	295
41	HVHA Oven 3 Conv	23.2	76.11	270
42	IR Oven 3 Conv CHN	18	59.05	285
43	Sampler Conveyor	7.1	23.29	450
44	Cooler 2 Conveyor	17.9	58.73	330
45	Incline Conveyor	10.8	35.43	480
46	Spacing Conveyor	10.8	35.43	300
47	Aux Stacker Belt	1.6	5.25	420
48	Aux Feeder Belt	3.5	11.48	300
49	Feeder Outfeed Roll	13.8	45.28	365
50	1st Pass Infd Rolls	5.5	18.04	340
51	1st Pass LH Trim	1.8	5.91	90
52	1st Pass RH Trim	1.8	5.91	90
53	1st Pass Out Belt	9.7	31.82	360
54	1st Pass Adj Conv	9.7	31.82	560
55	Spreader Conveyor	2.4	7.87	510
56	2nd Pass Xfer Rolls	6.6	21.65	415
57	2nd Pass Feed Drive	4.2	13.78	220
58	2nd Pass Out Belt	8.1	26.57	245
59	3rd Pass Feed Drive	4.2	13.78	220
60	3rd Pass Out Belt	8.1	26.57	245
61	Humidifier 1A Conv	3.7	12.14	270
62	HUM 1A Dwell Conv	8.8	28.87	140
63	Humidifier 2A Conv	3.7	12.14	270
64	HUM 2A Dwell Conv	7.5	24.61	140
65	Humidifier 1B Conv	3.7	12.14	140
66	Hum 1B Dwell Conv	8.8	28.87	200
67	Humidifier 2B Conv	3.7	12.14	140
68	Hum 2B Dwell Conv	9.6	31.50	240
69	L1 Blowof Xfer Roll	3	9.84	380
70	L2 Blowof Xfer Roll	3	9.84	380
71	L1 Blowof Infeed	3.5	11.48	380
72	L2 Blowof Infeed	9.4	30.84	380
73	Blowof Conveyor	6.3	20.67	300
74	L1 Inspect Conv	5.5	18.04	290
75	L2 Inspect Conv	5.5	18.04	290
76	L1 Stacker Infeed	10.7	35.10	400
77	L2 Stacker Infeed 1	5.2	17.06	400
78	L2 Stacker Infeed 2	9.5	31.17	420
79	Sortline 1 Belt Conv	2	6.56	500
80	Sortline 2 Belt Conv	2	6.56	500

THE PRODUCTS SPREADSHEET

Product ID	Description
1	2P ARCH TEXTURED
2	3P TEXTURED
3	6P TEXTURED
4	4P TEXTURED
5	4P ARCH TEXTURED
6	2P ARCH SMOOTH
7	2P SMOOTH
8	2P SCANDIC SMOOTH
9	3P WARDROBE SMOOTH
10	3P SYMETRICAL SMOOTH
11	4P SMOOTH
12	4P SYMETRICAL SMOOTH
13	6P SMOOTH

THE WIP SPREADSHEET

Product ID	Description	Cutting Buffer initial Stock Level	Warehouse Stock Level 01.01.2009	Warehouse Demand	Demand Frequency Days
1	2P ARCH TEXTURED	9430	297133	221878	28
2	3P TEXTURED	5225	76471	156695	12
3	6P TEXTURED	6130	130658	156518	15
4	4P TEXTURED	1125	43465	58434	3
5	4P ARCH TEXTURED	3225	39488	35671	13
6	2P ARCH SMOOTH	4625	21070	13755	13
7	2P SMOOTH	2825	20649	40278	13
8	2P SCANDIC SMOOTH	9430	297133	221878	28
9	3P WARDROBE SMOOTH	5225	76471	156695	12
10	3P SYMETRICAL SMOOTH	6130	130658	156518	15
11	4P SMOOTH	1125	43465	58434	3
12	4P SYMETRICAL SMOOTH	3225	39488	35671	13
13	6P SMOOTH	4625	21070	13755	13

THE CUT & COAT PRODUCTION SCHEDULE SPREADSHEET (1)

A	B	C	D	E	F	G
Day	Day No	Run Schedule	Cut&Coat Planned	Die 1/1	Die 1/2	Batch Size
Mon	1	Shift Cycle Downtime	0	2P ARCH TEXTURED	3P TEXTURED	220
Tue	2	Market Downtime / Running	45,000	2P ARCH TEXTURED	3P TEXTURED	220
Wed	3	Running	65,000	2P ARCH TEXTURED	3P TEXTURED	220
Thu	4	Running	65,000	2P ARCH TEXTURED	3P TEXTURED	220
Fri	5	Running / Market Downtime	20,000	2P ARCH TEXTURED	3P TEXTURED	150
Sat	6	Shift Cycle Downtime	0	2P ARCH TEXTURED	3P TEXTURED	150
Sun	7	Shift Cycle Downtime	0	2P ARCH TEXTURED	3P TEXTURED	150
Mon	8	Shift Cycle Downtime	0	2P ARCH TEXTURED	3P TEXTURED	150
Tue	9	Running	40,000	2P ARCH TEXTURED	3P TEXTURED	220
Wed	10	Running	65,000	2P ARCH TEXTURED	3P TEXTURED	220
Thu	11	Running	65,000	2P ARCH TEXTURED	3P TEXTURED	220
Fri	12	Running / Market Downtime	20,000	2P ARCH TEXTURED	3P TEXTURED	220
Fri	13	Shift Cycle Downtime	0	2P ARCH TEXTURED	3P TEXTURED	220
Fri	14	Shift Cycle Downtime	0	2P ARCH TEXTURED	3P TEXTURED	150
Sat	15	Shift Cycle Downtime	0	2P ARCH TEXTURED	6P TEXTURED	150
Sun	16	Market Downtime / Running	50,000	2P ARCH TEXTURED	6P TEXTURED	150
Mon	17	Running	65,000	2P ARCH TEXTURED	6P TEXTURED	150
Tue	18	Market Downtime / Running	50,000	4P TEXTURED	6P TEXTURED	220
Wed	19	Running / Market Downtime	10,000	4P TEXTURED	6P TEXTURED	220
Thu	20	Shift Cycle Downtime	0	4P TEXTURED	6P TEXTURED	220
Fri	21	Shift Cycle Downtime	0	4P TEXTURED	6P TEXTURED	220
Sat	22	Shift Cycle Downtime	0	4P TEXTURED	6P TEXTURED	220
Sun	23	Market Downtime / Running	50,000	4P TEXTURED	6P TEXTURED	150
Mon	24	Running	65,000	4P TEXTURED	6P TEXTURED	150
Tue	25	Market Downtime	0	4P TEXTURED	6P TEXTURED	150

THE CUT & COAT PRODUCTION SCHEDULE SPREADSHEET (2)

H	I	J	K	L	M	N	O	P	Q	R	S
Day No	Run Schedule Line 1	Cut&Coat Planned	Die 1/1	Die 1/2	Batch Size		Run Schedule	No Assigned		Door Type	No Assigned
1	5	0	1	2	220		Market Downtime / Running	1		2P ARCH TEXTURED	1
2	1	45000	1	2	220		Running	2		3P TEXTURED	2
3	2	65000	1	2	220		Running / Market Downtime	3		6P TEXTURED	3
4	2	65000	1	2	220		Market Downtime	4		4P TEXTURED	4
5	3	20000	1	2	150		Shift Cycle Downtime	5		2P SMOOTH	5
6	5	0	1	2	150					4P ARCH TEXTURED	6
7	5	0	1	2	150					2P ARCH SMOOTH	7
8	5	0	1	2	150					2P SCANDIC SMOOTH	8
9	2	40000	1	2	220					3P WARDROBE SMOOTH	9
10	2	65000	1	2	220					3P SYMETRICAL SMOOTH	10
11	2	65000	1	2	220					4P SMOOTH	11
12	3	20000	1	2	220					4P SYMETRICAL SMOOTH	12
13	5	0	1	2	220					6P SMOOTH	13
14	5	0	1	2	150						
15	5	0	1	3	150						
16	1	50000	1	3	150						
17	2	65000	1	3	150						
18	1	50000	4	3	220						
19	3	10000	4	3	220						
20	5	0	4	3	220						
21	5	0	4	3	220						
22	5	0	4	3	220						
23	1	50000	4	3	150						
24	2	65000	4	3	150						
25	4	0	4	3	150						

THE RAW DATA SPREADSHEET (1)

A	B	C	D	E	F	G	H	I	J	K	L	M
Min Val	0.1	0.1	0.3	0.3	0	0	0.1	0.3	0.2	0.2	0	0
Max Val	26.2	12.6	16	5.9	29.4	22.1	5.5	5.1	8.4	18.7	11.4	15.9
No of Rows	25	25	25	25	25	25	25	25	25	25	25	25
ID	L1Refiner MTTR	L1Mat Forming MTTR	L1Press MTTR	L1Unloader MTTR	L1Other MTTR	L2Refiner MTTR	L2Mat Forming MTTR	L2Press MTTR	L2Unloader MTTR	L2Other MTTR	CCZone1 MTTR	CCZone2 MTTR
1	1.8	1.7	1	2.1	17.7	22.1	1	1.4	2.2	15.3	2.8	3.5
2	9.1	1.2	5.9	5.9	23.9	1.5	4.1	3.5	3.6	1.2	9.4	13
3	26.2	5.9	1.4	2.1	11.7	0.3	0.2	0.6	2.3	0.8	4.2	5.8
4	3.1	2.1	4.6	3.7	3.3	2.5	0.4	3	8.4	4.3	7.3	5.8
5	1.2	0.7	2.1	2.4	2.2	0.9	1	1.4	2	3.7	5.5	8.3
6	13.7	0.2	6.3	3.3	25	1.1	3.8	1	3.8	18.7	4.9	8.1
7	2.5	0.3	0.3	0.7	3.5	1.4	0.1	0.4	0.7	2.3	2.5	15.9
8	0.6	0.7	7	0.6	0.9	0.1	0.1	0.6	0.4	0.8	0.5	1.7
9	4.4	3.9	1.2	2	2.6	0.1	0.1	1.4	1.6	6.9	6.4	5.3
10	3.4	12.6	6.3	1.4	20.2	0.3	0.1	0.3	1.2	2.3	5.6	9
11	0.1	1.9	2.7	1.1	18.8	0.1	0.2	2.5	2.8	3.4	11.4	5.1
12	4.9	0.9	2.8	3.4	13.3	1.6	0.7	0.7	1.4	1.9	5.7	7.1
13	2.3	0.5	1	0.5	1.3	0.3	0.3	0.3	3.4	0.7	5.4	4.6
14	2.8	0.5	16	2.6	2.4	1	1.3	2.4	3.9	3.6	3.4	5.3
15	0.2	0.1	3.9	2	6.2	3.8	0.3	0.3	1.7	1.3	3.7	4.3
16	2.2	1.4	9.6	2.7	6	12.8	0.1	2.1	1.9	4.2	8	10.4
17	2	1.1	8.8	4.3	0	2.7	0.1	1	1.9	9.2	9.9	8.4
18	0.8	1.8	3	4	22	0.7	0.3	1.4	0.6	1.9	6	8
19	15.4	0.1	4	2.4	13.2	0.1	0.1	2.5	0.7	0.6	6.8	12.1
20	0.8	0.2	1.8	2.8	29.4	0	0.4	0.5	0.2	0.9	0.7	3.2
21	2.1	5.1	10.4	1.6	6.1	1	5.5	1.7	2	4.4	8	9.3
22	1.2	0.5	1.5	0.3	10.2	4.6	4.9	0.8	1.1	0.8	9.7	2.4
23	3.4	0.9	9.1	4.4	1.2	1.3	0.4	1.2	3.3	2.3	9	6
24	4.9	1.7	10.5	2.2	2	0.3	1.1	1.8	0.3	0.2	6.3	8.4
25	1.1	1.9	4.8	1.9	8.9	1.1	0.1	5.1	1.9	1	3.1	6.6

THE RAW DATA SPREADSHEET (2)

N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE
88	4	6	72	1	1	59	0	1	4	1	1	27	0	0	0.8	0	0
114	32	31	87	8	5	104	10	5	45	25	3	87	44	10	1112.5	2.6	0
180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180
MCC 91 Running	**Mcc 91 Mkt DT**	**Mcc91 Shift Cycle DT**	**MCC92 Running**	**Mcc 92 Mkt DT**	**Mcc92 Shift Cycle DT**	**MCC93 Running**	**Mcc 93 Mkt DT**	**Mcc93 Shift Cycle DT**	**MCC94 Running**	**Mcc 94 Mkt DT**	**Mcc94 Shift Cycle DT**	**MCC95 Running**	**Mcc 95 Mkt DT**	**Mcc95 Shift Cycle DT**	**L1 Refiner Power Running**	**L1Refiner Power MarketDT**	**L1Refiner Power Shift CycleDT**
111	30	7	84	4	5	71	4	1	37	1	2	63	8	0	1022.9	0	0
109	30	6	83	4	4	70	0	1	37	2	2	61	12	1	1060.4	0	0
108	29	7	82	4	4	70	4	3	36	2	1	48	16	1	1027.7	0	0
111	30	6	85	3	4	71	3	4	40	1	2	77	11	1	1014.8	0	0
108	30	7	84	2	4	71	3	3	37	2	2	74	18	1	1019	0	0
109	30	7	84	5	4	71	4	3	40	2	2	57	21	1	1037.9	0	0
109	30	6	84	5	4	71	3	3	38	2	1	61	13	1	1083.3	2.6	0
110	30	20	84	4	4	71	4	3	38	1	2	56	15	1	1103.7	0	0
110	30	30	86	4	4	72	3	3	39	2	2	80	16	4	1105.5	0	0
110	31	30	85	5	4	71	4	2	39	2	2	74	13	9	1109.2	0	0
112	30	30	87	4	4	72	3	3	41	1	3	72	9	2	1109.7	0	0
102	30	31	82	5	4	68	5	4	32	2	2	63	8	2	1029.5	0	0
112	31	30	86	4	5	72	10	3	41	2	3	73	8	1	945.4	0	0
106	30	31	82	5	4	69	9	3	32	3	2	61	8	2	887.4	0	0
104	31	30	80	5	4	70	7	4	34	2	3	66	9	2	867	0	0
113	31	30	84	4	5	71	3	3	36	3	2	76	8	1	891.3	0	0
107	31	30	82	5	4	70	4	4	34	2	3	67	9	2	943.1	0	0
108	30	31	82	5	5	69	4	3	33	3	2	59	8	2	889.3	0	0
101	29	30	80	5	4	69	5	3	33	2	2	56	22	1	740.6	0	0
101	30	30	81	4	4	70	3	4	36	1	3	59	21	2	690.2	0	0
92	30	30	77	5	5	63	5	3	22	2	2	58	25	1	654.6	0	0
94	30	31	74	6	4	64	4	3	15	1	3	48	25	2	716	0	0
96	30	31	75	4	5	62	4	4	13	2	2	52	22	2	861	0	0
107	29	31	80	5	4	69	4	3	29	2	3	61	20	2	895.9	0	0
109	30	30	82	5	4	70	5	4	36	1	3	67	25	2	909.2	0	0
110	29	31	82	5	5	69	4	3	34	2	2	70	20	1	903	0	0
108	30	31	81	4	4	70	4	3	33	1	3	65	23	2	905.1	0	0
106	29	30	82	5	4	69	5	4	34	2	2	70	22	2	895.1	0	0
108	29	21	85	4	4	72	4	3	35	1	3	57	7	2	849.2	0	0

THE RAW DATA SPREADSHEET (3)

AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR
2	1	1	0	0	0	7	2	2	60	22	14	0
111	3	3	319	39	63	131	7	3	208	132	67	124
180	180	180	180	180	180	180	180	180	180	180	180	180
L1 MCC31 Dryers Running	**L1MCC 31 Dryers Market DT**	**L1 MCC31 Dryers Shift Cycle DT**	**L1 MCC32 Dryers Running**	**L1 MCC 32 Dryers Market DT**	**L1MCC32 Dryers ShiftCycle DT**	**L1 MCC41 Refining Running**	**L1MCC41 Refining MarketDT**	**L1MCC41 Refining ShiftCycle DT**	**L1MCC42 PreloadLoader PressPumpA Running**	**L1MCC42 PreloadLoader PressPumpA MarketDT**	**L1MCC42 PreloadLoader Press Pump A Shift Cycle DT**	**L1MCC43 Press Pumps BC Running**
103	1	1	304	0	1	122	3	3	191	42	41	106
103	2	2	307	4	0	115	3	2	188	42	39	102
102	2	2	311	0	0	100	2	2	185	42	40	99
98	2	1	306	0	0	117	3	2	190	42	40	107
103	2	2	306	0	0	125	3	3	197	42	40	107
102	2	2	307	1	0	124	3	2	199	42	40	112
103	3	1	309	0	0	128	3	2	203	41	40	117
101	2	2	306	1	0	124	3	2	203	58	40	118
100	2	2	307	0	1	125	2	3	206	59	37	121
104	1	1	308	0	0	124	3	2	200	47	33	112
102	2	2	306	0	0	121	3	3	207	64	32	120
65	2	2	310	0	0	84	2	2	176	63	33	74
94	1	1	311	0	0	102	3	3	189	63	33	95
106	2	2	314	0	0	97	2	3	192	63	34	103
104	2	2	311	1	1	121	3	2	198	63	34	110
103	1	1	308	0	0	121	3	3	207	63	34	119
103	2	2	310	0	0	120	3	3	200	63	34	113
78	2	2	317	0	0	74	2	2	174	63	34	75
95	2	1	313	0	0	95	3	3	184	63	36	94
104	1	2	312	0	0	100	3	3	191	63	35	106
103	2	2	308	0	0	120	3	2	201	62	42	120
101	2	1	308	1	1	122	3	3	201	63	41	120
85	1	2	307	0	0	117	3	2	191	60	41	107
96	2	2	308	0	0	113	3	3	190	56	42	106
102	2	2	305	0	61	118	5	3	202	56	42	117
106	2	1	307	0	61	119	5	2	196	56	48	112
104	2	2	307	0	32	121	6	3	198	55	67	116

THE RAW DATA SPREADSHEET (4)

AS	AT	AU	AV	AW	AX	AY	AZ	BB	BC	BD	BE
0	0	7	0	0	36	10	10	12	1	1	42
40	1	126	59	54	116	111	16	37	3	2	172
180	180	180	180	180	180	180	180	180	180	140	140
L1MCC43 Press Pumps BC Market DT	**L1MCC43 Press Pumps BC Shift Cycle DT**	**L1MCC44 Press Pump D FilterUnloader Running**	**L1MCC44 Press Pump D FilterUnloader Market DT**	**L1MCC44 Press Pump D FilterUnloader Shift Cycle DT**	**L1MCC45 Resin Wax Pumps Running**	**L1MCC45 Resin Wax Pumps MarketDT**	**L1MCC45 Resin Wax Pumps Shift Cycle DT**	**L1MCC61 MatForming Cleanup Running**	**L1MCC61 MatForming Cleanup MarketDT**	**L1MCC61 MatForming CleanupShift CycleDT**	**L1MCC62 Precompress or LoadPress Running**
0	1	118	0	1	111	16	15	30	1	1	168
1	0	113	0	0	111	15	15	34	1	1	166
0	0	112	0	0	111	15	15	30	2	1	165
0	0	116	0	0	110	15	15	30	1	2	166
0	0	115	0	0	111	15	15	31	1	1	164
0	0	117	1	0	111	14	15	33	1	1	165
0	0	120	0	0	111	15	15	32	2	2	163
1	1	121	46	0	111	15	15	31	1	1	164
0	0	122	44	0	111	15	15	32	2	1	165
0	0	117	1	0	111	15	15	35	2	2	164
0	0	121	26	0	111	16	15	35	1	1	165
0	0	80	26	1	111	15	15	32	2	2	135
0	0	100	25	0	112	15	15	29	1	1	155
1	1	108	26	0	111	15	15	32	2	1	164
0	0	115	26	0	111	15	15	36	2	1	164
0	0	121	26	0	111	15	15	34	1	2	166
0	0	116	25	0	115	15	15	31	2	1	164
0	0	86	26	0	111	15	15	30	1	1	150
0	0	100	26	2	112	15	15	32	2	1	160
0	1	112	25	0	112	15	15	30	2	2	167
1	0	121	26	0	112	15	15	31	2	1	167
0	0	122	26	0	111	15	14	31	1	1	166
0	0	112	26	0	111	15	15	31	2	1	161
0	0	111	25	0	111	15	15	32	2	2	163
0	1	121	26	0	111	15	11	30	1	2	169
1	0	116	26	2	111	15	11	30	2	2	167
0	0	119	26	9	111	15	11	32	1	1	167
0	0	119	26	9	111	15	11	31	2	2	167
0	0	107	25	8	111	14	11	28	2	2	165

THE RAW DATA SPREADSHEET (5)

BF	BG	BH	BI	BJ	BK	BL	BM	BN	BO	BP	BQ	BR
14	22	2	2	2	163.5	0	0	20	5	5	310	9
118	43	264	53	52	1160	0	0	124	29	30	324	68
140	140	140	140	140	140	140	140	140	140	140	140	140
L1MCC62 Precompressor LoadPress MarketDT	**L1MCC62 Precompressor LoadPressShift CycleDT**	**L1MCC63 Post Press Running**	**L1MCC63 PostPress MarketDT**	**L1MCC63 Post Press Shift Cycle DT**	**L2 Refiner Power Running**	**L2 Refiner Power Market DT**	**L2 Refiner Power Shift Cycle DT**	**L2 MCC33 Dryers Running**	**L2 MCC33 Dryers Market DT**	**L2 MCC33 Dryers Shift Cycle DT**	**L2 MCC34 Dryers Running**	**L2MCC 34Dryers Market DT**
41	29	254	3	3	913.1	0	0	114	26	28	320	61
42	28	254	3	3	1070.2	0	0	113	28	28	320	62
41	28	253	3	2	1160	0	0	112	27	29	321	62
42	29	251	2	3	1155.7	0	0	108	29	28	321	61
42	30	255	3	2	1121.8	0	0	112	28	26	318	62
60	29	254	3	3	1006.4	0	0	113	26	27	319	61
118	29	257	3	2	962.1	0	0	103	29	30	319	61
42	35	254	3	3	952.3	0	0	106	24	26	317	62
43	41	254	2	2	984.1	0	0	69	23	25	317	63
41	41	257	3	3	1087.8	0	0	20	26	27	318	64
40	43	254	18	2	1097.3	0	0	81	27	25	317	63
40	41	240	52	3	1112.5	0	0	104	26	26	318	63
40	41	251	53	2	1107.7	0	0	105	29	25	315	64
40	42	258	53	3	1096.6	0	0	107	26	25	313	63
39	42	258	37	2	1109.3	0	0	107	28	26	312	64
39	40	256	6	3	1079.6	0	0	107	28	24	314	64
40	40	257	2	2	854.3	0	0	108	26	23	317	63
40	40	247	4	3	876.4	0	0	109	28	25	315	64
41	41	253	3	2	970.7	0	0	96	29	23	317	63
40	41	256	3	3	926	0	0	114	26	23	315	64
40	40	258	2	2	937.6	0	0	117	25	22	315	9
40	40	255	3	3	953.8	0	0	112	25	23	314	64
39	41	249	2	2	975.6	0	0	114	24	25	315	64
40	41	252	3	2	967	0	0	91	24	24	322	63
40	40	255	3	3	917.4	0	0	114	23	8	316	63
40	39	256	2	3	912.6	0	0	114	24	9	315	64
39	41	257	3	3	937.4	0	0	116	10	8	316	64
38	40	254	53	2	994.2	0	0	117	10	9	315	64
38	40	256	53	3	1016.9	0	0	116	10	8	317	64

THE RAW DATA SPREADSHEET (6)

BS	BT	BU	BV	BW	BX	BY	BZ	CA	CB	CC	CD	CE
0	5	2	2	62	0	0	0	0	0	34	0	0
69	108	5	3	196	122	28	125	3	1	140	28	16
140	140	140	140	140	140	140	140	140	140	140	140	140
L2MCC 34Dryer Shift Cycle DT	**L2 MCC51 Refining Running**	**L2MCC 51 Refining Market DT**	**L2 MCC51 Refining Shift Cycle DT**	**L2 MCC52 Preload Loader Press PumpA Running**	**L2 MCC52 Preload Loader Press PumpA Market DT**	**L2 MCC52 Preload Loader Press PumpA Shift Cycle DT**	**L2MCC 53 Press Pumps BC Running**	**L2MCC53 Press Pumps BC Market DT**	**L2MCC53 Press Pumps BC Shift Cycle DT**	**L2MCC54 PressPump D Filter Unloader Running**	**L2MCC54 PressPump D Filter Unloader Market DT**	**L2MCC54 PressPumpD Filter Unloader ShiftCycleDT**
62	97	3	2	192	0	0	119	0	0	123	1	0
61	98	2	3	191	1	0	118	0	0	122	1	1
62	94	3	3	189	0	0	113	0	0	119	1	0
61	96	3	2	187	0	0	111	0	1	118	1	0
62	95	2	3	196	0	0	123	0	0	126	1	1
61	95	3	3	192	0	8	119	0	0	124	2	3
62	102	3	2	189	0	28	118	1	0	122	1	10
61	92	2	3	193	0	26	118	0	0	123	1	8
61	58	2	3	165	24	0	79	0	0	92	28	1
62	5	3	2	120	23	0	0	0	0	34	26	0
62	82	2	3	175	23	0	87	0	1	101	26	1
61	99	3	2	190	22	0	117	0	0	122	27	0
61	101	3	3	195	23	0	124	1	0	128	26	1
62	101	2	2	195	23	0	123	0	0	128	26	0
61	99	3	3	194	23	0	123	0	0	127	26	0
62	100	2	2	194	23	0	123	0	0	127	27	1
61	98	3	3	186	23	0	109	0	0	118	26	0
61	98	3	3	190	23	0	116	0	1	123	26	1
62	79	3	2	176	23	0	96	0	0	109	27	0
61	92	3	3	195	23	0	120	0	0	126	26	1
62	102	3	3	190	96	0	117	1	0	123	10	0
62	102	3	2	196	97	0	122	0	0	127	10	1
61	98	2	3	194	122	0	123	0	0	128	10	1
62	76	3	3	167	122	0	76	0	1	92	3	1
2	87	3	3	190	122	0	116	0	0	123	1	1
0	101	3	2	195	103	0	122	0	0	127	1	2
0	101	3	3	195	0	0	122	0	0	127	1	2

THE RAW DATA SPREADSHEET (7)

CF	CG	CH	CI	CJ	CK	CL	CM	CN	CO	CP	CQ
19	2	2	142	1	1	74	0	0	1	1	1
87	85	4	275	7	3	127	3	1	38	3	3
140	140	140	140	140	140	140	140	140	140	144	184
L2 MCC55 ResinWax Pumps Running	**L2MCC55 ResinWax Pumps MarketDT**	**L2MCC55 ResinWax Pumps ShiftCycle DT**	**L2MCC71 Mat Forming Cleanup Running**	**L2 MCC 71 Mat Forming Cleanup MarketDT**	**L2MCC71 MatForming Cleanup ShiftCycle DT**	**L2MCC72 Precompressor LoadPress Running**	**L2MCC72 Precompressor LoadPress MarketDT**	**L2MCC72 Precompressor LoadPress ShiftCycleDT**	**L2 MCC73 Post Press Running**	**L2 MCC73 PostPressMarket DT**	**L2MCC73 PostPress ShiftCycle DT**
77	2	2	271	3	3	122	1	0	35	1	2
76	2	2	271	2	2	122	0	0	34	2	1
77	3	3	270	3	3	122	0	0	33	1	2
77	2	2	266	3	3	120	0	1	31	1	1
77	2	2	270	2	2	125	0	0	34	2	1
77	3	2	270	3	3	124	1	0	33	1	2
76	2	2	264	3	3	121	2	0	31	1	1
77	2	3	266	2	2	121	2	0	31	1	1
76	3	2	235	3	3	103	3	0	32	1	2
77	2	2	185	2	3	76	3	0	27	1	1
76	3	2	248	3	2	114	2	1	29	2	1
76	2	3	265	3	3	125	3	0	29	1	2
76	2	2	266	3	3	126	2	0	31	1	1
77	3	2	267	2	2	124	3	0	32	2	2
76	2	2	267	3	3	124	2	1	35	1	1
80	3	3	266	7	2	124	3	0	31	1	1
86	2	2	267	3	3	121	2	0	33	2	1
86	3	2	271	3	3	122	3	0	38	1	2
86	2	3	261	3	2	113	2	0	37	2	1
86	3	2	269	2	3	124	3	1	30	1	1
86	84	2	273	3	2	123	0	0	31	2	1
87	85	3	271	2	3	124	0	0	31	2	2
86	85	2	273	2	3	122	0	0	35	2	1
87	85	3	259	2	2	106	0	0	29	2	1
86	85	2	272	2	3	120	1	1	33	2	2
87	85	2	274	2	2	122	0	0	34	2	1
87	2	3	275	1	2	122	1	1	38	2	2
86	3	2	275	2	2	122	0	0	34	2	2

THE DISTRIBUTIONS SPREADSHEET (1)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
		Frequency Input ID																							
Ref	**User Distribution Name**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
1	L1RefinerMTTR	1	2	3	2	4	2	2	2	0	1	2	0	0	0	0	0	0	1	0	0	0	0	0	0
2	L1MatFormingMTTR	2	3	3	2	3	1	1	3	3	0	0	0	0	0	0	1	0	0	0	0	1	0	0	1
3	L1PressMTTR	1	0	0	3	2	1	1	0	2	1	0	0	2	0	1	1	0	0	1	2	0	1	0	0
4	L1UnloaderMTTR	1	0	1	1	1	0	0	1	0	0	1	0	1	0	1	2	2	1	0	2	0	2	1	0
5	L1OtherMTTR	1	0	2	1	3	1	2	0	0	0	1	2	0	0	0	1	0	1	0	0	1	0	1	1
6	L2RefinerMTTR	1	8	2	5	3	0	2	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
7	L2MatFormingMTTR	8	2	3	3	0	0	1	0	0	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0
8	L2PressMTTR	3	0	1	1	2	1	1	0	2	0	1	0	4	0	0	1	1	0	0	1	0	0	1	2
9	L2UnloaderMTTR	1	1	1	3	0	0	2	0	1	2	0	5	1	1	0	0	1	0	0	1	1	1	1	1
10	L2OtherMTTR	1	0	6	3	0	2	3	0	0	1	2	2	1	0	0	0	0	0	1	0	0	0	0	0
11	CCZone1MTTR	1	0	0	1	1	1	0	1	1	0	0	3	2	4	1	1	2	0	0	1	1	2	3	1
12	CCZone2MTTR	1	0	0	0	0	0	1	1	1	3	2	2	1	1	1	1	2	2	5	3	1	2	3	0
13	MCC91Running	1	0	2	0	1	0	0	0	3	0	1	0	3	0	2	0	4	4	0	6	0	3	0	9
14	Mcc91MarketDT	23	0	11	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0	13	0
15	Mcc91ShiftCycleDT	3	0	4	0	17	0	15	0	0	0	0	0	1	0	2	0	10	0	14	0	51	0	12	0
16	MCC92Running	2	0	0	0	1	0	0	4	0	0	4	0	0	0	5	0	0	6	0	0	7	0	0	13
17	Mcc92MarketDT	1	0	0	0	0	0	0	3	0	0	0	0	0	0	15	0	0	0	0	0	0	100	0	0
18	Mcc92ShiftCycleDT	46	0	0	0	0	0	0	0	0	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0
19	MCC93Running	1	0	2	0	1	2	6	5	7	9	17	26	61	0	60	45	8	1	0	0	0	0	0	0
20	Mcc93MarketDT	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	57	0	0	0	0	104	0	0	0
21	Mcc93ShiftCycleDT	2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
22	MCC94Running	1	0	0	0	0	0	0	0	0	0	1	3	0	0	1	1	0	0	0	0	1	1	3	1
23	Mcc94MarketDT	13	0	0	45	0	59	0	51	0	5	0	1	0	0	0	1	0	0	0	0	0	1	0	0
24	Mcc94ShiftCycleDT	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	MCC95Running	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	2	0	0	3	0	2	5	6	1
26	Mcc95MarketDT	4	0	31	61	7	2	0	0	2	10	0	3	2	1	2	2	1	1	3	0	0	2	0	4
27	Mcc95ShiftCycleDT	12	0	0	0	0	127	0	0	0	0	37	0	0	0	0	0	0	0	0	0	1	0	0	0
28	L1RefinerPowerRunning	2	7	2	0	1	1	2	3	0	2	3	2	1	0	0	4	0	2	1	0	3	4	4	0
29	L1RefinerPowerMarketDT	184	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	L1RefinerPowerShiftCycleDT	192	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	L1MCC31DryersRunning	5	20	4	1	3	2	0	0	0	1	2	0	0	1	0	1	1	0	0	0	0	1	1	2
32	L1MCC31DryersMarketDT	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	L1MCC31DryersShiftCycleDT	49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	L1MCC32DryersRunning	1	0	0	0	0	1	0	0	0	0	4	0	1	0	0	5	5	1	0	1	0	2	0	0

THE DISTRIBUTIONS SPREADSHEET (2)

AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB
																										Return Value ID	
25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2
0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.10	0.6
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.10	0.4
0	0	0	1	1	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.30	0.6
0	0	0	1	1	0	1	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0.30	0.4
0	0	0	0	0	0	1	0	1	0	1	0	0	1	0	0	1	0	1	0	0	0	0	0	0	1	0.00	0.6
0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.00	0.5
0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0.10	0.2
0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.30	0.4
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.20	0.4
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0.20	0.6
2	2	1	0	3	0	1	0	1	0	1	2	0	0	0	1	0	1	1	2	0	0	0	0	0	1	0.00	0.2
0	3	3	0	1	1	1	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	1	0.00	0.3
0	11	0	11	0	6	0	21	0	22	16	0	18	0	28	0	25	0	22	0	13	0	13	0	7	3	88.00	88.5
0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.	2	24	0	76	0	26	3	4.00	4.6
10	0	2	0	1	0	2	0	0	0	0	0	0	0	0	0	10	0	5	0	0	0	0	0	13	8	6.00	6.5
0	0	0	30	0	0	27	0	0	32	0	0	34	0	0	0	39	0	0	32	0	0	13	0	0	6	72.00	72.3
0	0	0	0	57	0	0	0	0	0	0	1	0	0	0	0	0	0	4	0	0	0	0	0	0	1	1.00	1.1
0	30	0	0	0	0	0	0	0	0	0	0	0	79	0	0	0	0	0	0	0	0	0	0	0	8	1.00	1.1
0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	59.00	59.9
0	14	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	0	0	0	1	0.00	0.2
0	76	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	1	1.00	1.1
1	0	2	0	3	8	6	0	6	4	16	14	17	0	21	25	34	28	24	0	19	8	5	0	0	1	4.00	4.8
0	1	0	1	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1.00	1.5
0	117	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	44	1.00	1.0
8	10	7	19	17	7	22	18	29	13	18	15	12	8	7	4	3	7	2	2	1	2	0	0	0	2	27.00	28.2
10	13	4	1	4	0	0	0	1	0	0	0	0	1	1	2	0	1	1	1	0	0	0	1	1	2	0.00	0.9
0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0.00	0.2
3	0	2	0	5	4	2	4	1	6	3	9	7	4	14	13	24	16	13	19	17	15	12	5	4	6	0.80	23.5
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.00	0.1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.0
0	1	2	4	1	2	0	2	1	2	0	4	3	1	3	2	4	1	7	12	35	59	37	11	9	4	2.00	4.2
0	144	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1.00	1.0
0	141	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1.00	1.0

THE DISTRIBUTIONS SPREADSHEET (3)

BC	BD	BE	BF	BG	BH	BI	BJ	BK	BL	BM	BN	BO	BP	BQ	BR	BS	BT	BU	BV	BW	BX	BY	BZ
3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
1.2	1.7	2.2	2.8	3.3	3.8	4.4	4.9	5.4	6.0	6.5	7.0	7.6	8.1	8.6	9.2	9.7	10.2	10.8	11.3	11.8	12.4	12.9	13.4
0.6	0.9	1.1	1.4	1.6	1.9	2.1	2.4	2.7	2.9	3.2	3.4	3.7	3.9	4.2	4.4	4.7	4.9	5.2	5.5	5.7	6.0	6.2	6.5
0.9	1.3	1.6	1.9	2.2	2.5	2.9	3.2	3.5	3.8	4.1	4.5	4.8	5.1	5.4	5.7	6.1	6.4	6.7	7.0	7.3	7.7	8.0	8.3
0.5	0.6	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.4	2.5	2.6	2.7	2.8	2.9	3.0	3.2
1.2	1.8	2.4	3.0	3.6	4.2	4.8	5.4	6.0	6.6	7.2	7.8	8.4	9.0	9.6	10.2	10.8	11.4	12.0	12.6	13.2	13.8	14.4	15.0
0.9	1.4	1.8	2.3	2.7	3.2	3.6	4.1	4.5	5.0	5.4	5.9	6.3	6.8	7.2	7.7	8.1	8.6	9.0	9.5	9.9	10.4	10.8	11.3
0.3	0.4	0.5	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.9
0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8
0.5	0.7	0.9	1.0	1.2	1.4	1.5	1.7	1.9	2.0	2.2	2.4	2.5	2.7	2.9	3.0	3.2	3.4	3.5	3.7	3.9	4.0	4.2	4.4
1.0	1.3	1.7	2.1	2.5	2.8	3.2	3.6	4.0	4.4	4.7	5.1	5.5	5.9	6.2	6.6	7.0	7.4	7.8	8.1	8.5	8.9	9.3	9.6
0.5	0.7	0.9	1.2	1.4	1.6	1.9	2.1	2.3	2.6	2.8	3.0	3.3	3.5	3.7	4.0	4.2	4.4	4.7	4.9	5.1	5.4	5.6	5.8
0.6	1.0	1.3	1.6	1.9	2.3	2.6	2.9	3.2	3.6	3.9	4.2	4.5	4.9	5.2	5.5	5.8	6.2	6.5	6.8	7.1	7.5	7.8	8.1
89.1	89.6	90.1	90.7	91.2	91.7	92.2	92.8	93.3	93.8	94.4	94.9	95.4	96.0	96.5	97.0	97.6	98.1	98.6	99.1	99.7	100.2	100.7	101.3
5.1	5.7	6.3	6.9	7.4	8.0	8.6	9.1	9.7	10.3	10.9	11.4	12.0	12.6	13.1	13.7	14.3	14.9	15.4	16.0	16.6	17.1	17.7	18.3
7.0	7.5	8.0	8.6	9.1	9.6	10.1	10.6	11.1	11.6	12.1	12.6	13.1	13.7	14.2	14.7	15.2	15.7	16.2	16.7	17.2	17.7	18.2	18.8
72.6	72.9	73.2	73.5	73.8	74.1	74.4	74.8	75.1	75.4	75.7	76.0	76.3	76.6	76.9	77.2	77.5	77.8	78.1	78.4	78.7	79.0	79.3	79.7
1.3	1.4	1.6	1.7	1.9	2.0	2.1	2.3	2.4	2.6	2.7	2.9	3.0	3.1	3.3	3.4	3.6	3.7	3.9	4.0	4.1	4.3	4.4	4.6
1.2	1.2	1.3	1.4	1.5	1.6	1.7	1.7	1.8	1.9	2.0	2.1	2.1	2.2	2.3	2.4	2.5	2.6	2.6	2.7	2.8	2.9	3.0	3.0
60.8	61.8	62.7	63.6	64.5	65.4	66.3	67.3	68.2	69.1	70.0	70.9	71.9	72.8	73.7	74.6	75.5	76.4	77.4	78.3	79.2	80.1	81.0	82.0
0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.7	2.9	3.1	3.3	3.5	3.7	3.9	4.1	4.3	4.5	4.7	4.9	5.1
1.2	1.2	1.3	1.4	1.5	1.6	1.7	1.7	1.8	1.9	2.0	2.1	2.1	2.2	2.3	2.4	2.5	2.6	2.6	2.7	2.8	2.9	3.0	3.0
5.7	6.5	7.3	8.2	9.0	9.9	10.7	11.5	12.4	13.2	14.0	14.9	15.7	16.6	17.4	18.2	19.1	19.9	20.7	21.6	22.4	23.2	24.1	24.9
2.0	2.5	3.0	3.4	3.9	4.4	4.9	5.4	5.9	6.4	6.9	7.4	7.9	8.3	8.8	9.3	9.8	10.3	10.8	11.3	11.8	12.3	12.8	13.2
1.1	1.1	1.2	1.2	1.2	1.3	1.3	1.4	1.4	1.4	1.5	1.5	1.6	1.6	1.7	1.7	1.7	1.8	1.8	1.9	1.9	1.9	2.0	2.0
29.4	30.7	31.9	33.1	34.3	35.6	36.8	38.0	39.2	40.5	41.7	42.9	44.1	45.4	46.6	47.8	49.0	50.3	51.5	52.7	53.9	55.2	56.4	57.6
1.8	2.7	3.6	4.5	5.4	6.3	7.2	8.1	9.0	9.9	10.8	11.7	12.6	13.5	14.4	15.3	16.2	17.1	18.0	18.9	19.8	20.7	21.6	22.5
0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.7	2.9	3.1	3.3	3.5	3.7	3.9	4.1	4.3	4.5	4.7	4.9	5.1
46.2	68.9	91.6	114.2	136.9	159.6	182.3	205.0	227.7	250.4	273.1	295.7	318.4	341.1	363.8	386.5	409.2	431.9	454.6	477.2	499.9	522.6	545.3	568.0
0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.9	1.0	1.0	1.1	1.1	1.2	1.2	1.3	1.3
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6.4	8.7	10.9	13.1	15.3	17.6	19.8	22.0	24.2	26.5	28.7	30.9	33.1	35.4	37.6	39.8	42.0	44.3	46.5	48.7	50.9	53.2	55.4	57.6
1.1	1.1	1.2	1.2	1.2	1.3	1.3	1.4	1.4	1.4	1.5	1.5	1.6	1.6	1.7	1.7	1.7	1.8	1.8	1.9	1.9	1.9	2.0	2.0
1.1	1.1	1.2	1.2	1.2	1.3	1.3	1.4	1.4	1.4	1.5	1.5	1.6	1.6	1.7	1.7	1.7	1.8	1.8	1.9	1.9	1.9	2.0	2.0
13.0	19.5	26.0	32.6	39.1	45.6	52.1	58.6	65.1	71.6	78.1	84.6	91.1	97.7	104.2	110.7	117.2	123.7	130.2	136.7	143.2	149.7	156.2	162.8
1.6	2.4	3.2	4.0	4.8	5.6	6.4	7.2	8.0	8.8	9.6	10.3	11.1	11.9	12.7	13.5	14.3	15.1	15.9	16.7	17.5	18.3	19.1	19.9

THE DISTRIBUTIONS SPREADSHEET (4)

CA	CB	CC	CD	CE	CF	CG	CH	CI	CJ	CK	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV	CW
27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
14.0	14.5	15.0	15.5	16.1	16.6	17.1	17.7	18.2	18.7	19.3	19.8	20.3	20.9	21.4	21.9	22.5	23.0	23.5	24.1	24.6	25.1	25.7
6.7	7.0	7.2	7.5	7.8	8.0	8.3	8.5	8.8	9.0	9.3	9.5	9.8	10.0	10.3	10.6	10.8	11.1	11.3	11.6	11.8	12.1	12.3
8.6	9.0	9.3	9.6	9.9	10.2	10.6	10.9	11.2	11.5	11.8	12.2	12.5	12.8	13.1	13.4	13.8	14.1	14.4	14.7	15.0	15.4	15.7
3.3	3.4	3.5	3.6	3.7	3.8	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.8	4.9	5.0	5.1	5.2	5.3	5.4	5.6	5.7	5.8
15.6	16.2	16.8	17.4	18.0	18.6	19.2	19.8	20.4	21.0	21.6	22.2	22.8	23.4	24.0	24.6	25.2	25.8	26.4	27.0	27.6	28.2	28.8
11.7	12.2	12.6	13.1	13.5	14.0	14.4	14.9	15.3	15.8	16.2	16.7	17.1	17.6	18.0	18.5	18.9	19.4	19.8	20.3	20.7	21.2	21.6
3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.1	5.2	5.3	5.4
2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0
4.5	4.7	4.9	5.1	5.2	5.4	5.6	5.7	5.9	6.1	6.2	6.4	6.6	6.7	6.9	7.1	7.2	7.4	7.6	7.7	7.9	8.1	8.2
10.0	10.4	10.8	11.2	11.5	11.9	12.3	12.7	13.0	13.4	13.8	14.2	14.5	14.9	15.3	15.7	16.1	16.4	16.8	17.2	17.6	17.9	18.3
6.1	6.3	6.5	6.7	7.0	7.2	7.4	7.7	7.9	8.1	8.4	8.6	8.8	9.1	9.3	9.5	9.8	10.0	10.2	10.5	10.7	10.9	11.2
8.4	8.8	9.1	9.4	9.7	10.1	10.4	10.7	11.0	11.4	11.7	12.0	12.3	12.7	13.0	13.3	13.6	14.0	14.3	14.6	14.9	15.3	15.6
101.8	102.3	102.9	103.4	103.9	104.4	105.0	105.5	106.0	106.6	107.1	107.6	108.2	108.7	109.2	109.8	110.3	110.8	111.3	111.9	112.4	112.9	113.5
18.9	19.4	20.0	20.6	21.1	21.7	22.3	22.9	23.4	24.0	24.6	25.1	25.7	26.3	26.9	27.4	28.0	28.6	29.1	29.7	30.3	30.9	31.4
19.3	19.8	20.3	20.8	21.3	21.8	22.3	22.8	23.3	23.9	24.4	24.9	25.4	25.9	26.4	26.9	27.4	27.9	28.4	29.0	29.5	30.0	30.5
80.0	80.3	80.6	80.9	81.2	81.5	81.8	82.1	82.4	82.7	83.0	83.3	83.6	83.9	84.2	84.6	84.9	85.2	85.5	85.8	86.1	86.4	86.7
4.7	4.9	5.0	5.1	5.3	5.4	5.6	5.7	5.9	6.0	6.1	6.3	6.4	6.6	6.7	6.9	7.0	7.1	7.3	7.4	7.6	7.7	7.9
3.1	3.2	3.3	3.4	3.4	3.5	3.6	3.7	3.8	3.9	3.9	4.0	4.1	4.2	4.3	4.3	4.4	4.5	4.6	4.7	4.8	4.8	4.9
82.9	83.8	84.7	85.6	86.6	87.5	88.4	89.3	90.2	91.1	92.1	93.0	93.9	94.8	95.7	96.7	97.6	98.5	99.4	100.3	101.2	102.2	103.1
5.3	5.5	5.7	5.9	6.1	6.3	6.5	6.7	6.9	7.1	7.3	7.6	7.8	8.0	8.2	8.4	8.6	8.8	9.0	9.2	9.4	9.6	9.8
3.1	3.2	3.3	3.4	3.4	3.5	3.6	3.7	3.8	3.9	3.9	4.0	4.1	4.2	4.3	4.3	4.4	4.5	4.6	4.7	4.8	4.8	4.9
25.8	26.6	27.4	28.3	29.1	29.9	30.8	31.6	32.4	33.3	34.1	35.0	35.8	36.6	37.5	38.3	39.1	40.0	40.8	41.7	42.5	43.3	44.2
13.7	14.2	14.7	15.2	15.7	16.2	16.7	17.2	17.7	18.1	18.6	19.1	19.6	20.1	20.6	21.1	21.6	22.1	22.6	23.0	23.5	24.0	24.5
2.1	2.1	2.1	2.2	2.2	2.3	2.3	2.3	2.4	2.4	2.5	2.5	2.6	2.6	2.6	2.7	2.7	2.8	2.8	2.8	2.9	2.9	3.0
58.8	60.1	61.3	62.5	63.7	65.0	66.2	67.4	68.6	69.9	71.1	72.3	73.5	74.8	76.0	77.2	78.4	79.7	80.9	82.1	83.3	84.6	85.8
23.3	24.2	25.1	26.0	26.9	27.8	28.7	29.6	30.5	31.4	32.3	33.2	34.1	35.0	35.9	36.8	37.7	38.6	39.5	40.4	41.3	42.2	43.1
5.3	5.5	5.7	5.9	6.1	6.3	6.5	6.7	6.9	7.1	7.3	7.6	7.8	8.0	8.2	8.4	8.6	8.8	9.0	9.2	9.4	9.6	9.8
590.7	613.4	636.1	658.7	681.4	704.1	726.8	749.5	772.2	794.9	817.6	840.2	862.9	885.6	908.3	931.0	953.7	976.4	999.1	1021.8	1044.4	1067.1	1089.8
1.4	1.4	1.5	1.5	1.6	1.6	1.7	1.8	1.8	1.9	1.9	2.0	2.0	2.1	2.1	2.2	2.2	2.3	2.3	2.4	2.4	2.5	2.5
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
59.8	62.1	64.3	66.5	68.7	71.0	73.2	75.4	77.6	79.9	82.1	84.3	86.5	88.8	91.0	93.2	95.4	97.7	99.9	102.1	104.3	106.6	108.8
2.1	2.1	2.1	2.2	2.2	2.3	2.3	2.3	2.4	2.4	2.5	2.5	2.6	2.6	2.6	2.7	2.7	2.8	2.8	2.8	2.9	2.9	3.0
2.1	2.1	2.1	2.2	2.2	2.3	2.3	2.3	2.4	2.4	2.5	2.5	2.6	2.6	2.6	2.7	2.7	2.8	2.8	2.8	2.9	2.9	3.0
169.3	175.8	182.3	188.8	195.3	201.8	208.3	214.8	221.3	227.9	234.4	240.9	247.4	253.9	260.4	266.9	273.4	279.9	286.4	293.0	299.5	306.0	312.5

THE DISTRIBUTIONS SPREADSHEET (5)

CX	CY	CZ	DA	DB	DC	DD	DE	DF	DG	DH	DI	DJ	DK	DL	DM	DN	DO	DP	DQ	DR
50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
26.2	4	8	12	8	16	8	8	8	0	4	8	0	0	0	0	0	0	4	0	0
12.6	8	12	12	8	12	4	4	12	12	0	0	0	0	0	0	4	0	0	0	0
16.0	4	0	0	12	8	4	4	0	8	4	0	0	8	0	4	4	0	0	4	8
5.9	4	0	4	4	4	0	0	4	0	0	4	0	4	0	4	8	8	4	0	8
29.4	4	0	8	4	12	4	8	0	0	0	4	8	0	0	0	4	0	4	0	0
22.1	4	32	8	20	12	0	8	0	0	4	0	4	0	0	0	0	0	0	0	0
5.5	32	8	12	12	0	0	4	0	0	8	4	4	0	0	0	0	0	0	0	0
5.1	12	0	4	4	8	4	4	0	8	0	4	0	16	0	0	4	4	0	0	4
8.4	4	4	4	12	0	0	8	0	4	8	0	20	4	4	0	0	4	0	0	4
18.7	4	0	24	12	0	8	12	0	0	4	8	8	4	0	0	0	0	0	4	0
11.4	2.17	0	0	2.17	2.17	2.17	0	2.17	2.17	0	0	6.52	4.34	8.69	2.17	2.17	4.34	0	0	2.17
15.9	2.17	0	0	0	0	0	2.17	2.17	2.17	6.52	4.34	4.34	2.17	2.17	2.17	2.17	4.34	4.34	10.86	6.52
114	0.39	0	0.78	0	0.39	0	0	0	1.17	0	0.39	0	1.17	0	0.78	0	1.56	1.56	0	2.35
32.0	12.63	0	6.04	0	0	0	0	0	0	0.54	0	0	0	0	0	0	0	0	0	0
31.0	1.66	0	2.22	0	9.44	0	8.33	0	0	0	0	0	0.55	0	1.11	0	5.55	0	7.77	0
87.0	0.78	0	0	0	0.39	0	0	1.56	0	0	1.56	0	0	0	1.96	0	0	2.35	0	0
8.0	0.54	0	0	0	0	0	0	1.64	0	0	0	0	0	0	8.24	0	0	0	0	0
5.0	25.55	0	0	0	0	0	0	0	0	0	0	0	0	9.44	0	0	0	0	0	0
104	0.39	0.0	0.78	0.00	0.39	0.78	2.35	1.96	2.75	3.53	6.67	10.20	23.92	0.00	23.53	17.65	3.14	0.39	0.00	0.00
10.0	0.55	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.55	0.00	0.00	0.00	0.00	31.32	0.00	0.00	0.00	0.00
5.0	1.11	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.56	0.00	0.00	0.00	0.00	0.00	0.00
45.0	0.39	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39	1.18	0.00	0.00	0.39	0.39	0.00	0.00	0.00	0.00
25.0	7.14	0.0	0.00	24.73	0.00	32.42	0.00	28.02	0.00	2.75	0.00	0.55	0.00	0.00	0.00	0.55	0.00	0.00	0.00	0.00
3.0	10.56	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
87.0	0.39	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39	0.00	0.00	0.00	0.00	0.39	0.78	0.00	0.00	1.18	0.00
44.0	2.20	0.0	17.03	33.52	3.85	1.10	0.00	0.00	1.10	5.49	0.00	1.65	1.10	0.55	1.10	1.10	0.55	0.55	1.65	0.00
10.0	6.67	0.0	0.00	0.00	0.00	70.56	0.00	0.00	0.00	0.00	20.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1112.5	0.79	2.78	0.79	0.00	0.40	0.40	0.79	1.19	0.00	0.79	1.19	0.79	0.40	0.00	0.00	1.59	0.00	0.79	0.40	0.00
2.6	99.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.0	100.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
111.0	1.98	7.94	1.59	0.40	1.19	0.79	0.00	0.00	0.00	0.40	0.79	0.00	0.00	0.40	0.00	0.40	0.40	0.00	0.00	0.00
3.0	20.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.0	25.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
319.0	0.40	0.00	0.00	0.00	0.00	0.40	0.00	0.00	0.00	0.00	1.59	0.00	0.40	0.00	0.00	1.98	1.98	0.40	0.00	0.40

THE DISTRIBUTIONS SPREADSHEET (6)

DS	DT	DU	DV	DW	DX	DY	DZ	EA	EB	EC	ED	EF	EG	EH	EI	EJ	EK	EL	EM	EN
21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
0	0	0	0	0	0	4	0	0	4	0	0	0	0	0	0	0	0	0	0	0
4	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	4	0	0	0	0	0	4	4	0	4	0	8	0	0	0	0	0	0	0	0
0	8	4	0	0	0	0	4	4	0	4	0	0	4	0	4	4	0	0	0	0
4	0	4	4	0	0	0	0	0	0	4	0	4	0	4	0	0	4	0	0	4
0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	4	0	0	0
0	0	4	8	0	0	0	0	4	0	0	0	0	4	0	0	0	0	0	0	0
4	4	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
2.17	4.34	6.5	2.17	4.34	4.34	2.17	0	6.52	0	2.17	0	2.17	0	2.17	4.34	0	0	0	2.17	0
2.17	4.34	6.52	0	0	6.52	6.52	0	2.17	2.17	2.17	0	0	2.17	0	0	0	0	2.17	0	0
0	1.17	0	3.52	0	4.31	0	4.31	0	2.35	0	8.23	0	8.62	6.27	0	7.05	0	10.98	0	9.80
1.09	0	7.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.54	0	0	0
28.33	0	6.66	0	5.55	0	1.11	0	0.55	0	1.11	0	0	0	0	0	0	0	0	0	5.55
2.74	0	0	5.09	0	0	0	11.76	0	0	10.58	0	0	12.54	0	0	13.33	0	0	0	15.29
0	54.94	0	0	0	0	0	0	31.31	0	0	0	0	0	0	0.54	0	0	0	0	0
0	0	0	0	0	16.6	0	0	0	0	0	0	0	0	0	0	0	43.8	0	0	0
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39	0.00	0.00	0.00	0.39	0.00	0.00	0.00	0.00	0.39	0.00	0.00	0.00	0.00
57.14	0.00	0.00	0.00	0.00	7.69	0.00	0.00	0.00	0.00	0.55	0.00	0.00	0.00	0.00	0.55	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	42.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	55.5	0.00	0.00	0.00
0.39	0.39	1.18	0.39	0.39	0.00	0.78	0.00	1.18	3.14	2.35	0.00	2.35	1.57	6.27	5.49	6.67	0.00	8.24	9.80	13.33
0.00	0.55	0.00	0.00	0.00	0.55	0.00	0.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.10	0.00	0.55	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	65.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.78	1.96	2.35	0.39	3.14	3.92	2.75	7.45	6.67	2.75	8.63	7.06	11.37	5.10	7.06	5.88	4.71	3.14	2.75	1.57	1.18
0.00	1.10	0.00	2.20	5.49	7.14	2.20	0.55	2.20	0.00	0.00	0.00	0.55	0.00	0.00	0.00	0.00	0.55	0.55	1.10	0.00
0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.19	1.59	1.59	0.00	1.19	0.00	0.79	0.00	1.98	1.59	0.79	1.59	0.40	2.38	1.19	3.57	2.78	1.59	5.56	5.16	9.52
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.40	0.40	0.79	0.00	0.40	0.79	1.59	0.40	0.79	0.00	0.79	0.40	0.79	0.00	1.59	1.19	0.40	1.19	0.79	1.59
0.00	0.00	0.00	0.00	0.00	77.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	73.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.79	0.00	0.00	0.79	0.00	0.00	0.00	0.79	0.00	0.00	0.40	0.00	0.00	0.00	0.40	0.40	0.40	0.00	0.00	0.00

THE DISTRIBUTIONS SPREADSHEET (7)

EO	EP	EQ	ER	ES	ET	EU	EV	EW	EY
									Percentage Total
42	43	44	45	46	47	48	49	50	
0	0	0	0	0	0	0	0	4.00	100
0	0	0	0	0	0	0	0	4	100
0	0	0	0	0	0	0	0	4	100
0	0	0	0	0	0	0	0	4	100
0	4	0	0	0	0	0	0	4	100
0	0	0	0	0	0	0	0	4	100
0	0	0	4	0	0	0	0	4	100
0	0	0	0	0	0	0	0	4	100
0	0	0	0	0	0	0	0	4	100
0	0	0	0	0	0	0	0	4	100
2.17	2.17	4.34	0	0	0	0	0	2.17	100
2.17	0	0	0	0	0	0	0	2.17	100
0	8.62	0	5.09	0	5.09	0	2.74	1.17	100
0	0	1.09	13.18	0	41.75	0	14.28	1.64	100
0	2.77	0	0	0	0	0	7.22	4.44	100
0	0	12.54	0	0	5.09	0	0	2.35	100
0	2.19	0	0	0	0	0	0	0.54	100
0	0	0	0	0	0	0	0	4.44	100
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39	100
0.00	0.00	0.00	0.00	1.10	0.00	0.00	0.00	0.55	100
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.56	100
10.98	9.41	0.00	7.45	3.14	1.96	0.00	0.00	0.39	100
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.55	100
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	24.44	100
2.75	0.78	0.78	0.39	0.78	0.00	0.00	0.00	0.78	100
0.55	0.55	0.55	0.00	0.00	0.00	0.55	0.55	1.10	100
0.00	0.00	0.00	0.00	0.56	0.00	0.00	0.00	0.56	100
6.35	5.16	7.54	6.75	5.95	4.76	1.98	1.59	2.38	100
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.54	100
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100
0.40	2.78	4.76	13.89	23.41	14.68	4.37	3.57	1.59	100
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.62	100
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.04	100
0.40	0.00	0.40	0.40	0.40	0.40	16.67	59.92	9.92	100

The Equipment Variables Spreadsheet

ID	Description	MTBF Distribution	MTTR Distribution	Notes
1	L1 Refiner		L1RefinerMTTR()	
2	L1 MatForming		L1MatFormingMTTR()	0 cycletime as process completed while on conveyor
3	L1 Press		L1PressMTTR()	Time taken to press panels
4	L1 Unloader		L1UnloaderMTTR()	Time taken to press panels
5	L1 Other		L1OtherMTTR()	
6	L2 Refiner		L2RefinerMTTR()	
7	L2 MatForming		L2MatFormingMTTR()	
8	L2 Press		L2PressMTTR()	
9	L2 Unloader		L2UnloaderMTTR()	
10	L2 Other		L2OtherMTTR()	
11	C&C Zone1		CCZone1MTTR()	
12	C&C Zone2		CCZone2MTTR()	
13	Mcc91Running		MCC91Running()	
14	Mcc91MarketDT		Mcc91MarketDT()	
15	Mcc91ShiftCycleDT		Mcc91ShiftCycleDT()	
16	Mcc92Running		MCC92Running()	
17	Mcc92MarketDT		Mcc92MarketDT()	
18	Mcc92ShiftCycleDT		Mcc92ShiftCycleDT()	
19	Mcc93Running		MCC93Running()	
20	Mcc93MarketDT		Mcc93MarketDT()	
21	Mcc93ShiftCycleDT		Mcc93ShiftCycleDT()	
22	Mcc94Running		MCC94Running()	
23	Mcc94MarketDT		Mcc94MarketDT()	
24	Mcc94ShiftCycleDT		Mcc94ShiftCycleDT()	

APPENDIX D

The code below represents the implementation of the Production Schedule for Line1. This has been explained in Chapter 4 of this thesis.

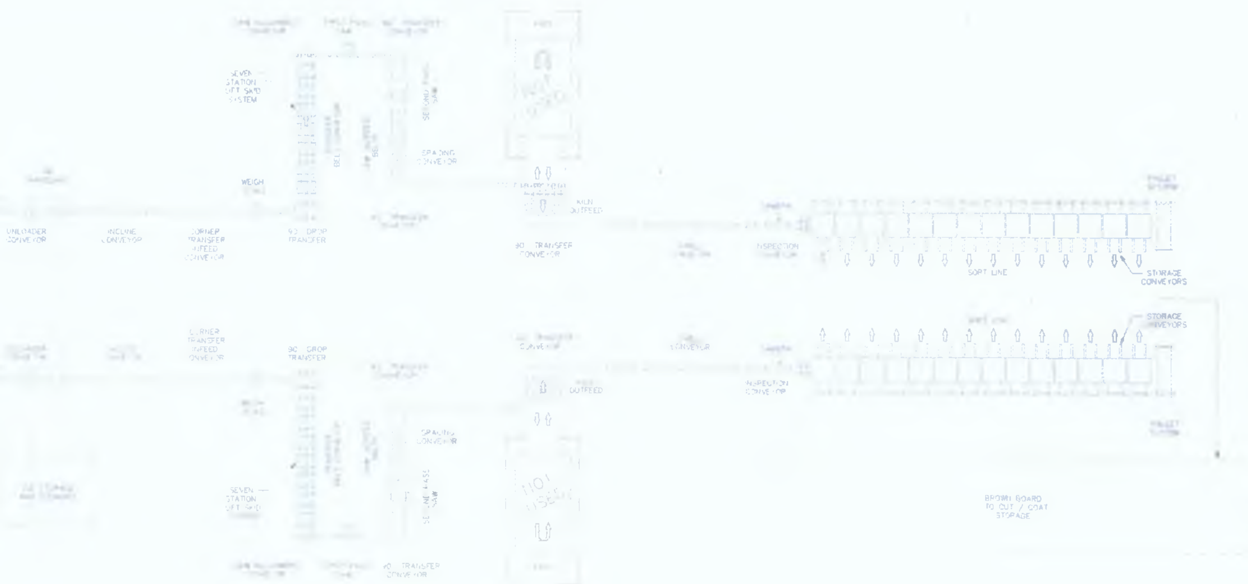
```
INT i=4
INT k=0
INC vL1ProductionScheduleRowRef
REAL CurrentTime
REAL MaxLineRunningSpeed = 1150 * 14

vL1DayNumber=arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 1]

IF arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 3]
                                   +vL1_Quantity_to_Produce>0 THEN
{
IF arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 2]=1 THEN
// This is the case of MARKET DOWNTIME / RUNNING
         {
        IF (arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 3]+
                          vL1_Quantity_to_Produce) > MaxLineRunningSpeed THEN
                 {
                 vL1_ProductionStart = 1
                 vL1_Quantity_to_Produce = vL1_Quantity_to_Produce +
                 arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 3]
                 WAIT 1440
                 }
        ELSE
                 {
                 WAIT 1440-(arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 3]
                          + vL1_Quantity_to_Produce)*1440/MaxLineRunningSpeed
                 vL1_ProductionStart = 1
                 vL1_Quantity_to_Produce = vL1_Quantity_to_Produce +
                          arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 3]
                 WAIT arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 3]*
                                          1440/MaxLineRunningSpeed
                 }
        }
ELSE IF arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 2] = 2 THEN
// In this case the line is RUNNING
        {
        vL1_ProductionStart = 1
        vL1_Quantity_to_Produce = vL1_Quantity_to_Produce +
        arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 3]
        WAIT 1440
        }
ELSE IF arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 2] = 5 THEN
// This is the case of RUNNING / DIE CHANGE
        {
        vL1_Quantity_to_Produce = vL1_Quantity_to_Produce +
                          arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 3]
        vL1_ProductionStart = 1
        CurrentTime = CLOCK()
```

```
		WAIT UNTIL vL1_Quantity_to_Produce = 0
		vL1_ProductionStart = 0
		DO
			{
			IF arLine1ProductionSchedule[vL1ProductionScheduleRowRef, i] =
			arLine1ProductionSchedule[vL1ProductionScheduleRowRef-1, i] THEN
				{
				INC k
				}
			INC i
			}
		UNTIL i=32
		k=28-k
		real x = N(arDieChangeTimes[k,1],arDieChangeTimes[k,2])
		WAIT x
		vL1_ProductionStart = 1
		WAIT 1440 - (CLOCK() - CurrentTime)
		}
	ELSE IF arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 2] = 3 THEN
	// This is the case of RUNNING / MARKET DOWNTIME
		{
		vL1_ProductionStart = 1
		vL1_Quantity_to_Produce = vL1_Quantity_to_Produce +
			arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 3]
		CurrentTime = CLOCK()
		inc vL1Timer
		INT trigger = vL1Timer+1
		ACTIVATE srL1Timer
		WAIT UNTIL vL1_Quantity_to_Produce = 0 or vL1Timer = trigger
		vL1_ProductionStart = 0
		WAIT 1440 - (Clock() - CurrentTime)
		}
	ELSE IF arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 2] = 4 THEN
	// This is the case of MARKET DOWNTIME
		{
		vL1_Quantity_to_Produce = vL1_Quantity_to_Produce +
				arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 3]
		IF vL1_Quantity_to_Produce > 0 THEN
			{
			CurrentTime = CLOCK()
			vL1_ProductionStart = 1
			WAIT UNTIL vL1_Quantity_to_Produce = 0
			vL1_ProductionStart = 0
			WAIT 1440 - (CLOCK() - CurrentTime )
			}
		ELSE
			{
			vL1_ProductionStart = 0
			WAIT 1440
			}
		}
	ELSE IF arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 2] = 7 THEN
	// This is the case of SHIFT CICLE DOWNTIME
		{
		vL1_Quantity_to_Produce = vL1_Quantity_to_Produce +
```

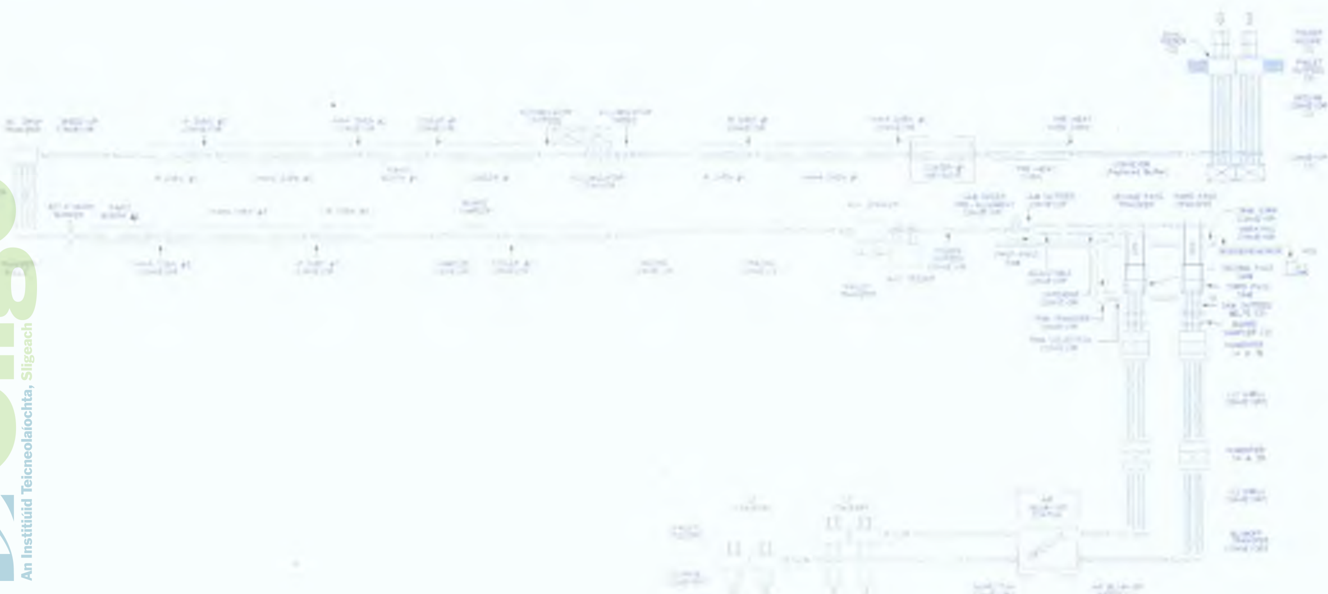
```
                    arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 3]
        IF vL1_Quantity_to_Produce > 0 THEN
                {
                CurrentTime = CLOCK()
                vL1_ProductionStart = 1
                WAIT UNTIL vL1_Quantity_to_Produce = 0
                vL1_ProductionStart = 0
                WAIT 1440 - (CLOCK() - CurrentTime )
                }
        ELSE
                {
                vL1_ProductionStart = 0
                WAIT 1440
                }
        }
ELSE IF arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 2] = 6 THEN
// This is the case of DIE CHANGE / RUNNING
        {
        CurrentTime = CLOCK()
        IF vL1_Quantity_to_Produce > 0 THEN
                {
                vL1_ProductionStart = 1
                WAIT UNTIL vL1_Quantity_to_Produce = 0
                }
        i=4
        k=0
        vL1_ProductionStart = 0
        DO
                {
                IF arLine1ProductionSchedule[vL1ProductionScheduleRowRef, i] =
                arLine1ProductionSchedule[vL1ProductionScheduleRowRef-1, i] THEN
                        INC k
                INC i
                }
        UNTIL i=32
                k=28-k
        x= N(arDieChangeTimes[k,1], arDieChangeTimes[k,2]) //put in distribution
        WAIT x
        vL1_ProductionStart = 1
        vL1_Quantity_to_Produce =
                arLine1ProductionSchedule[vL1ProductionScheduleRowRef, 3]
        WAIT 1440 - (CLOCK() - CurrentTime)
        }
vL1_ProductionStart = 0
}
ELSE
        {
        vL1_ProductionStart = 0
        WAIT 1440
        }
IF vL1_Quantity_to_Produce <0 THEN
        vL1_Quantity_to_Produce = 0
```

Appendix E

The Production Process of Line1 and Line2



THE CUT AND COAT PRODUCTION PROCESS



APPENDIX F

The figure below presents the correlation graph between production and energy consumption for the Cut and Coat Line.