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Simulation analysis of a multi-product flexible assembly line

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RYERSON UNIVERSITY

SIMULATION ANALYSIS OF A MULTI-PRODUCT FLEXIBLE ASSEMBLY LINE

by

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Simulation analysis of a multi-product flexible assembly line

Master of Applied Science, 2004
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Abstract

This thesis involves the use of simulation models to evaluate and optimize existing manufacturing assembly lines of electrical components. The goal of the simulation is primarily to mimic the existing production scenario in order to identify problematic areas such as bottleneck operations, conveyor speeds limiting production and factors inhibiting the performance of the resources. This simulation project uses a combination of the AweSim® software and logic programming using MS Visual Basic®. Through coding, the logic of the flow of the parts is demonstrated in the course of the steps such as the intermittent conveyors with single and double part flow. There are line selection rules in the models that follow restrictions which will affect the makespan, mean flow time and the utilization of the resources. Using different scenarios conclusions and recommendations are made on modifications to the existing production in order to improve makespan and mean flow time.

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Finally, the author wishes to thank his parents and friends for the support and kindness they have shown throughout the years. A special thank you to Vanda for putting up with "stressful" days and for always being there when most needed. Thank you from the bottom of my heart!

Table of Contents

List of Tables

List of Figures

List of Symbols and Acronyms

α_t	Represents the treatments effects in ANOVA
Δ_{tjk}	Represents the random effects or errors and are considered to be statistically independent Gaussian random variables with mean zero and variance σ^2
β_j	Represents the block effects in ANOVA
ASR	Angular Storage Rack
BOM	Bill Of Materials
CRT	Conveyor Run Time
CIT	Conveyor Idle Time
ε	Error used in mid-simulation calculations
e_i	Entity i generated passing through a check point in AweSim®
e_{i-1}	Entity following i generated passing through a check point in AweSim®
E_i	Expected frequency in each class of the goodness-of-fit test
$\overline{F}$	Mean Flow Time
F_B	ANOVA calculated random value statistic of blocks
FF_{20}	Flexible flow shop scenario with 20 stages
FF_c	Flexible flow shop with *c* stages
F_I	ANOVA calculated random value statistic of interactions
FJ_c	Flexible job shop with *c* stages
F_m	Flow shop with *m* machines
F_t	Forecasted value using the weighted moving average formula
F_T	ANOVA calculated random value statistic of treatments
$F(\gamma)$	q-quantile of X

$F_{\gamma 1,\gamma 2,\alpha}$	ANOVA Fisher test statistic used for comparison
GMRC	Gravity-Movement-Roller Conveyor
GT/CM	Group Technology/Cellular Manufacturing
$H_0^{(1)}$	First ANOVA null hypothesis where all treatment means are the same
$H_0^{(2)}$	Second ANOVA null hypothesis where all block means are the same
$H_0^{(3)}$	Third ANOVA null hypothesis where no interactions exist between treatments and blocks
HDA	HOF Dry Assembly
HFA	HOF Final Assembly
HOF	High Output Fluorescent
IMC	Intermittent-Mechanical Conveyor
J_m	Job shop with *m* machines
L	Parameter Likelihood estimation
θ	Population mean
$\hat{\theta}$	Sample mean
O_i	Observation frequency in the goodness-of-fit test
O_m	Open shop with *m* machines
$\hat{\theta}_r$	Sample mean within each replication
p_i	Part *i*
p_{i+1}	Part following part *i*
Primaries	HOF cores built in the first workstations of the HDA cell
$p(x_i)$	Probability of model *i* being produced
R	Total number of runs

R_{min}	Estimated initial minimum number of simulation runs
R_{new}	Calculated new minimum number of simulation runs
R_0	Initial number of simulation runs
ROI	Return on Investment
RT	Reel Transporter
S^2	Sample standard deviation
SBP	Shifting Bottleneck Procedure
Secondaries	Complimentary HOF cores built in workstation HDA-09 to HDA-10
SS_T	Variation between treatments using ANOVA
SS_B	Variation between blocks using ANOVA
SS_I	Possible variation due to interaction between treatments/blocks using ANOVA
SS_R	Residual variation using ANOVA
SS	Total variation using ANOVA
T_E	Initial simulation run length
$T_{E_{new}}$	Calculated new simulation run length
T_0	Initial simulation time to clear statistics
$T_{0_{new}}$	Calculated new simulation time to clear statistics
$t_{\alpha/2,R-1}$	T-distribution parameter found in statistical tables
χ_0^2	Chi-square test statistic
$\chi^2_{\alpha,k-s-1}$	Critical value found in statistical tables
μ_A	Mean of factor A when using ANOVA

μ_B	Mean of factor B when using ANOVA
WIP	Work In Process
x_i	Data value i
$x_{t,j,k}$	Matrix entry pertaining to the experiments with replications
$\bar{x}_{tj}$	Replication means when using ANOVA
$\bar{x}_t$	Treatment's mean when using ANOVA
$\bar{x}_j$	Block's mean when using ANOVA
$\bar{x}$	Overall mean when using ANOVA
Y_{r_i}	The i^{th} observation within replication r
γ_{tj}	Represents the treatment/block interaction effects in ANOVA
$Z_{\alpha/2}$	Standard-normal distribution parameter found in statistical table

CHAPTER 1 PREAMBLE

1.1 Introduction

This Chapter will focus mainly on the historical background of the manufacturing industry as well as the relevant events leading to today's benchmarks. Some contributions will be highlighted such as those of the Gilberths and Taylor on how work is measured and performed, as well as a reference to the first known assembly line. Later in the chapter, some references will be made to previous work done in terms of forming cellular manufacturing procedures, simulation with AweSim® and scheduling leading into the introduction of some of the methodology used in this research project.

1.2 Literature Review

Manufacturing systems have been evolving over the years to what we see today as lean high-tech fully mechanized industries with smooth flow of its product from start to finish. This evolution of the manufacturing industry began with the Industrial Revolution in 1770 when the diffusion of knowledge [24] began. Hence, the initial stages of the improvements of the living standards. Due to the abundance of money from the British colonies and freedom from war, the industry began focusing its attention on improving both the working conditions, which in turn improved the living conditions, and the technology used. Some great inventions such as the Watt's steam engine revolutionized how companies powered their equipment, as well as leading to great inventions such as the steam powered train. During these times, some began to question and to benchmark how work was being performed. The work of Frank and Lilian Gilberth founded the modern motion study technique [29]. They scientifically studied how the human body performed certain motions and analyzed how certain tasks could evolve by eliminating unnecessary motions, hence, the birth of the benchmarking which is still referenced today. On the other hand, Frederick Taylor also asked one of the fundamental questions on any study, "what is the best way to do this job?"[29]. He relied on facts, experiments and analysis of the methodology in the workplace, to mark the birth of the scientific study of work [29]. Along with the diffusion of knowledge, some important steps were being taken to disperse the craftsmanship of certain operations. At the early stages of the manufacturing industry, one person could build a sellable good from start to finish. The person could be said to be extremely knowledgeable about the product he/she was building, but this meant that any new apprentice could take years to master the skills required to become truly valuable to the company. With the industrial revolution, it marked the initial stages of the specialization of labour, which meant that a product could now be spread over a layout of workstations (assembly-line concept) which performed individual tasks as opposed to building the product as a whole in a single workstation. But, sciences were being applied throughout the industry which had not yet adopted the concept of assembly-line technology.

Contrary to what many people believe, Henry Ford was not the first to use the concept of the assembly line! The first documented assembly line was that of Samuel Colt, a producer of hand-guns [24] which organized its workstations such that the hand-gun production would flow from the start to finish with individual workers performing only a specialized task to eventually form a complete hand-gun. Because the work-in-process (WIP) only visited one workstation or machine in its complete path once, then this is what is known as a flow shop [31]. This idea was quick to spread because manufacturers were now producing faster and cheaper. Although the concept of an assembly line was ideal, some manufacturing facilities did not have work that flowed in a constant path. These were categorized as job shops (F_m), where "each job has its own predetermined route to follow and each job may visit each machine or workstation more than once" [31]. Therefore, jobs could go forward and then back and forward again. Nowadays, there are many variations and combinations of the flow shop and job shop including flexible flow shops (FF_c), which is a generalization of the flow shop and the parallel machine environments (which is the layout procedure of this research project), flexible job shop (FJ_c) and open shop (O_m) just to name a few [31]. One of the latest industry trends is to try to form cells of individual machines or workstation based on families of parts in order to try to create as much one-way flow as possible. This is widely known as Group Technology/Cellular Manufacturing (GT/CM), which, as the name explicitly implies, is the grouping of machine to form individual cells. The process of assigning machines and part families to cells is known as the cell formation and algorithms have been created [7,11,13,23,28,40] such that a reduction of objective functions, such as production cost, setup, or makespan is minimized. As with preceding processes, there are many advantages [9,38] in creating cells to either maximize or minimize the objectives of the company. The main advantages of creating cells include a reduction of the setup times, increase the one directional flow of parts [2], concentration of grouping of tasks translating into easier training of the personnel and reduction of WIP. When creating individual cells, the identification of the flow of the work can be easier identifiable and waste can be reduced [19], as well, there is the opportunity to create a responsibility factor of the workers in taking ownership of the tasks they are performing [14]. When this occurs, certain morale can be built and improvements are easily obtained because it becomes a win-win situation for both the company and workers involved. Also, when a group of workers are directly responsible for all the actions taken in terms of improving their conditions, it can in turn serve as a training tool for understanding not only what the individual does within the cell but to know the adjacent workstation to him/her improving the performance and the personal set of skills [22].

Regardless of the layout process implemented, scheduling is a major component of any manufacturing facility. Since the introduction of the job shop scheduling in the 1950's, there was a constant evolution of the techniques and algorithms developed over the years. There are many variables contributing to the complexity of scheduling work to the whole company or even to a single machine [4,10,30]. The objective function of each company may vary from industry to industry, but the general idea is to create the optimal and most economical schedule [37] that will take into account release dates [36], due dates, setup times [26], the number of part families [16], dispatching rules and other relevant factors contributing to the performance of the schedule. One of the procedures that is relevant to the thesis research is the shifting bottleneck procedure (SBP) [1] to solve scheduling problems. This procedure is further extended to solve various types of scheduling problems including open shops, assembly shops and shops where there is only partial ordering [33] and in some case also to solve real-life applications [21]. Given the complexity of the constraints of any schedule, nowadays companies resort to automation and software to solve and create complex schedules [17,18].

1.3 Simulation as a tool

Working hand-in-hand, the scheduling procedures developed over the years have helped software developers to create complex algorithms to solve almost any possible and imaginary scheduling problems, also, generalized simulation software has helped to solve complex problems using different procedures [6]. Many techniques have evolved, such as using object-oriented simulation [20] with its complex attribute functions as well as integration of existing company automated systems such as MRP to compliment with real data to compare scheduling techniques [15]. One of many generic software available is the AweSim® software developed by Symix Systems Inc., which will be used as a tool for this research project. It can solve a number of complex processes as well as give a visual status of the simulation [32]. It can be applied to any layout process ranging from a simple one-machine shop to a highly dynamic job shop [25,27] or flexible flow shop with numerous stages and machines to determine different effects that some constraints have on the entire production.

CHAPTER 2 DESCRIPTION OF THE CASE STUDY

2.1 Introduction

This chapter will begin by presenting a brief introduction of the company where the thesis was conducted as well as a description of the layout and characteristics of the manufacturing area under study such as workstations arrangement and material handling equipment used. The four objectives of the case study and the methodology used in achieving solutions to the problem will also be described later in the chapter.

2.2 Allanson International Inc. Case Study

Allanson International Inc. was founded in 1927 and originally manufactured automotive parts, as well as ignition and neon transformers. Today, Allanson manufactures, among other electrical products, around eighty different models of fluorescent light ballasts which are then sold in world wide markets. This project analyzes the Electronic High Output Fluorescent Ballasts (HOF) production area where the ballasts are manufactured. The layout and characteristics of the production area is composed of three main manufacturing cells known as the Dry-build that includes Primaries-build and Secondaries-build also known as HDA, Impregnation and Final-build known as HFA. The agglomeration of these cells is categorized as a Flexible Flow Shop (FF_{20}) [31] with twenty stages due to existing precedence constraints and multiple identical workstations. Also every product, regardless of model type, produced in this manufacturing area has to go through the same workstations in a sequential fashion in order to be complete (flow line production). The only difference in the work being performed at each workstation is that each model will have its own set of production requirements making the assembly different from each other, but the work is still designated specifically to that workstation, hence making the workstation flexible. Some workstations are designed to accommodate one, two or three operators performing identical tasks in order to balance the line and try to eliminate bottlenecks as much as possible. Workstations are arranged in a layout consisting of both parallel and series; hence there are places where similar tasks are performed in series while other parts of the production are performed in parallel. Also, operations are performed both manually and mechanically with the aid of machines and other tools including soldering irons, wire clippers and other material handling equipment. Parts and material move between workstations either by conveyor belts or manually. There are two types of conveyors throughout the HOF production area which are the Gravity-Movement-Roller (GMRC) conveyors and Intermittent-Mechanical-Conveyor (IMC) belts. The GMR conveyors work on a gravity principle where one end of the conveyor is slightly raised so that the product travels from the high-end to the low-end without any help other than that of gravity. The GMR conveyors are found between workstations HDA-01[1] through to HDA-03a and HDA-03b as well as from workstation HDA-09 through to HDA-11. The second type of conveyor, the IMC belts are mechanically moving conveyors, found in both the HDA and HFA cells which move parts between workstation HDA-03a through to HDA-07a, also between HDA-03b through to HDA-07b, HFA-02a through to HFA-05a and finally between HFA-02b through to HFA-03b. These IMC belts are powered by electrical motors and only have two settings that have to be set at the beginning of each production run. We have the Conveyor-Run-Time (CRT) and the Conveyor-Idle-Time (CIT) settings which represent the time the conveyor runs and the time the conveyor lies

[1] Please see Figure 2:1: Allanson Int. Inc. HOF Material Flow Chart on page 9 to locate the workstations.

motionless respectively. The CRT is set accordingly to a predetermined value which is the time that the conveyor must move in order to carry product from one workstation to the other. This CRT is directly related to the distance between workstations that use the conveyor; hence the distance between workstations must be identical in order for the products to stop at equal lengths. Furthermore, each conveyor will have its own CRT because of discrepancies between workstation layouts. Once the CRT is set, it will never be changed unless there are revisions to the overall layout of the cells involving changing the distances between workstations. The CIT, on the other hand, is set according to the product model being produced, which represents the longest process time on that line plus allowances. The CIT is usually set at a time interval greater than that of the bottleneck operation, hence allowing the workers to perform their tasks within the CIT time and become available for the upcoming event. The CIT must be constantly changed because orders are constantly being sent through involving the production of different models. There are charts with the correct settings that must be applied when working with a particular model that serve as a guide to the personnel responsible to change the conveyor settings.

Throughout this project the reader will be faced with a nomenclature for the workstations such as HDA-01 or HFA-05bi, and the reason to name the workstations in such a manner is simple. The first part of the naming, HDA or HFA simply represents the area of production in HOF. HDA means HOF DRY ASSEMBLY, and the number that follows simply represents the workstation number in the work-flow chart. As an example, HDA-03b means Workstation 3b in the HOF DRY ASSEMBLY cell. Similarly, HFA means HOF FINAL ASSEMBLY and the number that follows also represents the workstation in that production cell, again as an example, HFA-03aii is Workstation 3aii in the HOF FINAL ASSEMBLY cell. Also, in the case of a workstation having a number followed by two or three letter such as "aii" or "bi" it means that there is another workstation that is performing identical tasks and it can be either parallel or in series to it. Figure 2:1 illustrates the HOF material flow chart.

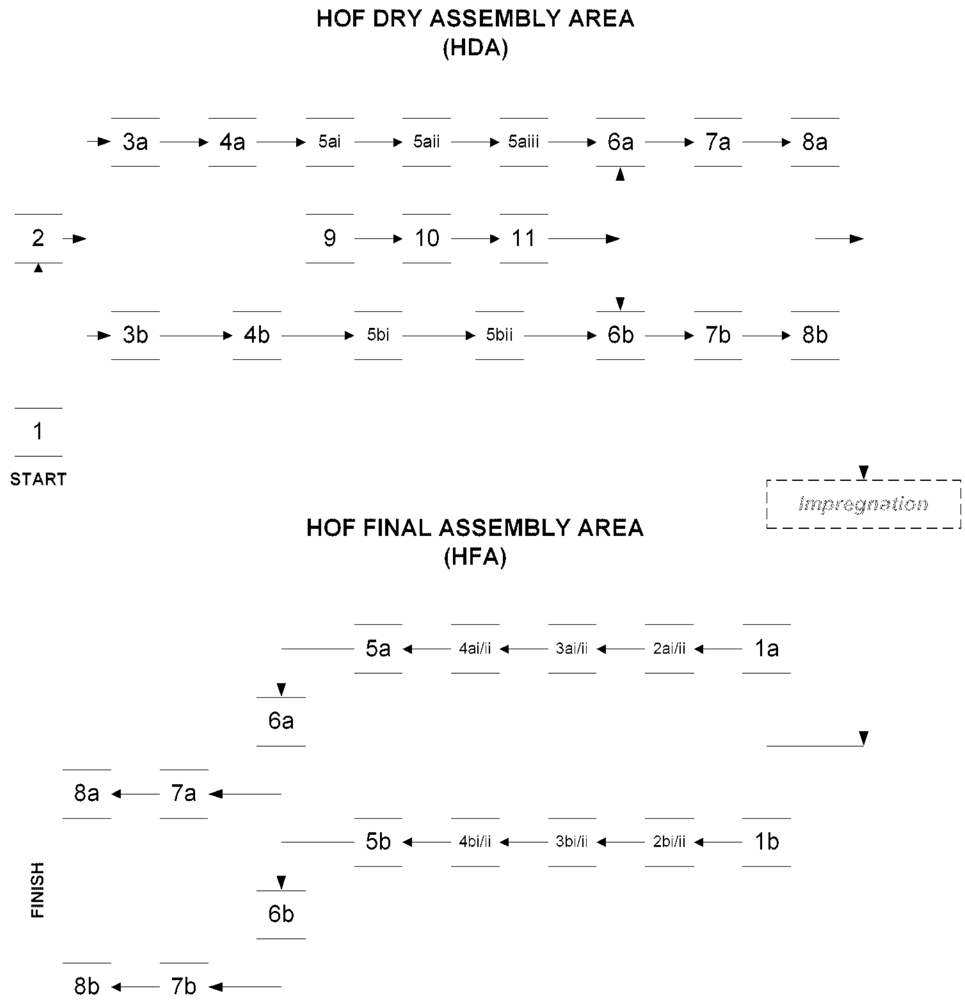

Figure 2:1 Allanson Int. Inc. HOF Material Flow Chart

The entire HOF production process begins at Workstation HDA-01 and Workstation HDA-09 (since they do not have any precedent workstations). The lines emanating from Workstation HDA-02 are then split into two lines. The products being produced in the line beginning with workstation HDA-03a are known as the "Large Jobs" and those being produced in the line starting with workstation HDA-03b are known as "Small Jobs", or, one may also refer to those lines as the "Large Jobs Line" and the "Small Jobs Line" respectively. The assemblies from these lines, beginning at Workstation HDA-01 are known as *Primaries*, being the main cores of the ballast which are then complimented with *Secondaries* at Workstation HDA-06a and 6b respectively. Secondaries are produced in the center cell, beginning in Workstation HDA-09 and ending in Workstation HDA-11.

The distinction between "Large Jobs" and "Small Jobs" is categorized by both model number and also by the number of Secondaries to a Primary core. The rule of thumb is that "Small Jobs" only take one Primary and one Secondary, while the "Large Jobs" will take one Primary and two Secondaries. Also, in the current production, models of the same kind will be produced only in one line at a time, hence making the lines become "designated". This rule will be extremely important when developing the simulation networks in AweSim®, such that the entities from one line can be routed to the other and the number of Secondaries to produce will be known (the simulation networks will be described in Chapter 3). Once the ballast cores are produced in the HDA cells, they will be routed to the Impregnation cell where they will be submitted to heating, impregnation and cooling to create a protective cover of resin and pitch to eliminate vibration, noise and reduce heat transfer. Once the cores are cooled to a point of being safe to be handled, they are then passed on to the HFA cell where once again they are sent either to one line known as the "Small Jobs Line" beginning at HFA-01a, or to the

"Large Jobs Line" beginning at HFA-01b. The process of assembly continues from the emanating workstation until they reach the end of the process at workstation HFA-08a or 08b which is the final packing and crating. This concludes the introduction to the layout of the HOF production area and some of the characteristics involved.

The second part of the introduction to the case study is the purpose or objective of this thesis. The first objective is to determine via simulation the utilization and idle times of the operators and/or machines and also to determine if this initial layout of the production line is properly balanced. The company does not have any current information regarding benchmarking or utilization of both workers and machines, hence the need to have indicators that will allow management to improve the production where necessary. To determine if the line is balanced, one will take a look at simulation indicators such as busy and idle times as well as queue lengths between the workstations. There is also a very important aspect for this simulation, which is the analysis of the arrival times of jobs from HDA-11 to workstations HDA-06a and HDA-06b. The arrival times of the Secondaries to the main lines is very important because it will determine how much waiting time is there at the above workstations, hence translating into operator's idle time as well as to determine if the production of secondaries is capable to keep up with the demand of the primaries. In regards to this point, Allanson is considering purchasing a second Secondary-Winding Machine and is interested to have a study that will show if investing in a new machine is economically justified. Based on the findings from this thesis, Allanson will make a decision to purchase or not this second Secondary-Winding Machine. The third reason for this analysis is to minimize the mean flow time ($\overline{F}$) that each unit will spend in the system. Hence, from a scheduling point of view, the analysis of the output from the simulation and testing different scenarios will determine how to best solve the Flexible Flow Shop problem $FF_{20} / prec / \overline{F}$. The fourth and last objective of this thesis is to determine the best scenario that would increase production within the same timeframe, in other words, produce more with the same time. To do this, different scenarios had to be created that would allow us to see how many parts were created in a specified time period.

The different scenarios of the simulation to improve the objective function will include dispatching rules such as First-In-First-Out (FIFO), and a series of trials with changing CITs until an optimal solution is found as well as different production rules of designated production lines and mixed-models production lines.

Since there are eighty different types of models in production, the thesis was limited to five models due to various reasons including limitations in data gathering and simplicity of the simulation models. The "Best-and-Worst Case" models are included in this simulation. The "Best-and-Worst Case" models are those that have the longest and shortest processing times as well as those that will either be produced in the "Large Jobs Line" or in the "Small Jobs Line". Models 696-AT, 672-AT and 496-AT were picked from the large jobs category, and 472AT and 272AT from the small jobs category. In order to determine the probability of production based on the model, the company sales data from the last three years was gathered and the Weighted Moving Average (WMA) [35] method was used to calculate the forecasted values to be produced. The formula for the WMA method is given below:

$$F_t = \frac{\sum_{t=1}^{n} (W_{t-1} \times D_{t-1})}{n} \quad \textbf{(2.1)}$$

where :

W_{t-1} is the respective weight of period $i-1$ and D_{i-1} is the demand for period $i-1$

also,

$$\sum_{i=1}^{n} W_i = 1$$

The equation above is used to calculate the forecasted data based on past values by assigning weights to the data, usually the largest weight is assigned to the most recent data and the lowest weight is assigned to the oldest data. The more data there is, the better the forecast will be. In the case of this thesis, the sales reports of the last three years were used. Hence data that is one year old has a weight of 5/8, two-year old data has a weight of 2/8 and three-year old data has a weight of 1/8 to calculate the forecasted sales data for the five models. Once the forecasted values were found for each model, the five models were then compared relative to each other and to total estimated sales. The probability of production is then the same value as the ratio of the models compared to the total forecasted sales value. The WMA method was used because the company has had a sudden growth in the sales of the HOF Ballasts in recent years, hence representing the way to give relevance to the most recent data when comparing to previous data.

2.3 Initial solutions to old problems

Without knowing a whole lot about the entire line, it was clearly identified that the setups on both winding machines (HDA-01 and HDA-09) were the longest in the entire production line regardless of the models being built. Initially, the setup of the winding machines involved the operator and the lead-hand as well as a forklift to move the wire-reels from storage to the workstation. Figure 2:2 depicts a sample of the magnetic-wire-reels used both by the winding machines in the HDA-01 and HDA-09 workstations.

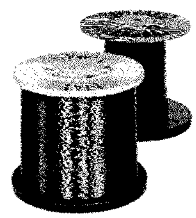

Figure 2:2 Essex 25RP reel used at Allanson HOF production area

The setup could occur either at the beginning of a production run or in the middle of production. A "partial setup" would occur when one or more magnetic-wire-reels would deplete while a HOF model was being produced (this occurred because the weight of the same gage wire-reels is not uniform), while a "full setup or change-over" occurs when the next HOF model being produced does not use the same gage of magnetic wire. Regardless of the type of setup, the operator would have to stop the machine and wait until the lead hand would come to her aid in order to change the reels. The magnetic-wire-reels average weight ranges anywhere from 150 to over 350lbs, which could not be easily moved by anyone, hence, the reason for the operator to wait for the lead-hand to come with a forklift to perform the task. On average, the full setups took an average of approximately 25 to 30 minutes primarily either because the lead-hand was not always available to immediately assist the operator or the forklift was not free. Therefore, the stoppage of the machine and the idling of the operator meant lost production and in the management's point of view, most importantly lost revenue.

2.3.1 The RT and the Hook

Designing a device that could hold the wire reels and be easily moved by the operator without needing any assistance and hence freeing up resources (the lead-hand and the forklift) would be a quick solution. The design of this device was decided to be done using an advanced 3D CAD program called AutoDesk Inventor™ in order be able to automatically create a Bill of Material database as well as a 3D analysis of how the components would interact [12]. The company had a mechanical device that picked up these wire reels from the pallets sent by the supplier that could be used to load the wire reels onto the device, therefore, the problem of loading would be solved. It was just a matter of designing the most economical device using "off the shelf" equipment such as standard casters and either wood or plastic. Hence, the creation of a device called the "Winding Machine Reel Transporter" known as the RT was made. Figure 2:3 depicts a loaded RT below.

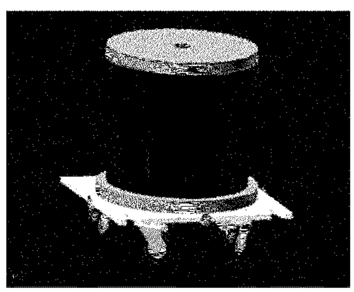

Figure 2:3 Loaded RT used in HDA-01 and HDA-09 workstations

Along with the RT, a tentative scheduling technique would be devised which involved the pre-loading of the RT according to gage at the beginning of the production week and storing them in a designated area created specifically for the storage of the loaded RTs near the workstations. The pre-loading would mean that the operator could simply "wheel" in the needed gage of wire and store the unused wire back into the designated location for future usage. It was also decided to have RTs loaded with extra wire in case a partial setup occurred. The specifications of the RT are listed in Table 2-1 where the physical characteristics as well as the components used are noted.

Table 2-1 RT specifications table

Name:	Reel Transporter (RT)
Length:	18in.
Width:	18in.
Height:	4¾in.
Weight:	11lbs
Rotation Radius	12¾in.
Max. Load Capacity:	500lbs
Height with 1 reel loaded:	19.12in.
Height with 2 reels loaded:	33½in.
Base-plate Material:	High Density Poly-Ethylene
Base-plate thickness:	½in.
Caster model:	Darcor 12-23R-XD
Wheel diameter:	3in.
Wheel material:	Neoprene
Caster Swivel Radius:	3in.
Caster overall height:	4¼in.
Special features:	1 center hold for plastic Reel-locator 2 Locking grooves 4 Pail locator washers on all 4 sides 8 "Hook" holes of Ø¾in.

In order for management to approve the addition of the RTs, both an economical and a practical analysis had to be performed and based on the return on investment (ROI) it would be either accepted or rejected. It was calculated that the RTs would reduce the setup time by 80% which in turn saved the company $11,286.12 annually and had a ROI of 2.9 months. From these numbers, management approved the project and the in-house production of RTs was initiated. The improvements were drastic right from the introduction of the RTs hence increasing the acceptance by both management and the operators of the workstations where the RTs were to be used. A manual with the specifications and "how to use" was developed where everything from the drawings of the board to the storage of the RTs and the preventive maintenance was explained in detail in order to serve both as a guide and for subsequent productions of additional RTs would be possible. To aid with the retrieving of the loaded RTs from under the shelves a "Hook" was also designed with ergonomics [24] in mind using the measurements obtained from tables of the average USA female. This hook allowed for the retrieve of the RTs without having to bend or lift. Figure 2:4 depicts the hook and a loaded RT.

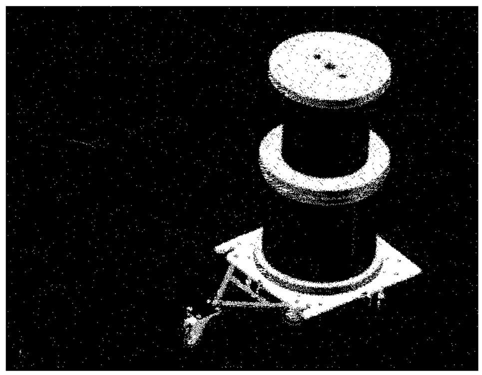

Figure 2:4 Hook and a double-loaded RT

2.3.2 Storage of the impregnation baskets

The lack of space at Allanson International Inc. is a problem that not only affects how storage space is designed but also the safety of the personnel working in the production areas. Hallways are usually high traffic areas for material handling equipment such as forklifts carrying very heavy equipment or components, which are potentially unsafe. Also, due to the proximity of the hallways and storage areas to the production lines in the HOF production area, any storing and retrieving operations translate into a safety concern by all. Due to the close proximity, forklift operators have to perform more than one manoeuvre to either store or retrieve items from shelves. Hence, another factor that increases the time required to perform the tasks as well as increase safety concerns due to obstructed views and also potential damage to equipment. A particular problem area in the HOF production area is the storage racks of the impregnation baskets. The baskets have to be stored perpendicular to the hallway due to the setup of the holding bars in the racks, hence, making the forklift having to be at 90° as well. The racks are very close to the HDA lines separated only by a hallway without any protective guards. In this area, there are many operators with their backs to the hallway and evidently to the racks and many times oblivious to the manoeuvring of the forklift behind them. The racks are also located near a new welding machine which must be protected against any damage caused by bumping of the forklifts. The relocation of the impregnation racks is not possible once again due to the lack of space elsewhere, hence something had to be done to the existing system. These potential unsafe activities lead to the design of the "Angular Storage Racks" (ASR) depicted in Figure 2:5

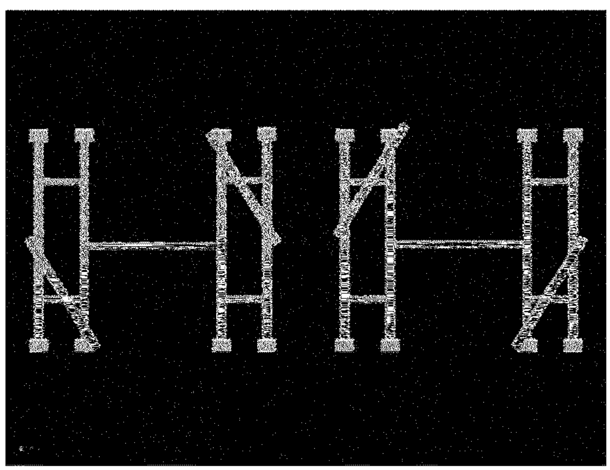

Figure 2:5 Angular Storage Racks for the impregnation baskets

The ASR storage system allows for the forklifts to store the impregnation racks with a single movement and the back of the forklift is now diverted away from the production lines, hence, reducing the risk of potential injury to the workers and minimizing the effect of the direct fumes coming directly from the forklift into the production area. This was both a safety and operation time reduction benefit that came out of simple observations of how the tasks are performed.

CHAPTER 3 SIMULATION MODELS

3.1 Introduction

This chapter is the most intensive part of the thesis because it covers in detail the steps in building the scenarios for the simulation model. It begins with an introduction to the data acquisition and then moves into the first scenario built representing the current production system at Allanson International Inc. as well as solution scenarios. The chapter is broken down into subsections pertaining to each scenario where the components and the flow charts are presented as well as the logic used in building and the issues arising from each step.

3.2 Data Acquisition

The first step taken in building the model was data acquisition. As explained in Chapter 2, the data acquisition was not possible for all the 80 models for several reasons, one being a time constraint and the second because not all models are produced in an observation period. Data in several departments had to be gathered in order to have a complete set of input data available to run the simulation models. This included sales data, so that production probabilities could be calculated, as explained previously. Also the actual production data and material handling data had to be gathered in order to compare and validate the simulation models. Information on the batch-lot size quantities being produced as well as capacities of machines also had to be collected in order to create a close approximation to the actual production scenario. The data acquisition for the production followed the principles of "Stop-Watch" techniques where the person obtaining data is directly observing each task and taking times from the beginning to the end of the task and reporting any intermediate steps with corresponding time-stamps. To ensure that there would be no biased data, familiarity with both the products being built as well as with the production personnel was necessary. It was also a priority to make the workers feel that this exercise would not interfere with their normal working standards in order to ensure that they would work at their normal pace. The biased portion was taken care by observing the same task being performed at different dates or times and by different operators in order to diversify the source of the data. Data collection became a constant factor in the production floor as different workstations at different times with different workers were being observed. Not only was production data taken in the form of time, but also observing the steps the operators took in order to complete their activity was imperative. With this step, routings for each product would be included, thus complementing the time with the production routings not existing until this thesis was performed. Since none of this data was found in the company, as it is the case with many other companies, each workstation should be observed and a minimum of twenty data points should be collected for each task (twenty parts of the same model produced at each workstation) arbitrarily[2]. This process took quite a bit of time because some tasks were quite lengthy and it would require a lot of observation time just for one workstation but nevertheless enough data points were collected. With all this data, there was obviously randomness in the system and hence the main reason for using simulation as opposed to using deterministic mathematical models. Simulation was used in order to see dynamic statistics over a period of time as opposed to using queuing models, which give no

[2] The minimum number of points should be thirty to ensure sound statistics [8], but due to time limitations it was decided that twenty data samples would be sufficient.

indication of the fluctuations of the statistics but instead only an average behaviour of the system. The randomness of this study included the probability of a model being produced, the batch size quantity to be produced which is directly related to the model, the ratio of Secondaries to Primaries also related to the model and the actual production time at each workstation would follow a probability density function (pdf) for each model as well.

3.3 Model Building

From the start of the thesis, a rule for naming the models was adopted, and that rule was to name any scenario in a way such that it would be easily recognizable from the others. In addition to this scenario naming rule, any network or control files pertaining to the scenario, was named the same way as the scenario. In the selected simulation software AweSim®, any scenario has a number of components such as networks and control files. To avoid confusion, all components of a scenario have been assigned the same initial file name. There were some attributes from the simulation models such as setup times and material handling time between some workstations that were omitted simply because it was necessary to keep this complex situation as simple as possible due to time restrictions.

Scenario building was initiated at the same time as data was being gathered in order to save time and since the actual data was not needed until the process of running and debugging the simulation scenarios was started. One had to become familiar with the AweSim® environment, the types of distributions it would accept, the behaviour of each entity and how to collect data for analysis were fundamental principals that had to be known even before attempting to begin with the simulation models. AweSim®, like most simulation software packages, had the capability to perform both simulation runs with specified parameters and also statistical tools to analyse the performance and behaviour of the model. Simple analysis such as activity utilization, busy and idle times and queue lengths are given statistics in the most basic models, hence any additional information and requests had to be coded as model inputs in MS Visual Basic so that outputs could be obtained that would allow conclusions and analyses of the objective functions be made.

Once the simulation model building process began, defining what and how the system would behave during the simulation was also a priority. The objective was to capture data on utilizations, operator idle times, queue lengths and particularly part arrival times at stations HDA-06a and HDA-06b as well as the main objectives were to determine the mean flow time of parts in this manufacturing system $(\overline{F})$ and the total parts produced in a given time period. Once a clear idea of how these objectives were going to be approached, the problem of designing the case study began by breaking down the overall problem into smaller more manageable portions and focusing the attention in particular areas which were simulated as different scenarios.

3.3.1 SALHDA and SALHFA Scenarios

The first step in building the simulation model was to create scenarios containing networks that would simulate the IMC belts in order to determine if the model would mimic the true production of the cells. A network model consists of a set of interconnected symbols that depict the operations of the system [23]. Two scenarios were created which simulated the production in the HDA and HFA cells called SALHDA and SALHFA[3] respectively, where the current manufacturing situation with First-In-First-Out (FIFO) priority rules for the existing queues in the system as well as the movement of parts between workstations in an intermittent way was simulated, hence mimicking the IMC belts. Only one scenario was created for each production cell to start with, since there would be no point in programming and coding for two identical IMC belts. Once one scenario was working one could simply apply the same rules and program for the second belt. To ensure that the proper numbers of parts were produced based on the model number and in comparison to the production charts in the manufacturing area, a Visual Basic prompt dialogue box was created to prompt for the model number at the beginning of the run to be simulated and then the entire simulation would be based solemnly for that model. As a first step, an initial number of runs and run length have to be decided. In this study, the initial number of runs was set to eight, and the run length was selected equal to two hours (7200 seconds). Justifications and adjustments in these two parameters will be discussed in Chapter 4. Also, to ensure that the results obtained would be from a steady-state interval, statistics were cleared after one hour (3600 seconds) and also in between runs. The termination period had to be set at two hours with statistics cleared at one hour because the existing production charts in the HOF cells are indicative of production per hour and hence the common base for comparison of results from the simulation with the real production. Keeping in mind that these scenarios were built simply to simulate the IMC belts, therefore, the rules of production such as model batch size and queue lengths were not part of the final analysis and hence made the programming and network building less complicated as it will be described next.

[3] Please see Appendix C to view the AweSim® network.

The simulation for the HDA cell scenario corresponds to the large-jobs line where there are a total of eight workstations (HDA-03a to HDA-08a) and within this line, workstations HDA-05ai, HDA-05aii and HDA-05aiii are identical and thus set in series, hence parts passing through these workstations will be worked on only once and will skip two workstations by remaining on the conveyor belt and moving only when the conveyor moves. This means that part p_i will be worked on workstation HDA-05ai and will skip both workstations HDA-05aii and HDA-05aiii, the next part p_{i-1} will skip workstations HDA-05ai and HDA-05aiii but will be worked on workstation HDA-05aii and finally part p_{i-2} will skip both workstation HDA-05ai and HDA-05aii but will be worked on workstation HDA-05aiii. In other words, there will be cycling of parts being designated to the three workstations, and hence this was a rule that had to be programmed in the model. It was necessary as well to know the total number of times the conveyor stopped and advanced from the first workstation (HDA-03a) until the last workstation (HDA-08a) as well as the intermediate steps between workstations since the layout of the workstations was not designed with equal spacing. From observation, it was noted that the conveyor stopped and moved a total of twenty two times from start to finish and within those twenty two moves there were intermediate moves between workstations that ranged from two moves (between HDA-03a to HDA-04a) to nine moves (HDA-05ai to HDA-06a). Also, there was a rule that only one part would be moved between workstations via the IMC belt at a time, as well, a rule had to be coded that would only allow parts to move once the conveyor moved and would allow workers to work on the parts once the conveyor stopped. It was decided to code a conveyor in AweSim® using the GATE [3] method, since it was flexible and easier to control using inputs. Using the

GATE method, the conveyor was modelled as the gate with an OPEN node representing a move and a CLOSE node representing a stoppage on the conveyor. A single entity generated at the beginning of the simulation would travel between the OPEN and CLOSE nodes with time intervals corresponding to the CRT and CIT respectively until the simulation ended. Also associated with the GATE, there were AWAIT nodes where the entities would wait until the gate opened and would allow them to move to the next available node in the simulation network; hence for each move the conveyor made, entities would move to either another AWAIT node where they would wait for the gate to open or to a workstation. Once an entity would reach a workstation it would then be processed for a specific time designated by a pdf[4] for that particular workstation. A workstation was modelled in AweSim® as a RESOURCE with a specified capacity and an AWAIT node where the entities would wait for the resource to become available and then allocating the resource to the part. The resource would only become free via a FREE node once the part was processed from the corresponding workstation which in turn would allow the resource to be captured again if there were any entities on the AWAIT node waiting to be processed. In order to ensure that only one part would move between nodes, it was also required to code the conveyor as a resource with capacity one that would allow only one entity to capture the resource and then free it again only after the entity had moved from one node to the next. Also, this scenario had to be flexible enough that would allow for more than one HOF model to be simulated without having to change any section, hence the need to create further nodes that would allow for USER INSERTS such as EVENT nodes that would collect information from the Visual Basic files associated with the scenario. The Event nodes served both the purpose of collecting

[4] Probability Density Functions are specified using techniques discussed in Chapter 4: Input Modeling.

information from the user inserts as well as simplifying the network by reducing the number of nodes required to perform the same task if events were not used otherwise. Some of the information coded in Visual Basic included the probability distribution function of the processing times for each workstation, the batch quantity of the model to be produced (for this scenario the batch size quantity was a constant at one thousand units since it was not critical for analysis), the CIT and CRT corresponding to each model, and other logic statements that affected the flow of entities and how the system has to behave during simulation such as selecting the correct CIT and CRT based on the model selected at the beginning of the simulation and requests for outputs such as confirmation of random numbers for each workstation and total parts produced[5]. These were the primary steps involved in creating the simulation network for the SALHDA scenario, which had to be complimented with a CONTROL FILE to control the way the simulation behaved such as termination and statistic clearance periods as well as USER INSERTS that would allow for flexibility described above.

The entity flow for this scenario would begin by generating a single entity which would then activate an event that would ask the user to select a model via a Visual Basic input box. Once the model was selected, it would then unbatch the single entity into a number of independent entities with size equal to the batch size specified in the Visual Basic file, which for this case the total number of parts to be produced consisted of one thousand units to be built (enough so that the simulation would terminate and there would still be parts in queues) in order to saturate the system and fill up the first await nodes. All these entities would then pass to the next node which is again another event node

[5] Please see Appendix B to view a sample of some Visual Basic coding pertaining to the different rules of the simulation model.

where the processing times attributes for the model would be stored in each individual entity as well as assign an entity type used in selecting the CRT and CIT for the gate representing the conveyor so that the correct times would be applied for the movements and holding times. All these entities would then continue to the next nodes being AWAIT nodes for the conveyor and resources. The movement continued until they reached the series workstations where a SELECT node would apply a rule of cycling in order to accommodate the rule of skipping workstations in series. The entire process repeats itself throughout the network until the flow comes to the end where a COLLECT node collects information on how long the entity has spent in the system during the simulation so that one could have an idea of how long this process takes on average. The entities exit the system via the TERMINATE node where entities passing through this node are destroyed. Once the terminating time has been reached, in this case two hours, the simulation finishes and any entity in the system is cleared. Figure 3:1 illustrates the flow chart for the entities in the SALHDA scenario.

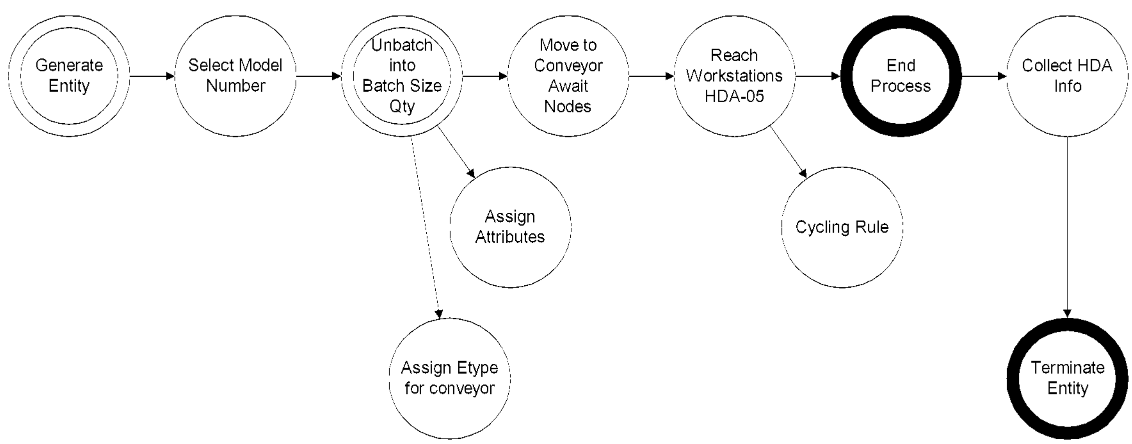

Figure 3:1 SALHDA scenario entities flow chart

In order to determine if the system was behaving accordingly, animation was another part of the scenario that had to be considered. The output from the simulation would not be enough to know if the entities would be flowing according to the rules specified before. Therefore, two animations were built where one could observe either concurrently or post-simulation if the entities were waiting at the designated conveyor AWAIT nodes and moving only when the conveyor GATE would open as well as if the cycling of workstations HDA-05 was being done. Once all these components were created, the scenario was complete and ready to be initiated and debugged. At this point the input data was required to test and also to observe the behaviour of the scenario.

The SALHFA scenario was created using the SALHDA scenario since there were many similarities between the two. The only difference was the fact that in the HFA cell there were no workstations in series but rather in parallel (between HFA-02 to HFA-04 both in the "a" and "b" sections) hence these workstations in this scenario had the capacity for the resources increased to two since there are two operators performing the same task in parallel. Again, since there were two identical IMC belts in the HFA cell, the scenario was built with only one belt for the same reason as specified in the SALHDA scenario previously. In this scenario, the IMC belt was also designed as a GATE as in the SALHDA scenario with its corresponding AWAIT nodes. Since the two scenarios were identical, only the setup of the workstations had to be revised and updated and the number of entities allowed to move between workstations was also increased from one to two. There were also differences in the movements of the conveyor between the two scenarios. The HFA cell was properly designed with equally spaced workstations, hence the conveyor only moved once between workstations and stopping right in front of a worker making the network building easier than previous. As opposed to multiple AWAIT nodes in between workstations, in this case there was only one AWAIT node related to the GATE in between workstations since there was only one conveyor move. Figure 3:2 illustrates the flow chart for the entities in SALHFA scenario.

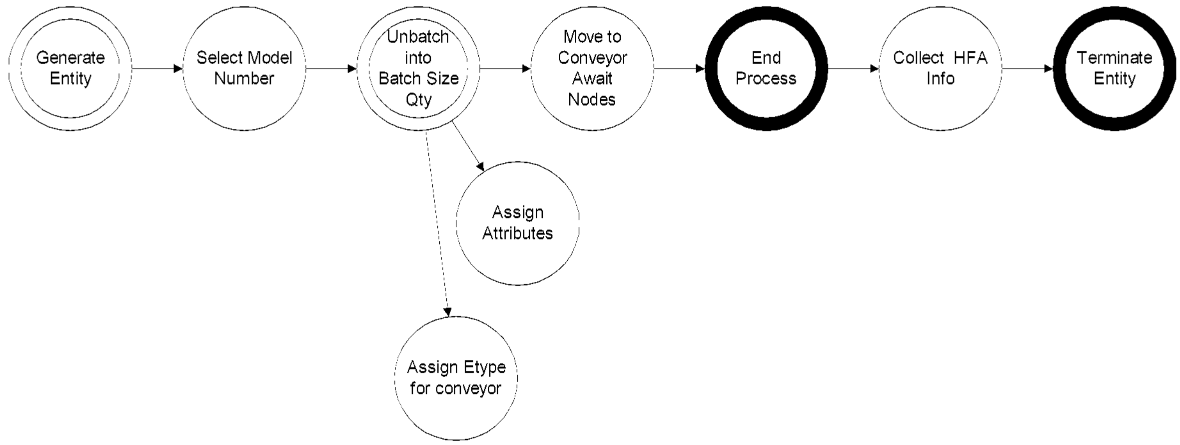

Figure 3:2 SALHFA scenario entities flow chart

In the case of the SALHFA scenario and due to its simplicity, animation in this case was not required as it was the case of the SALHDA scenario because entities moved in an orderly fashion. One could determine any problems with the flow simply by looking at the output from the simulation, in this case by examining the queue lengths. If the queue lengths were more than two entities at its maximum, then there would be enough evidence that more than two entities moved between workstations and hence violating one of the rules.

So far, the two most important scenarios were built and ready to be tested in order to determine if the conveyors were properly coded and the logic of the flow of the entities were properly modelled. Once the models were verified and validated through comparison with the actual output, the major network of the BASECASE scenario as discussed in Section 3.3.2 would be developed.

3.3.2 BASECASE scenario

The BASECASE scenario was a complete simulation of the existing production scenario at HOF production area including a designated line selection rule, conveyor movements (both IMC and GMR), model production lot sizes, queue selection rules and all the other flow constraints such as batching quantities at each workstation. At this point, data collection was well on its course to be completed with the exception of collection of processing times for each workstation based on model number for which the complete set for the five different models had not yet been concluded. By this time all the steps involved in the production of HOF ballasts were mapped as well as the rules and flow of parts between workstations and between the cells HDA and HFA. The BASECASE scenario represented the true randomness of the system. This randomness came from the following sources:

- Product models
- The model lot size
- The ratio of secondaries to primaries pertaining to each model
- The IMC belt settings unique to each model
- The processing time of each model on each workstation

Some of the network building for this scenario was already initiated, while building the previous scenarios (SALHDA and SALHFA) with the coding of the IMC conveyors in both cells. There were many other steps that needed to be done even before the building of the network had begun which included the calculation of the probability of production of each model and the scheduling technique used to initiate orders in both the HDA-01 and HDA-09 workstations. Presently, orders begin production based on a simple inspection of the inventory by the Production Lead-Hand who from experience will decide which models to produce. There is no scheduling technique implemented at the HOF line presently, hence a rule had to be created in order to test and analyse the simulation models being built.

Using the data calculated by the WMA method explained in Chapter 2, the overall percentage of a model from the total production would indicate a probability of being produced. Therefore, a cumulative chart for the probability of production of each model was constructed. This chart was then used to select the product to be produced during the simulation by comparing a system generated uniformly distributed random number in the range [0, 1) to the cumulative probability of the models. All this was done in a Visual Basic file pertaining to this scenario just as those files explained in the previous examples. Table 3-1 indicates the probabilities of production for each of the five models used in this thesis.

Table 3-1 Probability of production of the five HOF models

Model	Overall Percentage of Production	Cumulative Probability
272AT	12%	0.000 – 0.120
472AT	22.1%	0.120 – 0.341
496AT	31.5%	0.341 – 0.656
672AT	12.9%	0.656 – 0.785
696AT	21.5%	0.785 – 1.000

Therefore it was calculated that each product model was given the probability of being produced $p(x_i)$ where i = model number. In this case model 696AT was calculated to be produced 21.5% of the overall production, model 672AT was calculated as 12.9%, model 496AT had a 31.5% share of the total production while model 472AT was calculated as 22.1% and finally model 272AT was calculated as being produced 12% of the overall production.

Now that the probability of production for each model has been calculated, the model production lot size had to be changed in order to suit the parameters of the simulation and those existent within the production area. Such parameters include the number of units processed and batched at various workstations in both the HDA and HFA cell. Within the HDA cell, workstations HDA-01 and HDA-02 process four parts at a time which in turn batch their production into trays of thirty five units to pass on to the subsequent workstations. Similarly, workstation HDA-09 processes in batches of eight units simultaneously which then in turn also batches its production into trays carrying thirty five units to pass on to succeeding workstations. Workstations HDA-03 to HDA-08 process a single unit at any given time and pass on to the following workstation one unit at a time as well. Workstations HDA-10 and HDA-11 work on a single unit but batch their production into trays of thirty five units so that their production can be carried on to the next workstation. Once the production is finished in the HDA cell, concluding with the processing at workstation HDA-08, the production is then batched into baskets containing either one hundred and fifty or two hundred and thirty units to be sent for the Impregnation cell where the units are processed as a batch. Exiting the Impregnation cell, the baskets are sent to the HFA cell as they have entered. Once they reach the HFA cell, the units are worked on at workstation HFA-1 in batches of five simultaneously which in turn are then passed on to the next workstation in batches of two units. Workstation HFA-02 through to HFA-04 process in batches of two units and HFA-05 through HFA-08 work on single units and pass to subsequent workstations in single units as well. Figure 3:3 illustrates the number of units that pass from one workstation to the next in the entire HOF production area.

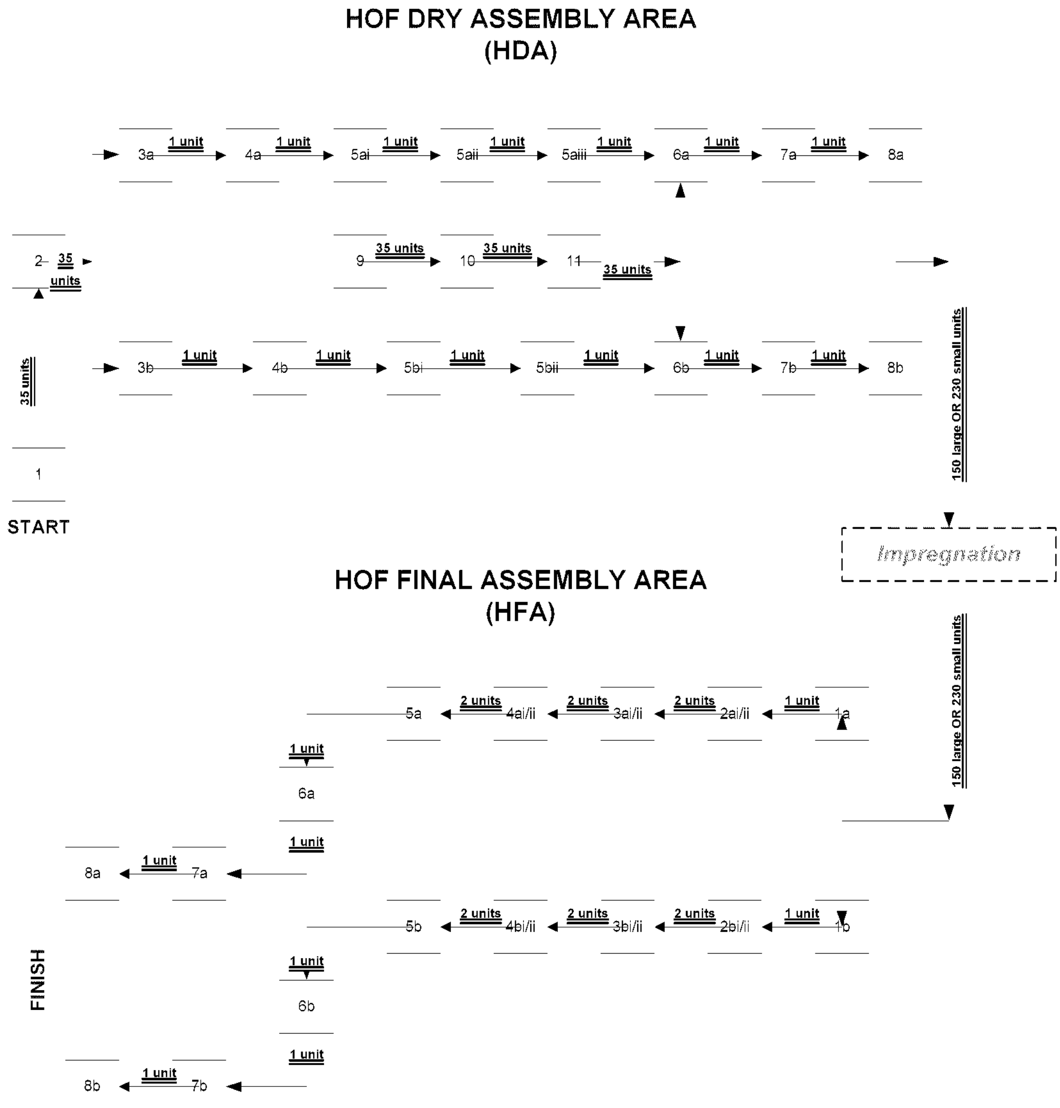

Figure 3:3 Number of units passing to subsequent workstations flow chart at HOF

Since the number of units that are transferred from one workstation to the next are not the same throughout the HOF cell, there was a need to modify the existing production lot size quantities to fit the simulation model by finding a common number in order to avoid problems such as entities being lost or entities losing attributes due to batching and un-batching processes. Currently, when an order is to be produced, the production lot size quantity is specified in the Kanban tag of the model in the inventory department or if it is a special order case, the total units to be produced must be enough to fulfill the order plus enough units to replenish the stock. Although these are the numbers currently used when producing orders, by changing the lot quantity to a common multiple of four, five, eight and thirty five has made the flow and rules of the simulation more stable and less prone to debugging problems. Table 3-2 illustrates the present model production lot size quantity and the altered model production lot size quantity used in the simulation as well as the multiples of the altered production lot size quantity in relation to four, five, eight and thirty five units.

Table 3-2 Model lot batch quantities and altered values

Model	Current Production Lot Size Quantity (Units)	Altered Production Lot Size Quantity (Units)	Multiple of 4 Units (Batches)	Multiple of 5 Units (Batches)	Multiple of 8 Units (Batches)	Multiple of 35 Units (Batches)
272AT	460	560	140	112	70	16
472AT	920	840	210	168	105	24
496AT	750	840	210	168	105	24
672AT	460	560	140	112	70	16
696AT	750	840	210	168	105	24

From the calculated production lot size quantity quantities, one could see that some models would have a larger number of units to be produced in a production run, while other models will have fewer units produced. This could raise some problems when comparing the total production after a simulation and the total percentage of products calculated via the WMA method. Once the production lot size quantity to be simulated for each model was calculated, it was time to decide on the scheduling technique to be used in order to initiate a production run for an order. Currently, the Production Lead-Hand will order the beginning of production of a model based on a simple inspection through the inventory department and collecting information on which items have reached the re-order points. Comparing the models to rush-orders brought by the sales department and to priorities based on sales data, an order processing is initiated. It was also noted that workstations HDA-01 and HDA-09 were busy at all times, but an order could be initiated at any one of these workstations and needed not be simultaneously since an order could be processed faster in one station than the other. Due to the nature of the model's primary to secondary ratio, it is based on experience that the Lead-Hand will order the processing of a production lot size quantity to be initiated at either workstation HDA-01 or HDA-09. In the case of simulation models, they do not run based on human judgments, thus a scheduling rule had to be implemented in the system. The scheduling technique adopted involved two simple rules that were decided for an order to be initiated. The first rule was that at start up, an order is sent to be processed simultaneously to both workstations HDA-01 and HDA-09, since there are no units at any AWAIT nodes and no orders to be processed. The second rule, that was applied to the period after the first order, was that an order must be initiated once both await nodes of workstation HDA-01 and HDA-09 reached a level bellow one hundred and four units[6]. This represents twenty six and thirteen batches of four and eight units respectively to be processed at these workstations or just under three trays of thirty five units.

[6] This number was chosen such that during the course of a simulation run, either HDA-01 or HDA-09 would be close to 100% average utilization, hence mimicking the current scenario without having either workstation waiting for excessive periods of time or having both completely blocked up with orders waiting to be processed.

Having both the production lot size quantity and the production scheduling problems solved, it was time to solve the designation of models and orders to the production lines and how to adjust the conveyor properties once an order of a different model was initiated. In order to save time on setups, all the units of the same model must be sent to the same production line, meaning that only after an order of a different model is initiated that both lines will be working in parallel. This can be problematic, if a series of orders generated randomly happen to be of the same model, one of the lines in both the HDA and HFA cells will be idle while the other line is operating. This will be minimal if the simulation length is very long, but if not, then it will be clearly evident if the situation occurs where there will be multiple orders of the same model. Therefore, there were two different rules that had to be coded into the production line selection. As explained previously, there are two lines named Large-jobs and Small-jobs in each of the production cells, where products could be processed. The first rule applied to a selection based on the comparison of the existing number of units in the line. According to this rule, if one line had fewer units than the other, then the order would be directed to the line with the lowest number of units. On the other hand, if the lines had the same number of units, then line selection would be randomly picked based on a comparison of a generated uniformly distributed random number between zero and one and an assigned equal range for each line. The later example will happen when the simulation model first initiates since there are no entities present in the system and line selection is based randomly. The second rule for the line selection is based on previous orders such that entity e_{i+1} is checked against entity e_i and then a decision to direct the entity to the correct production line is made regardless of the number of units existing in both lines. When the simulation begins, there are no records of existing entities, hence the system will shift to the first rule and do a number comparison. If there are units on both lines, the present order is compared to the orders being presently processed and if the present model is the same as one of the orders in the lines, then all the production for that order is directed to the same line as the previous order of the same model. If the model of the latest order is different from both orders in process, then the system will resort back to rule number one and make a decision based on a comparison of numbers.

Once the previous problems were surpassed and modelled, the remaining hurdle to be passed was the behaviour of the conveyor. In the previous scenarios, the conveyors had to work based on a single model, but the BASECASE scenario would have to deal with all five different models at the same time, hence the need for a system that would keep track of what was being produced and what was going to be produced. Fortunately, the logic used for the line selection rule could also be applied for the conveyor (with minor adjustments). The rule used at Allanson International Inc. was that the CIT would only be changed once the entire order had passed through and the first unit of the new order would come to the last workstation on the conveyor. Since there is a check point at the beginning of the conveyor in workstation HDA-03, where the line selection rules comes into play, the system could also set the current entity type for the conveyor. At the end of the line, in workstation HDA-08, there would be another check of the model where a comparison would be made and the settings for the conveyor would also be made.

In a nutshell, the rules for the conveyor are as follows:

- If no entity has passed through the first and second check point on the line, set the belt CIT based on the first entity arriving on the conveyor.
- If an entity has passed through the last checkpoint and the next entity is of the same type as the last, then maintain the CIT as it is.
- If the arriving entity is different from the last entity checked at the last checkpoint, then maintain the CIT until the new entity passes through the last checkpoint which enables the complete order to be processed at the same speed and only after all the order has been processed, then the CIT can be changed.

Having all the problems solved, then the process of building the BASECASE scenario began with the setup of the network as well as the creating a Visual Basic file. This process was made simultaneously because there was a need to link some of the nodes of the AweSim® network with the logic of input controls for the rules specified previously. The network building began by first importing both networks from the SALHDA and SALHFA scenarios into the BASECASE network in order to save time since they were already made and could be used in this scenario. Then there was a need to duplicate both networks since the entire production area had to be simulated which included four IMC belts. Once all the IMC belts and their associated workstations and AWAIT nodes were mapped, there was a need to create the remaining workstations and nodes that would control the flow of the entities throughout the simulation. Two SELECT nodes were introduced for the line selection rule in both the HDA and HFA cells as well as multiple event nodes that would enable the collection and identification of the entity attributes including model number and production lot size quantities. After all the nodes were created, the entire HOF line was mapped in a network. Fig 3.4 illustrates the complete flow chart of the entities in the BASECASE scenario model.

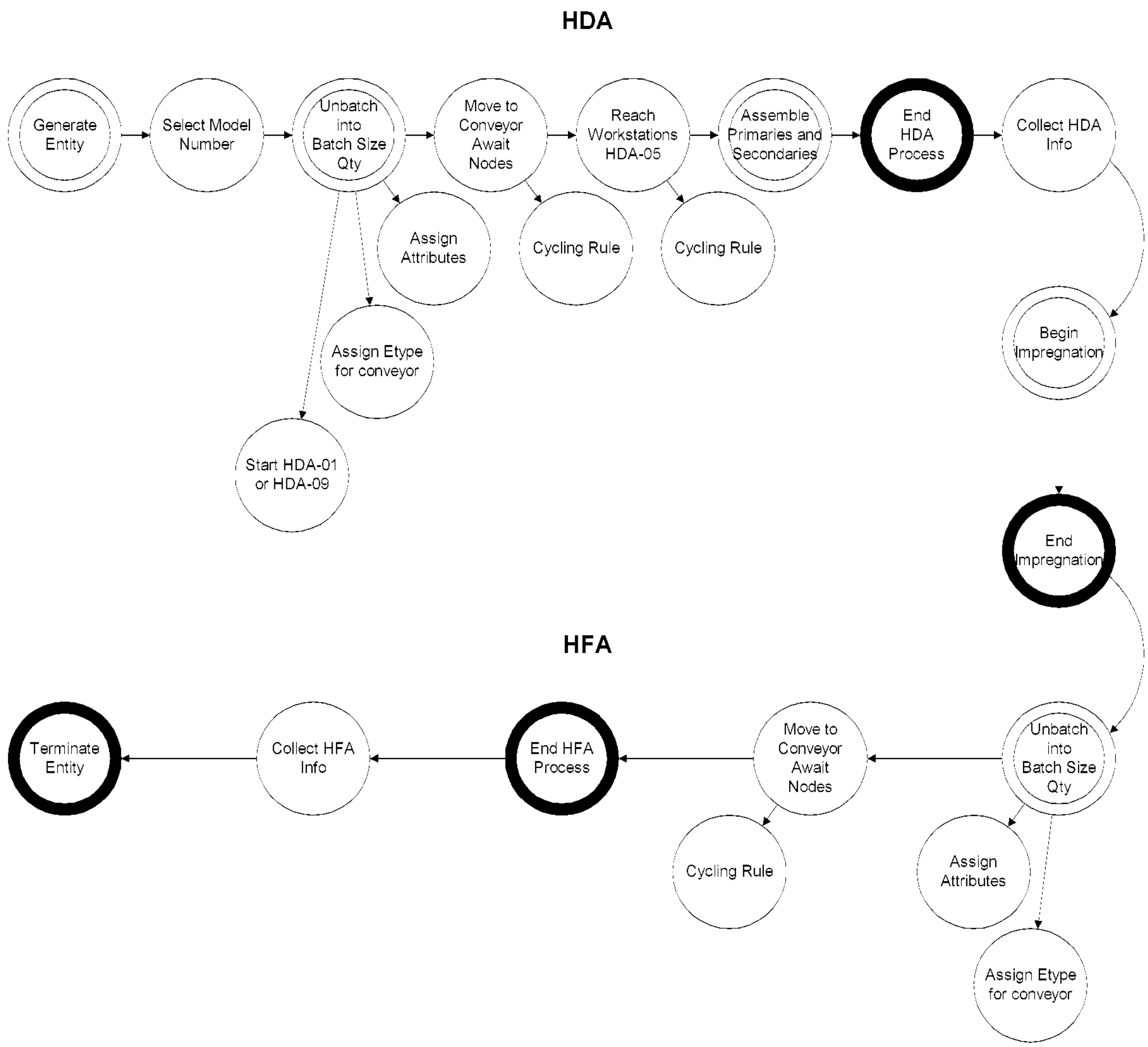

Figure 3:4 BASECASE scenario entities flow chart

In this scenario, an entity is generated at a CREATE node every sixty seconds where it passes on to a GOON node where the scheduling rule is checked, if the AWAIT nodes of workstations HDA-01 and HDA-09 is below one hundred and four units, then the entity is routed to an ASSIGN node where the current simulation time is captured otherwise the entity is terminated. Once an entity passes through, then it enters an

EVENT node where the model selection takes place in Visual Basic and then the single entity gets un-batched into a total number of independent and identical entities. After this point, each entity is routed to two separate lines via another GOON node where the entities enter the primaries and secondaries lines. Once the entities reach the secondaries lines, another un-batching takes place and that is where the ratio of primaries to secondaries is observed. If a model has one primary and one secondary, then there is no further un-batching. Otherwise, if the model requires one primary and two secondaries, the entity that travelled to the secondaries line will be un-batched into two new entities also of the same model number. As for the entities continuing through the primaries line, each entity gets assigned attributes of the processing times for the upcoming workstations. Once they are processed through workstations HDA-01 and HDA-02, they will reach a SELECT node where line selection takes place again in the Visual Basic file. Once the entities are selected to a designated line, they will enter another EVENT node at which point an ETYPE is assigned for the conveyor as a model number (this is also the first checkpoint for the conveyor and for line selection). Once the assigning takes place, the processing is done the same way as has been previously explained in SALHDA scenario until the entities reach workstation HDA-06 where the assembly of primaries and secondaries take place. From the secondaries section, once the entities exit from workstation HDA-11, they are routed to an ACCUMULATE node where the entities are either bundled from two to one or from one to one entity. This is done so that the entities being routed to workstation HDA-06 are ready to be assembled. After the accumulation, the entities are routed once again to waiting QUEUEs where they wait for the complementary entity to arrive. The assembly takes place in an ASSEMBLE node where entities are checked by model number and emanate from the previous queues. If the entity waiting in the primaries queue is the same model as the entity arriving to the secondaries queue and vice versa, then an assembly takes place, otherwise the entity waits in the queue until another entity being of the same model arrives at the complimentary queue to be assembled.

Once the assembled entity arrives at the HDA-06 workstation, it is then processed and flows to the last assembly workstations HDA-07 and HDA-08 at which data is collected once again before exiting the HDA cell in order to check the model number for the conveyor rules. Before the entity exits the HDA cell, data is collected once again via a COLLECT node which will indicate the overall flow time of each entity. Also, a maximum, minimum and average flow time will be given in a report once the simulation model is run. From the HDA cell, entities are batched into baskets containing either two hundred and thirty or one hundred and fifty units and are sent into the Impregnation Cell where they are processed. Leaving the Impregnation cell, entities are un-batched from the baskets and once again face another SELECT node where a line selection has to be made (using the same rules as previously). Once the entities are routed to the designated line, the first checkpoint of the HFA conveyor is met. At this point the model number is checked and the proper steps are taken in setting the HFA IMC belt's CIT and the current simulation time is recorded. The process once again repeats itself as explained in the SALHFA scenario until the entities reach the end of the line where the second checkpoint is met and the model number is recorded for the conveyor setup as well as another COLLECT node collects the time the entity spent in the HFA cell. The entire process finishes at a TERMINATE node where entities are destroyed. This concludes the building and flow of the entities in the current system by means of an AweSim® network along with a Visual Basic file.

The next step in the building process of the BASECASE scenario was the creation of a control file where both the parameters of the simulation such as limits on the variable and global attributes, termination period as well as the number of simulation runs and how statistics should be cleared are indicated. It was decided that the BASECASE scenario should be simulated for a total of three weeks (432000 seconds) and a total of six initial runs. Once the control file was created, it was also necessary for this scenario to have various animations in order to verify if both the line selection and conveyor rules were being followed as well as other important components such as the order scheduling. Therefore, five animation windows were created which covered the critical points of the simulation and allowed for visual analysis. Once the simulation ran properly it was time to analyse the output and create solution scenarios for the objectives of the thesis.

3.3.3 Modified CIT and multi-line selection scenarios

Once the entire HOF production area was simulated and analysed, it was necessary to think of the process of solving the thesis's objective functions. Some of the solutions were evident from simple observations of the tasks and operations being performed on the work floor while others require further simulations and the creation of "what if" scenarios. Some of the immediate solutions included the design, building and implementation of the winding machines Reel Transporter (RT), which reduced the setup time on the winding machines by eighty percent as well as the Impregnation Racks design revision which solved some of the problems with space for tow-truck's manoeuvres and improved hallway safety for the personnel[7]. Some of these practical solutions helped reduce setups and hence improved productivity on the HOF production line immediately, but simulation had to be used in order to determine how the average flow time or the throughput time would be affected if some of the production attributes were modified such as modifying the CIT and change the way orders are produced in the assembly lines in regards to line selection. Therefore, "what if" scenarios were modelled in order to test a combination of these changes and obtain the best solutions to allow for analysis to be performed. Since there are two factors contributing to the solution, thus four possible scenarios had to be modelled; hence a solution matrix was created as depicted in Table 3-3.

Table 3-3 Scenario solution matrix for the HOF production line

Factors		Conveyor Idle Time (CIT)	
	Possibilities	Current	Modified
Line Selection	Designated	BASECASE	SIMPRCON
	Cycling	SNOLINES	SNOLIMPC

The three scenarios pertaining to the possible solutions, SIMPRCON, SNOLINES and SNOLIMPC were mere images of the BASECASE scenario where only minor adjustments or modifications were made. Before these scenarios were built, it was decided that the modifications of the CIT of the belts in both HDA and HFA cells should be tested independently from the overall simulation, thus two more scenarios, SHDAIMPR and SHFAIMPR, were created. Once again, the two new scenarios included modifications made to the existing SALHDA and SALHFA scenarios respectively, which in turn also allowed for some time saving when modeling. These two

[7] As explained previously in Chapter 2.

scenarios did not change in terms of the AweSim® networks, but changes were made to the Visual Basic file pertaining to each scenario where the attributes of the belts were modified. It was decided to experiment with a scenario where the belts would be constantly running, meaning that the CIT would be set to zero. This in turn would represent the maximum theoretical production capability of the line during a production run, hence allowing for a comparison of the existing production, found in the SALHDA or SALHFA and that of the output from the new scenarios. The output from the new scenarios was also an indicator of where the bottleneck operations would lie, since now the production was based on the slowest operations as opposed to the previous scenarios where the belt would dictate the production.

Once both the SHDAIMPR and SHFAIMPR scenarios were fully tested and analysed, the next step was to test the zero CIT possibility in the entire HOF production via a simulation of the SIMPRCON scenario where designated line selection rule of the entities was still used. After the simulation was complete, the results were analysed and it was time to try and test a different possibility where the line selection rule was changed from designated to cycling, meaning that the two lines in both the HDA and HFA cell would be producing the same product simultaneously. This new scenario, SNOLINES, would indicate if more parts would be produced within the same simulation period or if the mean flow time would be significantly reduced by simply changing the line selection rule from designated to cycling. The only change made in this case happened in the network where the line SELECT node was now changed from being designated in Visual Basic to a cycling rule where entities would be directed to the queues of the two lines in a cyclic way. The same objective was applied when a combination of both the zero CIT and the cycling line selection rule would be simulated in the SNOLIMPC scenario. In this scenario, the production was simulated based on bottleneck operations, since CIT was set at zero, and both lines of each cell were producing the same product model simultaneously. In the case of the SNOLIMPC scenario, there was a need to change both the AweSim® network and the coding in the Visual Basic file. All new scenarios were simulated using the same control files as previous and also the same animations where needed. Once all the simulation scenarios were ran, the next step was to have a preliminary statistical analysis to determine if the number of runs and the simulation termination time was adequate for the accuracy selected. This analysis will be discussed in the next chapter.

CHAPTER 4 INPUT MODELING AND OUTPUT ANALYSIS

4.1 Introduction

In this chapter, statistical analysis of the input data and the simulation output will be discussed. The chapter is organized into three sections where the first section will cover the apparatus used to gather data, followed by the second section on input modeling and finally the third section on output analysis. The input modeling section will cover the aspects of performing statistical analysis to the raw data in order to fit distributions to be used in the simulation models. The output analysis section will cover the aspects of the methods used in three periods of the simulation. Once the first simulation models were run, the initial output and control files had to be revised via statistical analysis for parameter estimation and the outcome of these revisions were subjected to the ANOVA method with replications, whose formulation is covered in the last section of the chapter.

4.2 Data gathering apparatus

The initial steps taken in this thesis included data gathering and process mapping as explained previously in Chapter 3. In order to save time and simplify the steps involved in data gathering and data processing, it was decided to use advanced techniques and instrumentation as opposed to the traditional stopwatch, paper recordings and eventual data transferring from paper to computer techniques. The instrumentation used was to some extent advanced in order to facilitate and reduce the steps involved in data collection as well as in data recording and manipulation. A hand-held computer (PDA), the Palm M100 with v3.5 operating system, was used in conjunction with a software application called Stop3Watch® v2.02 by Alfred K. F. Leung as the stopwatch and data collector. The way the system worked was identical to the traditional techniques but rather in an electronic format eliminating various steps and reducing paper work as well as data entry and processing. All the steps including gathering, recording and data transfer took place in one device as opposed to using different instruments and applications. The manufacturing operations were observed and data was collected via the Stop3Watch® software using the handheld computer, where the processing times were automatically recorded in forms of text called notes at the end of each observation. These notes were then transferred from the PDA to a laptop computer either via a direct-serial cable connector or via Infrared (IR). The process of data gathering and data exporting to notes using the Stop3Watch® software is depicted in Figure 4:1.

Figure 4:1 Data collection and exporting using the Stop3Watch® software application

Once the production data collected was transferred to the laptop in the form of individual notes containing information on a particular workstation or operation, they were then exported from Microsoft Outlook to Microsoft Excel in order for the data to be observed and organized. Each note contained information organized in three sections. The first section included information on the product model number, followed by a section indicating the workstation number where the data was gathered and information on all the steps associated with the processing of that particular model on that specific workstation. The last section contained the time observed and recorded via the Stop3Watch® software associated with the intermediate processing steps of section two and the total time required for the operation calculated as a sum of the individual steps. Each processing step involved in the operation was recorded as a "lap", therefore the total number of laps would be equal to the total number of processing steps that made up the processing of the model on the particular workstation being observed. An example of a note collected using the handheld computer via the Stop3Watch® and then exported to Microsoft Excel® is depicted in Figure 4:2

3 Normal Normal
496-AT
HDA-01
load bobbins
processing time
unload bobbins
load new bobbins
wrap bobbins
3 Normal Normal
Stop3Watch Records: 15/7/02 5:33 pm

Lap		Watch 1 (LT)
	1	00:13.0
	2	01:15.6
	3	00:17.3
	4	00:15.6
	5	00:44.2
All		02:45.6

Figure 4:2 Sample data note using Stop3Watch®

In the above note, model 496AT was being observed at workstation HDA-01 which included five different steps in order to complete a processing cycle. In section two of the note, the operation steps are written and then the corresponding time is recorded as laps in section three, note that there are 5 steps, hence 5 laps. These three sections were used to organize the data in Microsoft Excel for later usage in different tasks. The first two sections included information used on routing sheets, while the third section would be used to extract the timing of processes in order to perform time studies such as line balancing and also to perform statistical analysis such as input modeling described in the next section of this chapter.

4.3 Input modeling

Once all the processing data was gathered for the chosen models, 696AT, 672AT, 496AT, 472AT and 272AT, it was time to analyse the data in depth in order to be used in the simulation models. The first step in the analysis of the data was to make sure that indeed twenty sample points per workstation were collected, if not, then further data collection for that particular model on the corresponding workstation had to be done (time permitting). Once all twenty data samples were collected, data was organized in such a way that all had a common time unit, where in this case *seconds* was the time unit selected for all the analysis and input for the simulation models. Hence, a conversion process took place. The collected data was then organized per model per workstation in the same way that was collected (not in either ascending or descending order) because it was required to maintain the data "raw", hence techniques could be used to estimate statistical parameters. The parameter estimation and distribution fitting[8] was performed using Stat::Fit® version 1.10.05.1, a freeware software developed by Geer Mountain Software Company. The raw data was extracted from Microsoft Excel and then imported into Stat::Fit® where the fitting for continuous distributions functions were tested and ranked based on the best fit. The process of the fitting follows the traditional techniques

[8] Please see Appendix A to view a sample of the distribution fitting of the data for the different HOF models of workstation HDA-01.

such as q-q plots, Maximum Likelihood Estimators and Goodness-Of-Fit Tests explained in the proceeding sections.

4.3.1 q-q plots

The next major step in analysing the data was to determine the distribution that each workstation's processing time would follow. The fitting is done by following the principals of input modeling. The software organizes the data and builds histograms with a certain number of equal intervals. Once the histogram is built, it then compares with different distributions previously specified by the user to the data and ranks the different distribution fits based on Chi-Square method (comparison fits based on A-D and K-S are also available). Specifying the distributions to fit prior to the fitting enables the user to select only those distributions pertaining to the simulation software in choice, in this case AweSim®, since any other distribution not used in the software would simply mean additional information that is not useful. Once the distributions are specified, the software then plots the Quantile-Quantile plots (q-q plot). As compared to histograms, q-q plots are useful tools when the data points are less than 30. In this study, only twenty data samples were collected per workstation per model, hence making the q-q plot a better choice. The foundation of q-q plots is explained below.

If X is a random variable with the cumulative distribution function $F(x)$, then the q-quantile of X is that value γ such that $F(\gamma) = P(X \leq \gamma) = q$, for $0<q<1$. Next by ordering the sample data $X = \{x_i, i = 1,2,3,...,n\}$ from smallest to largest we get a new ordered group denoted as $\{y_j, j = 1,2,3,...,n\}$ where $y_1 \leq y_2 \leq y_3 \leq ... \leq y_n$ and j is the order number. "The q-q plot is based on the fact that y_j is an estimate of the $(j-1/2)/n$

quantile of X. In other words, y_j is approximately $F^{-1}\left(\frac{j-\frac{1}{2}}{n}\right)$" [4]. If the fit is "good",

then the plot of y_j versus $F^{-1}\left(\frac{j-\frac{1}{2}}{n}\right)$ will be approximately a straight line, but never exactly linear.

4.3.2 MLE (Maximum Likelihood Estimators)

The next major step in distribution fitting is called the "Parameter Estimation". Stat::Fit® uses the Maximum Likelihood Estimator (MLE) of a distribution, which are the parameters of that function that maximize the probability of obtaining the given data set. For any density function $f(x)$ with one parameter α, and a corresponding n set of sample values x_i an expression called the Likelihood may be defined as $L = \prod_{i=1}^{n} f(X_i, \alpha)$. To find MLE we simply maximize L with respect to α. That is $\left(\frac{dL}{d\alpha}\right) = 0$ and then solve for α. For some distributions, the MLE does not work, such as Gamma, in these cases Stat::Fit® resorts to a hybrid algorithm, which combines the standard MLE approach with a moment matching procedure.

4.3.3 Goodness-of-Fit test

The Goodness-of-Fit test used in all the input models was based on the Chi-Square test. Goodness-of-Fit test is a very useful tool that enables the analyst to determine if the fitted distribution can be accepted or rejected. In simple words, the test compares the distribution of the collected data with the candidate distribution's probability density function (pdf). The test begins by arranging the n observations into a set of k class intervals or cells (similar to when building the histogram). The observation frequency O_i is then found and the expected frequency $E_i = np_i$ in each class, where p_i is the theoretical probability associated with the i^{th} class interval. The test statistic given by $\chi_0^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$ approximately follows a Chi-Square distribution with *k-s-1* degrees of freedom. Choosing a confidence level of α, the critical value $\chi^2_{\alpha,k-s-1}$ is obtained. Once both the test statistic and the critical value are found, a comparison is made. The test will reject the null hypothesis (i.e., candidate distribution closely fits the data) if $\chi_0^2 > \chi^2_{\alpha,k-s-1}$ or will fail to reject if $\chi_0^2 \leq \chi^2_{\alpha,k-s-1}$. Although the number of observed sample data in each of the workstations was not significantly large, some distributions were not fitted due to the rejection of the test statistic, thus, the highest ranked acceptable pdf is then selected.

4.3.4 Transformations of probability density functions

Once all of the different workstation's data per model was put through the three steps, explained previously, and information was collected on their distribution and statistical parameters to be used when modeling the simulation networks, it was finally required to transform the data into a usable format to be used by AweSim®. Each model at each workstation now was fitted based on a probability density function (pdf) ranked by Stat::Fit® which now could be used in either the Visual Basic file or the network directly, but the only problem was that this fitted distribution had to be transformed in order to allow AweSim® to accept the parameters, hence another step involved in manipulating the data was to actually transform the highest ranked distribution fitted to the data into a suitable format. The main reason for these transformations was in part due to the acceptability of the distribution functions used in AweSim®, not all distributions are used in AweSim® and hence some fitted distributions had to be transformed[9]. An example of a transformation of the distribution function fitted by Stat::Fit® for model 272AT in workstation HDA-01 into a function acceptable by AweSim® is depicted in Table 4-1

Table 4-1 Model 272AT fitted distribution for workstation HDA-01 and its transformation

Fitted distribution in Stat::Fit®	Transformed distribution into an acceptable AweSim® format
Pearson6(75.8, 0.104, 78.6, 2.25)	75.8+0.104*GAMA(0.104,78.6,0)/GAMA(0.104, 2.25,0)

By completing this last step, all the collected processing data was now ready to be used in the simulation models and the scenarios could now be tested, ran and debugged in order for the first steps in the analysis of the output to be performed.

4.4 Output analysis

The output analysis section of the thesis can be divided into three different subsections namely the pre-simulation, mid-simulation and post-simulation. Each of these subsections involves decisions and techniques used to formulate or simply estimate parameters of the simulation models. The reason for the output modeling is to have the results of the simulations statistically justified. The techniques used in the output analysis are only pertaining to the estimation of statistics on processing times and number of parts produced in the simulation runs.

[9] Please see Appendix B to see the complete set of distribution transformations based on HOF model per workstation.

4.4.1 Pre-simulation output analysis

As it was mentioned previously, the initial number of runs, R_0, and run length, T_E, had to be estimated when the simulation models were first created. Since the existing production data was based on an hourly production and an order will presently take a few days for the whole process to be completed, it was decided that any simulation of the entire HOF production area should be simulated to mimic a minimum of a three-week production run, hence, the termination period was set at four hundred and thirty two thousand seconds ($T_E = 432000$). This period was purposely selected in order to significantly reduce the start-up interval bias data and also not to have the simulation model running for a period longer than a few computer hours. Since this initial output analysis was used to collect data on the entire simulation (including the bias data which had to be observed in order to allow for the truncation technique to be applied), therefore, statistics were only cleared at the beginning of the simulation ($T_0 = 0$). It was also initially decided that eight runs ($R_0 = 8$) should be simulated in order to have statistically sound results. Each run started with a different seed number and statistics of the states of the entities should be collected at every 12,000 seconds in order to have data points throughout the simulation period to allow for the truncation method to be applied as it will be explained in the next subsection of this chapter. The starting seeds were randomly generated via MS Excel and then included in the control file of the individual scenarios. In order to use the seed value generated with MS Excel, a SEEDS statement was introduced in the control file where the number and the stream were specified before the simulation began. Once the simulations were tested with the individual control files, an AweSim® output was generated and the values of the average processing times at the designated intervals were then collected as well as an overall average processing time of the entities and the total number of parts produced in the individual simulation runs. The collection of the state variables at different intervals in the simulation was achieved by using a MONTR statement in the control files with a SUMMARY option where statistics were collected at the designated interval, in this case at every 12,000 seconds. These rules would be applicable to the BASECASE, SIMPRCON, SNOLINES and the SNOLIMPC scenarios. For the scenarios pertaining to the simulation of the IMC belts of both cells, namely the SALHDA, SALHFA, SHDAIMPR and the SHFAIMPR it was decided that again eight runs ($R_0 = 8$) should be simulated for each scenario but the termination period should be at 7,200 seconds (2 hours) ($T_E = 7200$) with statistics cleared at 3,600 seconds (1 hour) ($T_0 = 3600$) in order to collect only data pertaining to the steady-state interval, as it was explained earlier, and to compare the output of the simulations with the real hourly production output.

The number of runs and the termination periods on the scenarios modeled were intentionally over estimated since some of the simulations took no longer than three hours to be completed while other simulations, in the case of the IMC belt simulations, only took a few minutes, therefore, computational time was not a concern.

4.4.2 Mid-simulation output analysis

Once the simulation models ran with the parameters specified in the pre-simulation output analysis, it was required to validate the scenarios and their results [4]. In the case of the IMC belt simulation, the model represented a terminating simulation over a time interval $[0, T_E]$ and the results were in the form of observations $Y_1, Y_2, Y_3, ..., Y_n$, the goal was to estimate the population average $\theta = E\left(\frac{1}{n}\sum_{i=1}^{n} Y_i\right)$ and standard deviation. The mid-simulation output analysis was used to calculate the new run lengths as well as the new number of runs in order to achieve a close approximation via simulation of the population parameters. Each statistically independent run produces a report where the average processing time of the entities as well as a total number of units produced is given. Based on the output of the multiple runs, the sample average, $\hat{\theta} = \frac{1}{n}\sum_{i=1}^{n} Y_i$ and standard deviation, $S^2 = \frac{\sum_{i=1}^{n} Y_i^2 - n\hat{\theta}^2}{n-1}$ of all runs were calculated. Based on the $100(1-\alpha)$ confidence level and the accuracy, ε, specified by the modeller, the estimated minimum number of runs can be found using the inequality 4.1 depicted below and using the calculated sample means and standard deviations.

$$R_{\min} \geq \left(\frac{z_{\alpha/2} \times S_0}{\varepsilon}\right)^2 \quad \textbf{(4.1)}$$

where S_0 is the sample standard deviation and ε is the accuracy

Once the initial estimated minimum number of runs is calculated via inequality 4.1, and since $t_{\alpha/2, R-1} \approx z_{\alpha/2}$ for large run numbers, the next inequality based on the *t*-distribution can be used to test possible candidates greater than the minimum number of runs previously calculated. This new inequality will determine the new minimum number of replications that a simulation should be ran in order to achieve statistically sound results based on the confidence level and error allowed. The new inequality 4.2 is depicted below.

$$R_{new} \geq \left(\frac{t_{\alpha/2, R-1}{}^{2} \times S_{0}{}^{2}}{\varepsilon^{2}} \right) \quad \textbf{(4.2)}$$

where S_0 is the sample standard deviation and ε is the accuracy

Once the possible run number candidates surpasses the new inequality, then the new number of runs is found and is used to calculate the new run length as well as the new time to clear statistics as depicted in equations 4.3 and 4.4 respectively below.

$$T_{E_{new}} = \left(\frac{R_{new}/R_0}{T_0 + T_E} \right) \quad \textbf{(4.3)}$$

where:

R_0 is the initial number of runs specified in the pre - simulation output modeling,

R_{new} is the new number of runs calculated using inequality 4.2,

T_0 is the first time to clear statistics specified in the pre - simulation output modeling,

T_E is the run termination time specified in the pre - simulation output modeling

$$T_{0_{new}} = \left(\frac{R_{new}/R_0}{T_0} \right) \quad \textbf{(4.4)}$$

where:

R_0 is the initial number of runs specified in the pre - simulation output modeling,

R_{new} is the new number of runs calculated using inequality 4.2,

T_0 is the first time to clear statistics specified in the pre - simulation output modeling,

The modeller at this point can use the information calculated and apply it to the same simulation scenarios and decide either to use the same time to clear statistics and termination period as initially specified, but now with the new number of runs, or simply have one simulation run with the newly calculated time to clear statistics and new termination period. In the case where the IMC belts were simulated and the total number of units produced had to be validated when comparing the simulation results with the actual production, the method of independent replications had to be applied. The accuracy used for the IMC belt scenarios was set at two units and the $100(1-\alpha)$ confidence level was set at 95%, hence, $\alpha = 0.05$.

In the scenarios that simulated the entire HOF production area, not just the IMC belts as described before, there were observations taken within each replication or run in order to determine the "warm-up" period. In the case of these scenarios, the truncation method was applied in order to determine and eliminate the "warm-up" bias data by not using some of the observation points when calculating the run mean and standard deviation. Therefore, observations at specific time intervals were taken in each run. Hence, Y_{r_i} is the i^{th} observation within replication r, for $i = 1,2,...,n_R$ where $R =$ total number of runs, which the sequence of these observations is an autocorrelated sequence within the replication. Since the goal of the simulation was to obtain the population mean and standard deviation, estimators had to be calculated within the sample data to accomplish this. Hence, the sample mean within each replication was calculated using equation 4.5

$$\hat{\theta}_r = \frac{1}{n_r}\sum_{i=1}^{n_R} Y_{r_i} \qquad \textbf{(4.5)}$$

The replication sample means, $\hat{\theta}_1, \hat{\theta}_2, \hat{\theta}_3, ..., \hat{\theta}_R$ are statistically independent and are unbiased estimators of the population mean θ, therefore, the point estimator $\hat{\theta}$ can be found using equation 4.6

$$\hat{\theta} = \frac{1}{R}\sum_{r=1}^{R} \hat{\theta}_r \qquad \textbf{(4.6)}$$

When using the truncation method, at each interval of the observations, an interval mean is calculated based on the values obtained from the different runs. These interval means are then subjected to a cumulative mean where the averages of the previous intervals are summed and divided by the total number of intervals. When the truncation is applied, there are a series of observations deleted from the calculations of the cumulative means and the values are then plotted on a line graph[10] where visual observations can be made and a truncation interval can be deduced. This truncation interval is then used as an initial time to clear statistics, T_0, when running the scenario, as well as all the values previous to this initial time when calculating the average value for the individual runs. Once the averages for the individual runs are calculated, the same formulation discussed previously can be applied to calculate the minimum number of runs, $R_{\min}$, the new possible candidate runs, R_{new}, the new simulation termination time based on the new possible candidate runs, $T_{E_{new}}$ and the new time to clear statistics, $T_{0_{new}}$.

When simulating the scenarios to calculate the mean flow time, $\overline{F}$, namely the BASECASE, SIMPRCON, SNOLINES, and the SNOLIMPC scenarios, the accuracy was set at twenty minutes (1200 seconds) and the $100(1-\alpha)$ confidence level was set at 95%, hence, $\alpha = 0.05$. Using the same scenarios to calculate the total number of parts produced in the simulation, the accuracy for the number of parts was set at three hundred, since the production was mimicked initially at three weeks, therefore, this number is not as large as it may initially seem.

4.4.3 Post-simulation output analysis

Once the mid-simulation output analysis was performed for each scenario and the new parameters were calculated, it was finally time to run the different scenarios with

[10] Please see Chapter 5.

updated information on the AweSim® control files. This time, the results obtained from the new simulations were statistically independent and fitted the levels of accuracy desired. The post-simulation output analysis [34] is now applied to the analysis of the actual output of the simulations, meaning analysing and formulating hypothesis test and accepting or rejecting the null hypothesis. The main technique used on the post-simulation output modelling was the two-factor ANOVA with replications for each of the objective functions, the mean flow time of entities and total parts produced.

When designing the experiment, the objective is to compare the factor means, μ_A and μ_B where A is the line selection factor and B is the conveyor speed factor respectively and determine if there is any interaction between the factors, hence enabling to determine if indeed the two factors are independent variables.

Since there are replications, each entry on the matrix depicted on Table 4-2 is categorized as a value of $x_{t,j,k}$.

Table 4-2 Matrix tabulated form pertaining to the experiments with replications

		Conveyor Speed (*j*)	
	Levels	**Current CIT**	**Zero CIT**
Line Selection (*t*)	**Designated**	$x_{1.1.1}$	$x_{1.2.1}$
		$x_{1.1.2}$	$x_{1.2.2}$
		$x_{1.1.3}$	$x_{1.2.3}$
		$x_{1.1.4}$	$x_{1.2.4}$
		$x_{1.1.5}$	$x_{1.2.5}$
		$x_{1.1.6}$	$x_{1.2.6}$
	Cycling	$x_{2.1.1}$	$x_{2.2.1}$
		$x_{2.1.2}$	$x_{2.2.2}$
		$x_{2.1.3}$	$x_{2.2.3}$
		$x_{2.1.4}$	$x_{2.2.4}$
		$x_{2.1.5}$	$x_{2.2.5}$
		$x_{2.1.6}$	$x_{2.2.6}$

Once all the observations were entered in the matrix, the ANOVA process begins by calculating the averages of the replications in each level, the treatments' mean, the blocks' mean and the grand mean, hence the following formulas (4.7 to 4.10) were used:

Replication mean: $\bar{x}_{tj} = \left(\frac{1}{c}\right)\sum_{k=1}^{c} x_{tjk}$ **(4.7)**

Treatment's mean: $\bar{x}_{t} = \left(\frac{1}{bc}\right)\sum_{j,k} x_{tjk}$ **(4.8)**

Block's mean: $\bar{x}_{j} = \left(\frac{1}{ac}\right)\sum_{t,k} x_{tjk}$ **(4.9)**

The overall mean: $\bar{x} = \left(\frac{1}{N}\right)\sum_{t,j,k} x_{tjk} = \left(\frac{1}{a}\right)\sum_{t=1}^{a} \bar{x}_{t} = \left(\frac{1}{b}\right)\sum_{j=1}^{b} \bar{x}_{j}$ **(4.10)**

When using the two-factor ANOVA method with replications, there are five variations involved, namely the variation between treatments, the variation between blocks, the variation due to possible treatment-block interactions, the residual variation and the total variation. Each variation has its own formulation and is used to compare test statistics having a Fisher probability density function described later in this section. The formulation for each of the variation is given below in equations 4.11 to 4.15:

Variation between treatments: $SS_T = \sum_{t,j,k} \left(\bar{x}_t - \bar{x}\right)^2 = bc\sum_{t=1}^{a} \left(\bar{x}_t - \bar{x}\right)^2$ **(4.11)**

with $(a-1)$ degrees of freedom

Variation between blocks: $SS_B = \sum_{t,j,k} \left(\bar{x}_j - \bar{x}\right)^2 = ac\sum_{j=1}^{b} \left(\bar{x}_j - \bar{x}\right)^2$ **(4.12)**

with $(b-1)$ degrees of freedom

Variation due to possible treatment/block interaction:

$SS_I = \sum_{t,j,k} \left[\bar{x}_{tj} - \left(\bar{x}_t + \bar{x}_j - \bar{x}\right)\right]^2 = c\sum_{t,j} \left[\bar{x}_{tj} - \left(\bar{x}_t + \bar{x}_j - \bar{x}\right)\right]^2$ **(4.13)**

with $(a-1)(b-1)$ degrees of freedom

Residual variation: $SS_R = \sum_{t,j,k} \left(x_{tjk} - \overline{x}_{tj}\right)^2$ **(4.14)**

with $ab(c-1)$ degrees of freedom

Total variation: $SS = \sum_{t,j,k} \left(x_{tjk} - \overline{x}\right)^2$ **(4.15)**

with $N-1 = abc-1$ degrees of freedom

By calculating the variations of the model, a mathematical model can then be created as follows in equation 4.16

$$x_{tjk} = \overline{\mu} + \alpha_t + \beta_j + \gamma_{tj} + \Delta_{tjk} \quad \textbf{(4.16)}$$

where:

$\overline{\mu}$ is the grand mean based on "a" treatments, "b" blocks and "c" replications

α_t represents the treatment effects and are such that $\sum_{t=1}^{a} \alpha_t = 0$, so that $\mu_t = \overline{\mu} + \alpha_t$

β_j represents the block effects and are such that $\sum_{j=1}^{b} \beta_j = 0$, so that $\mu_j = \overline{\mu} + \beta_j$

γ_{tj} represents the treatment-block interaction effects

Δ_{tjk} represents the random effects or errors and are considered to be statistically independent Gaussian random variables with mean zero and variance σ^2

Based on the above mathematical model, three null hypotheses can be formulated where:

1. $H_0^{(1)} : (\alpha_t = 0)$, i.e., every α_t value is zero, so that all treatment means are the same
2. $H_0^{(2)} : (\beta_j = 0)$, i.e., every β_j value is zero, so that all block means are the same
3. $H_0^{(3)} : (\gamma_{tj} = 0)$, i.e., every γ_{tj} value is zero, so that no interactions exist between treatments and blocks.

Moreover, under the three null hypotheses above, the three random value statistics, depicted below, all conform to Fisher probability density functions:

1. $F_T = \frac{SS_T / (a-1)}{SS_R / [ab(c-1)]}$ **(4.17)**

2. $F_B = \frac{SS_B / (b-1)}{SS_R / [ab(c-1)]}$ **(4.18)**

3. $F_I = \frac{SS_I / [(a-1)(b-1)]}{SS_R / [ab(c-1)]}$ **(4.19)**

These functions, according to a specific $100(1-\alpha)$ confidence level, can then be compared with the appropriate values of $F_{\gamma_1,\gamma_2,\alpha}$ obtained from tables. Therefore, these calculations can all be depicted in Table 4-3 where the ANOVA table for a two-factor experiment with replications is shown.

Table 4-3 ANOVA table [8] for a 2-factor experiment with replications

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square Value	*F* $[\gamma_1, \gamma_2]$
Between Treatments (A)	SS_T (I)	(*a*-1)	$S_T^2 = \frac{SS_T}{(a-1)}$	$F_T = \frac{S_T^2}{S_R^2}$ with $\gamma_1 = (a-1)$ $\gamma_2 = (b-1)$
Between Blocks (B)	SS_B (II)	(*b*-1)	$S_B^2 = \frac{SS_B}{(b-1)}$	$F_B = \frac{S_B^2}{S_R^2}$ with $\gamma_1 = (b-1)$ $\gamma_2 = ab(c-1)$
Interaction (A-B)	SS_I (III)	(*a*-1)(*b*-1)	$S_I^2 = \frac{SS_I}{(a-1)(b-1)}$	$F_I = \frac{S_I^2}{S_R^2}$ with $\gamma_1 = (a-1)(b-1)$ $\gamma_2 = ab(c-1)$
Residual	SS_R (IV)	*ab*(*c*-1)	$S_R^2 = \frac{SS_R}{ab(c-1)}$	
Total	SS (V)	*abc*-1		

When the calculations are complete for the ANOVA, then the hypotheses are tested. Normally the third null hypothesis is tested first in order to determine if there is actually interaction between the factors. Two outcomes are possible, 1) there is indeed statistically significant interaction between the factors and 2) there is no interaction. Once there is evidence that there are no statistically significant interactions, then the first and the second null hypotheses are tested by comparing S_T^2/S_R^2 and S_B^2/S_R^2 respectively with the appropriate $F_{\gamma_1;\gamma_2;\alpha}$ value. On the other hand, if there is evidence that there are interactions between the factors, then the first and second null hypotheses are tested by comparing S_T^2/S_I^2 and S_B^2/S_I^2 with the appropriate $F_{\gamma_1;\gamma_2;\alpha}$ value respectively.

As it was the case of the input modeling of the thesis, these calculations were made using the selected software. In the case of the output analysis for the post-simulation period, the MS Excel software was used with an addition of the Analysis ToolPack where ANOVA calculations with two-factors and replications were available. In the next chapter, discussions of the results and recommendations will be presented.

CHAPTER 5 ANALYSIS AND DISCUSSION

5.1 Introduction

In this chapter, the aspects of the simulation output analysis as well as the discussion that follows each scenario will be examined. The chapter is divided into sub-sections where the individual scenarios are described and their output is validated. The solutions to thesis objective functions are also described and analysed in each section pertaining the corresponding scenario. The first two scenarios simulating the IMC belts are analysed and compared to the actual production in order to be validated an then used in the scenarios simulating the entire HOF production.

5.2 Current CIT IMC belt simulation output analysis

The first models simulated in this thesis were those of the IMC belts in both the HDA and HFA cell respectively. A total of four scenarios were built which included two scenario mimicking the current production (SALHDA and SALHFA) and two scenarios that simulated the IMC belts with zero CIT (SHDAIMPR and SHFAIMPR). Each scenario containing eight runs was simulated for the five individual HOF models, hence, a total of one hundred and sixty runs were simulated.

Once the first two scenarios were tested, it was imperative to validate the simulation models by firstly testing the initial run number ($R_0 = 8$) based on a 95% confidence interval and a simulation accuracy of two parts and secondly by comparing the output with the actual production of each HOF model. The first step in the validation of the simulation output was to determine if the initial number of runs selected would be enough to justify statistically the output as explained in section 4.4.2 Mid-simulation output analysis of Chapter 4. Hence, after each simulation, the output was exported to MS Excel® where the mean and standard deviation were calculated. Figure 5:1 exemplifies the partial output of a simulation, which is this case was the first run out of eight of the model 272AT in the SALHDA scenario where the number of observations was exported to be included in the calculations pertaining to the number of units produced.

** OBSERVED STATISTICS REPORT for scenario SALHDA **

Label	Mean Value	Standard Deviation	Number of Observations	Minimum Value	Maximum Value
Time in HDAL	5400.182	1042.645	130	3611.621	7183.631

Figure 5:1 Sample output of the SALHDA scenario simulation of model 272AT

Based on inequality 4.1 the estimated minimum number of runs was then calculated and tested against inequality 4.2[11] where the final number of runs was calculated and the new simulation parameters were specified. If the calculated results of inequality 4.2 were less than the initial run number $R_0 = 8$, then it was evident enough according to the statistical test that the number of simulations would be sufficient to accept the results already simulated. On the other hand, if the number calculated from inequality 4.2 was greater than that of the initial number of runs simulated, in that case there would be a need to simulate a new run with the specified parameters calculated via equations 4.3 and 4.4 respectively. Fortunately, all simulations pertaining to the SALHDA were statistically sound and none needed to be simulated again with new parameters, hence the output of the eight runs was accepted with a 95% confidence level.

[11] Please see Appendix D for a sample of the calculations pertaining to each HOF model and to each scenario.

Now that the initial number of runs was accepted, the output of the runs had to be compared with the actual production in order to validate the scenario. The comparison was made between the average of the eight runs with the corresponding production based on the model. Hence Table 5-1 was constructed where the simulated averaged units produced in the SALHDA scenario and the actual production in the HDA cell based on model was plotted and the difference was then calculated.

Table 5-1 SALHDA scenario output validation table

HOF Model	Simulated Avg. Parts Produced (Sim. Avg.)	Actual Production Output (Prod. Out.)	Difference (Sim. Avg.)-(Prod. Out.)
272AT	130	130	0
472AT	110	110	0
496AT	90	90	0
672AT	90	90	0
696AT	90	90	0

From the results observed in Table 5-1 and by analysing the "Difference" column one can se that there is no difference between the results obtained from the simulation when comparing to the actual production. Hence, the scenarios are mimicking the true production and based on first principles, the simulation model is accepted.

The same had to be done with the SALHFA scenario where the number of runs had to be justified and the output had to be statistically sound as well as a clear indicator via comparison that the simulation was mimicking the production on the HFA cell. Therefore, as it was the case with the SALHDA scenario, the initial number of runs, $R_0 = 8$, were sufficient to accept the output of the simulation with a 95% confidence interval[12] and the number of parts produced in the simulation matched the total production per hour pertaining to each model as is exemplified in Table 5-2 below.

Table 5-2 SALHFA scenario output validation table

HOF Model	Simulated Avg. Parts Produced (Sim. Avg.)	Actual Production Output (Prod. Out.)	Difference (Sim. Avg.)-(Prod. Out.)
272AT	80	80	0
472AT	70	70	0
496AT	66	67	-1
672AT	54	54	0
696AT	54	54	0

Once again, based on the accuracy selected, $\varepsilon = 2\,\text{parts}$, one can see by examining Table 5-2 that the simulation truly mimicked the production on the HFA cell. Hence, the model is once again accepted from first principles.

Both scenarios, SALHDA and SALHFA, are mimicking the current production in the two cells respectively. Hence, both models are used in the BASECASE and other models simulating the entire production area with confidence that the results will be accurate. Since the purposes of these two scenarios was to primarily code and simulate the IMC belts, then there only two further analysis that can be performed on the output of both scenarios. The first analysis performed is to know which workstation is being utilized the most where the belts are being used and hence indicating perhaps a bottleneck operation on the line and the second analysis of the output that can be performed is, also an objective function of the thesis, the mean flow time of the entities on each simulation. By performing the analysis of identifying the possible bottleneck operation, the first workstations of both scenarios cannot be included in the analysis since both networks do not include them as being part of the workstations utilizing the belts, as well as the

[12] Please see Appendix D for a sample of the calculations pertaining to each HOF model and to each scenario.

preceding workstations not coded in the model which are fundamental to the entire production of the individual cells.

Therefore, in regards to the possible spotting of the bottleneck operation in both cells, the output of both scenarios was examined and the utilizations of the workstations used in the networks were looked at. Figure 5:2 exemplifies an AweSim® output that indicates the utilization of the RESOURCES and hence used in the process of comparing the workstations to determine the possible bottleneck operation is depicted below.

** RESOURCE STATISTICS REPORT for scenario SALHDA **

Resource Number	Resource Label	Average Util.	Standard Deviation	Current Util.	Maximum Util.
13	HDA_03L	1.000	0.000	1	1
15	HDA_04L	1.000	0.000	1	1
17	HDA_05L	0.889	0.343	1	2
19	HDA_06L	0.422	0.494	0	1
21	HDA_07L	0.266	0.442	0	1
23	HDA_08L	0.000	0.000	0	1
160	HDALC_SET	1.000	0.000	1	1

Resource Number	Current Capacity	Average Available	Current Available	Minimum Available	Maximum Available
13	1	0.000	0	0	1
15	1	0.000	0	0	1
17	3	2.111	2	1	3
19	1	0.578	1	0	1
21	1	0.734	1	0	1
23	1	1.000	1	0	1
160	1	0.000	0	0	1

Figure 5:2 Sample AweSim® output report depicting the utilization of the RESOURCES

All workstations in each run, except the ones mentioned previously, were compared with each other in terms of their utilization given by the simulation report. The workstation that had the highest average utilizations in all runs was singled out and the average and standard deviation was calculated in order to estimate an interval based on a 95% confidence level. Using the methodology mentioned in section 4.4.2 of Chapter 4, and an accuracy level of $\varepsilon = 2\,\%$, the necessary steps were taken in order to ensure that the data obtained would be statistically sound, and hence usable for the calculations.

After calculating the average and standard deviation, the utilization interval was calculated via formula 5.1 depicted below.

$$\theta \pm t_{\alpha/2, R-1}\sigma(\theta) \qquad \textbf{(5.1)}$$

The highest value that equation 5.1 could reach would be 1.000, indicating a fully utilized workstation based on the selected confidence interval. Hence, after all the comparisons and calculations were performed, two tables depicted below, Table 5-3 and Table 5-4, were constructed indicating the possible bottleneck operation based on the HOF model being produced and the average and interval utilization for the HDA and HFA cell respectively.

Table 5-3 SALHDA possible bottleneck operation identification table

Workstation range: HDA-04L to HDA-07L			Interval Estimation θ ± tα/2,fσ(θ)	
HOF Model	Possible bottleneck operation	Simulation average utilization	LH	RH
272AT	HDA-06L	0.413	0.392	0.435
472AT	HDA-05L	0.378	0.368	0.388
496AT	HDA-06L	0.598	0.568	0.627
672AT	HDA-05L	0.493	0.485	0.501
696AT	HDA-05L	0.479	0.469	0.489

The utilization obtained in the output reports after a simulation were not straight forward and could not be used as is because in some instances, such as in the case of the workstations HDA-05L and HFA-02L through to HFA-04L the average utilization had to be divided by the corresponding number of operators. Hence, for example, if RESOURCE HDA-05L utilization was 0.899, the true average utilization of each operator would be $0.899/3 \approx 0.3$ or 30% because there are three operators in that operation and so on and so forth. Therefore, after analysing Table 5-3, one can see that the bottleneck operation shifts according to the model being produced. Hence, an indication that the thesis can also be known as a shifting bottleneck and the proper procedures can be applied [1] in terms of scheduling. In regards to the HDA cell, after analysing the output, one could determine that the operations are not balanced. Thus, there is a great difference in the utilization of the operators for each model being produced. Also from observations of the output, the overall utilization is very low when comparing to the industry benchmark averaging at 80%. The low utilization in this case can be attributed to the belt's CIT being set too high making the operators wait for too long for the product from the previous workstation to arrive at their workstation. Hence, as a consequence they have a low utilization. The similar table for the HFA cell is depicted below.

Table 5-4 SALHFA possible bottleneck operation identification table

Workstation range: HFA-02L to HFA-05L			Interval Estimation $\theta \pm t\alpha/2,f\sigma(\theta)$	
HOF Model	Possible bottleneck operation	Simulation average utilization	LH	RH
272AT	HFA-02L	0.724	0.707	0.740
472AT	HFA-05L	0.973	0.954	0.991
496AT	HFA-04L	0.933	0.905	0.960
672AT	HFA-04L	0.863	0.835	0.892
696AT	HFA-02L	0.782	0.741	0.823

In the case of the HFA cell, the same occurs as in the HDA cell where the possible bottleneck operation shifts according to the model being produced. On the other hand, in the case of the HFA cell, the operations are very well balanced overall since the utilizations of the workstations are very similar from one to the other. Also, there is a high utilization factor which indicates that the belt's CIT is set at, or close to, the proper setting for the model being produced.

In terms of the average flow time, $\overline{F}$, similar steps to those taken for the utilization analysis were done in order to obtain the average time an entity spent from the time it was generated until it exited the system. In both scenarios, SALHDA and SALHFA, the average time an entity took was directly related to the belt movements, since the entity could only advance to the next node in the network when the belt GATE would open. Therefore, the average flow time given in the reports includes all the time intervals that the belt moved plus waiting times in both QUEUES and AWAIT nodes as well as processing times in the ACTIVITIES of the network. Similar to the previous analysis but now with an accuracy level of $\varepsilon = 30\,\text{seconds}$ and a 95% confidence level, two tables, Table 5-5 and 5-6, were constructed pertaining to each cell where the information analysed is presented in a tabular form depicted below.

Table 5-5 SALHDA scenario mean flow time of entities based on HOF model table

				Interval Estimation $\theta \pm t\alpha/2,f\sigma(\theta)$	
HOF Model	Batch Size Qty	Number of observations	Average time in the system	LH	RH
272AT	560	130	5414.673	5400.753	5428.593
472AT	840	110	5384.981	5374.673	5395.288
496AT	840	90	5383.380	5374.097	5392.663
672AT	560	90	5380.168	5378.585	5381.750
696AT	840	90	5381.491	5371.526	5391.456

By observing Table 5-5, one can determine that the system is behaving accordingly to the true production since the average time spent in the system for all models are very similar, but each model has a higher output rate because of the fastest and slowest processing times pertaining to the models. For example, when comparing the fastest producing model, 272AT, and the slowest producing model, 696AT, one can see that an entity of model 272AT is processed on average in 41.574 seconds while an entity of model 672AT is processed on average in 59.794 seconds or at a rate of 30.5% slower. The final conclusions cannot be drawn from the observation of the above table because the mean flow time cannot be based on the simulation of two hours, but rather on the overall simulation of the BASECASE scenario, also, the SALHDA scenario simulated one model at a time and the statistics are independent from other models. Thus, when making conclusions in regards to the mean flow time, a mixed models simulation has to be performed with statistically sound interval estimation. Similarly, Table 5-6 is depicted below indicating the average flow time of the entities of the SALHFA scenario.

Table 5-6 SALHFA scenario mean flow time of entities based on HOF model table

HOF Model	Batch Size Qty	Number of observations	Average time in the system	Interval Estimation $\theta \pm t\alpha/2, f\sigma(\theta)$	
				LH	RH
272AT	560	80	5398.465	5381.787	5415.143
472AT	840	70	5420.159	5384.779	5455.540
496AT	840	67	5398.508	5325.371	5471.644
672AT	560	54	5404.384	5368.482	5440.285
696AT	840	54	5396.522	5359.792	5433.251

Once again, the same conclusions can be drawn as it was the case of the SALHDA scenario output mentioned previously. When comparing the results of model 272AT and 696AT, one can see that an entity of model 272AT was processed on average in 67.48 seconds, while an entity of model 696AT was processed on average in 99.94 seconds or 32.5% slower. But again, these results cannot be used to conclude that the production in the HFA cell is done at this rate, but rather, this is an indicator of how the system behaves and the production difference between the models can be noted. When calculating the mean flow time, it is best done when a mixed model is simulated so that the indication of how long an entity will take from the time it was generated until it exits the system is better calculated when the system is saturated with different models and different number of entities in the all network nodes. Hence, leading us to the analysis of the BASECASE scenario described next.

5.3 Output analysis of the current production system simulation

Once both scenarios SALHDA and SALHFA were approved via the analysis of their output, it was statistically safe to use both models in the simulation of the complete HOF production area. Hence, the scenario BASECASE was created which encompassed both cells and all the material handling in between them. In this case, orders of different models were generated at random as explained previously in Chapter 3, and the model was simulated to mimic a three week (40 hours/week) production cycle. In the case of the BASECASE scenario, the belt models used were previously accepted and therefore the primary analysis of the output is in regards to the average flow time of the entities in the entire system beginning in the HDA and finishing in the HFA cell. From the initial output of the BASECASE scenario, the next analysis to be done is in regards to the number of parts produced in order to compare with different scenarios where different production rules would be simulated.

5.3.1 Analysis of the initial BASECASE simulation runs

When analysing for the mean flow time, once the output of the independent runs was collected at the specified time intervals (every 12,000 seconds), the truncation method was applied in order to eliminate the start-up interval biased data. Also, this was the initial step done for the parameter estimation. Hence, calculations had to be done in order to determine if the data obtained from the initial runs were statistically sound. After calculating the truncate cumulative means, a plot was generated in order to visually determine where the data should be truncated. Figure 5:3 below depicts the chart of the truncation data.

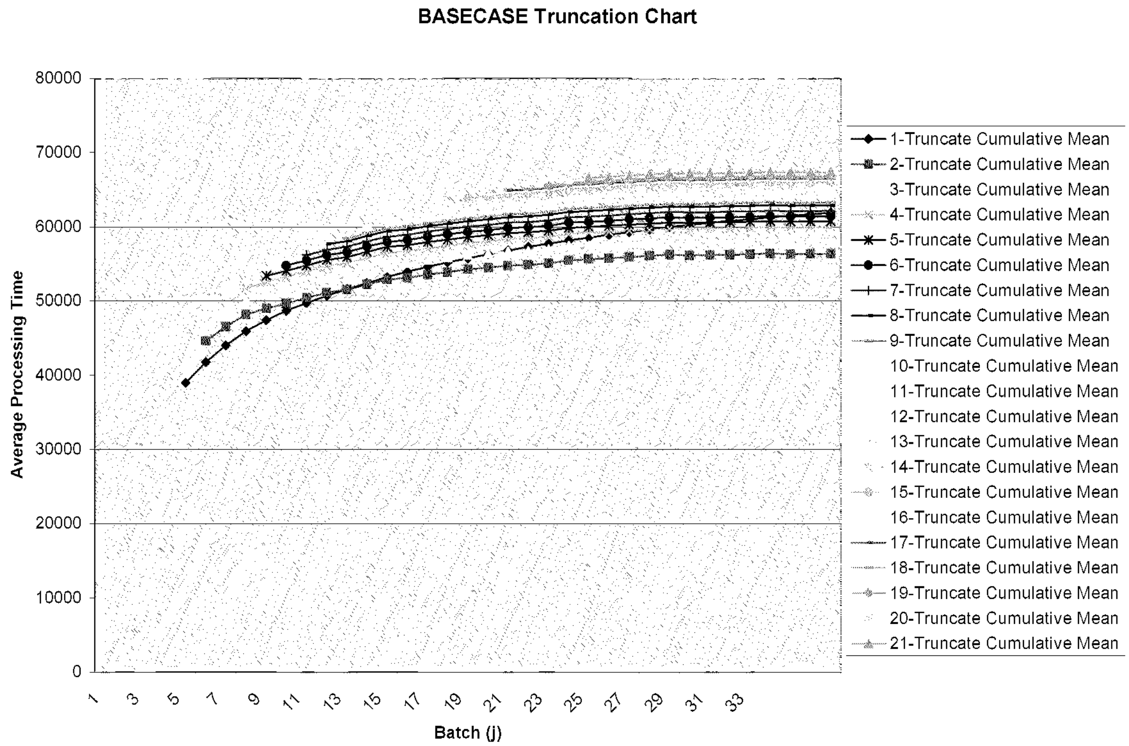

Figure 5:3 BASECASE scenario truncation chart

From a visual inspection of Figure 5:3, it was decided that a 15-truncate would be used in order to reduce the biased start-up data. Hence, the T_0 would be set at 204,000 seconds and the processing times would then be calculated based on the average of the observed data from 204,000 to $T_E = 432{,}000$ seconds. Based on the averages of the initial six runs, $R_0 = 6$, in the interval [204,000;432,000], with a 95% confidence interval and an accuracy level of $\varepsilon = 1{,}200$ seconds (20 minutes), the average processing time was calculated to be 66,839.559 seconds. Also, the calculated initial minimum number of runs $R_{\min} \geq \left(\frac{z_{\alpha/2} \times S_0}{\varepsilon} \right)^2$, was found to be 12, but when comparing with Inequality 4.2, it was found that the simulation should be simulated for a total of 20 runs in order for the output to be statistically sound. Therefore, the parameters for the new simulation were found to be $T_{0_{new}} = 680{,}000\,\text{seconds}$ and $T_{E_{new}} = 1{,}440{,}000\,\text{seconds}$.

Using the same output of the initial six runs, when analysing for the total number of parts, the same calculations for the parameter estimation had to be applied as before. In this case, as opposed to collecting and using the data at a given interval, the data was collected at the end of the simulation since what was intended was the total number of parts produced at the end of the three week period. From the output of the six runs, an average number of parts produced was calculated to be 10692 and since the accuracy level was at set at $\varepsilon = 300\,\text{parts}$ with a confidence level of 95%, the interval estimation based on Equation 5.1 would be between 9484 and 11,890 parts. In order to validate the output, once the minimum number of runs was tested against inequality 4.2 and it was found that a new simulation should be performed with a termination period of $T_{E_{new}} = 936{,}000\,\text{seconds}$ and there was no need to clear statistics at any point since what was being sought out was the total number of parts. At this point, the new parameter for the simulation to calculate the total number of parts was not useful because there was a need to determine the output from the other simulation scenarios pertaining to the full production. Hence, once the parameters for the other simulations were known, a common simulation parameter had to be established in order to compare the output of these simulations. At this point, there was no further analysis that could be done with the current output because it was statistically proven that a new run had to be performed with the parameters calculated in order for its output to be statistically valid.

5.3.2 Analysis of the solution runs of the BASECASE scenario

Once the new model to identify the mean flow time was simulated, the output was analysed for many things including bottleneck operations and also to determine if the primaries and secondaries production coincided in order to justify the investment on a new winding machine as explained in the introduction of the case study. Once again six runs were simulated with a termination period of $T_{E_{new}} = 1{,}440{,}000\,\text{seconds}$, which produced a total of 253,122 and 244,077 parts in the in the HDA and HFA cell respectively. The breakdown of the production is depicted in Table 5-7 and 5-8

Table 5-7 Total parts produced per model in both HDA and HFA cells table

No. of parts produced in the PROCESSING solution simulation based on model		
HDA	MODEL	HFA
18480	272AT	18480
56280	472AT	54614
89801	496AT	84688
28000	672AT	27180
60561	696AT	59115
253122		244077

Table 5-8 Percentage of each model in comparison to total production table

% of parts produced in the PROCESSING solution simulation based on model		
HDA	MODEL	HFA
7.30	272AT	7.57
22.23	472AT	22.38
35.48	496AT	34.7
11.06	672AT	11.13
23.93	696AT	24.22

When comparing the percentage of the production of the simulation on Table 5-8 with that of the probability of production given in Table 3-1, it is noted that indeed the number of parts produced of each HOF model is similar, therefore a clear indicator that the simulation once again is mimicking the actual production. Since the first analysis is in regards to the mean flow time, the output of the new simulation produced an average value of 74758.71633 seconds that an entity will take from the time being generated until it exits the system. This will be equivalent to 2.6 days (8 hours per days). Hence, any product being produced will most likely exit the system in 20.77 hours after it begins production which is equivalent to the current throughput time. Now it is time to use the output to be analysed for the properties of the balancing of the lines, Figure 5:4 is a sample of the output report where one can observe the utilization of the workstations.

** RESOURCE STATISTICS REPORT for scenario BASECASE **

Resource Number	Resource Label	Average Util.	Standard Deviation	Current Util.	Maximum Util.
1	PRIMARY_WIND_MC	0.736	0.441	1	1
2	FILAMENT_WIND_MC	0.670	0.470	1	1
3	SECONDARY_WIND_M	0.991	0.096	1	1
13	HDA_03L	0.272	0.445	1	1
14	HDA_03S	0.588	0.492	0	1
15	HDA_04L	0.253	0.435	1	1
16	HDA_04S	0.588	0.492	0	1
17	HDA_05L	0.400	0.633	1	3
18	HDA_05S	0.789	0.611	0	2
19	HDA_06L	0.160	0.366	0	1
20	HDA_06S	0.378	0.485	0	1
21	HDA_07L	0.082	0.274	0	1
22	HDA_07S	0.177	0.381	0	1
23	HDA_08L	0.000	0.000	0	1
24	HDA_08S	0.000	0.000	0	1
31	HDA_10	1.780	0.626	2	2
32	HDA_11	0.894	0.308	1	1
35	OVENS	1.591	0.650	1	4
36	TANKS	0.636	0.557	1	2
37	COOLING_RACK	1.902	0.813	2	5
50	HFA_01L	0.503	0.500	1	1
51	HFA_01S	0.524	0.499	0	1
52	HFA_02L	1.230	0.937	2	2
53	HFA_02S	1.377	0.881	0	2
54	HFA_03L	1.140	0.966	2	2
55	HFA_03S	1.183	0.956	0	2
56	HFA_04L	1.326	0.910	2	2
57	HFA_04S	0.476	0.831	0	2
58	HFA_05L	0.554	0.497	1	1
59	HFA_05S	0.698	0.459	1	1
62	HFA_07L	0.417	0.493	1	1
63	HFA_07S	0.476	0.499	0	1
64	HFA_08L	0.228	0.419	0	1
65	HFA_08S	0.261	0.439	1	1

Figure 5:4 Output report of the BASECASE scenario depicting the utilization of the RESOURCES

By performing a simple observation, one can pre-determine that the two cells are not equally balanced. The utilizations of the workstations in the HDA cell are much too different from one to the other and the highest utilized are those at the beginning of the line, concretely workstations HDA-01 and HDA-02. Also, the secondaries cell consisting of the HDA-09, HDA-10 and HDA-11 workstations seem to have their utilizations high which could symbolize a good balance of the tasks, but by observing the utilizations alone is not enough in order to determine if the line is balanced. One has to look at the queue lengths as well as the utilization, and again Figure 5:5 depicts the output report pertaining to the queue lengths.

** FILE STATISTICS REPORT for scenario BASECASE **

File Number	Label or Input Location	Average Length	Standard Deviation	Maximum Length	Current Length	Average Wait Time
1	RES. PRIMARY_WIN	79.342	70.653	235	104	10521.659
2	RES. SECONDARY_W	103.807	60.440	222	165	15854.780
3	RES. FILAMENT_WI	2.731	2.843	10	9	368.383
4	RES. HDA_10	63.099	79.178	332	27	1239.828
5	RES. HDA_11	105.074	126.987	485	22	2057.099
6	RES. HDA_03S	56.902	73.176	310	0	2860.164
7	RES. HDA_03L	18.326	40.727	302	121	1894.972
8	RES. HDA_04S	29.925	73.547	379	0	1504.143
9	RES. HDA_04L	4.205	12.947	94	1	442.171
10	RES. HDA_05S	0.000	0.005	1	0	0.003
11	RES. HDA_05L	0.000	0.000	1	0	0.000
12	RES. HDA_06S	1.640	4.175	34	0	82.455
13	RES. HDA_06L	0.919	3.425	34	0	94.751
14	RES. HDA_07S	0.054	0.259	3	0	2.705
15	RES. HDA_07L	0.046	0.278	4	0	4.759
16	RES. HDA_08L	0.000	0.000	1	0	0.000
17	RES. HDA_08S	0.000	0.000	1	0	0.000
20	RES. HFA_01L	14.709	19.747	90	44	5161.208
21	RES. HFA_01S	17.290	23.114	118	0	5589.241
22	RES. HFA_02L	0.000	0.000	1	0	0.000
23	RES. HFA_02S	0.000	0.000	1	0	0.000
24	RES. HFA_03L	0.001	0.028	2	0	0.062
25	RES. HFA_03S	0.001	0.029	2	0	0.055
26	RES. HFA_04L	0.075	0.278	3	0	5.751
27	RES. HFA_04S	0.003	0.054	2	0	0.177
28	RES. HFA_05L	0.316	0.545	3	1	24.194
29	RES. HFA_05S	0.382	0.524	3	0	24.478
32	RES. HFA_07L	0.001	0.028	1	0	0.059
33	RES. HFA_07S	0.000	0.008	1	0	0.004
34	RES. HFA_08L	0.000	0.000	1	0	0.000
35	RES. HFA_08S	0.000	0.000	1	0	0.000
120	RES. HDA_05L	0.000	0.000	1	0	0.000
121	RES. HDA_05L	0.000	0.000	1	0	0.000
123	RES. HDA_05S	0.000	0.007	1	0	0.005

Figure 5:5 Output report of the BASECASE scenario depicting the lengths of files

Using both Figure 5:4 and 5:5, the analysis in regards to the line balancing problem is clearer since now both the utilization and queue lengths are available. One can see many points of interest:

- HDA-09 utilization is the highest indicating that a new model to be built will usually have to wait for the previous model to finish at this workstation
- HDA cell is not balanced properly due to the low and uneven utilization factors of its workstations as well as the high number of entities in its queues
- HFA cell is well balanced
- HDA and HFA are not synchronized because of the uneven production between them

By analysing the same report, it is also evident that the production from the secondaries building cell will keep up with the production from the primaries lines. This point has to be noted because the current simulation used a designated production scenario where only one line at a time would be producing the same model, which means that the report from the other scenarios has to be analysed in order to determine if the secondaries can keep up with the primaries when the lines become cyclic in nature. Figure 5:6 depicts the queue lengths in relation to the production of the secondaries and the primaries.

** FILE STATISTICS REPORT for scenario BASECASE **

File Number	Label or Input	Location	Average Length	Standard Deviation	Maximum Length	Current Length	Average Wait Time
18	QUEUE	FINISHE	97.545	167.744	816	0	3296.619
37	QUEUE	HDA_06L	20.968	44.530	187	56	2146.519
38	QUEUE	HDA_06S	33.336	50.680	224	0	1675.637

Figure 5:6 BASECASE queue lengths of files pertaining to the assembly of primaries with secondaries

From Figure 5:6, one can see that the average length of file 18, which pertains to the queue where the production from the secondaries waits for the production from the primaries to be assembled, is greater than that of the files 37 and 38 respectively. This indicates a waiting of the entities emanating from the secondaries production cell and in turn meaning that the production of the secondaries can in fact keep up with the production of the primaries in this scenario. Now that the model simulating the existing production scenario has been analyzed, it is time to analyze the "what-if" scenarios where there is tweak of the CIT and also the line selection rules.

5.4 Zero CIT IMC belt simulation output analysis

As it was explained in Chapter 4, the test of eliminating the CIT was simulated first in the IMC belts scenarios, namely SHDAIMPR and SHFAIMPR scenarios, and then once accepted it was tested in the other scenarios pertaining to the entire HOF production area. By testing the zero CIT of the belts, it was a test to determine the theoretical maximum production that the workers could produce. Hence, a good indicator of where the true bottleneck operation would lie since the belts would now have no interference on the processing of the parts. It is imperative to point out that the values obtained from these simulations are only theoretical because if it is decided to eliminate the CIT of the belts, the workers will not perform at a constant rate due to fatigue and other ergonomic factors, and therefore the values of production will not be maintained. This was also an indicator of how much more per model could the lines produce, and again it could be used as a rule to set the CIT at a pace lower than the current value of the belts for future analysis. Both simulations were analysed the same was as previously. Firstly, the output of the runs had to be statistically tested in order to be validated and only after the output was validated that the reports were analysed for the three objective functions (the number of parts, the mean processing time and the bottleneck operation indicator).

Once again, eight initial runs were simulated and the output was tested for the individual HOF models. The initial termination period remained at $T_E = 7{,}200$ seconds and statistics were cleared at $T_0 = 3{,}600$ seconds in order to obtain the hourly production. Using a 95% confidence level and a simulation accuracy level of $\varepsilon = 2$ parts, the output was tested for validity. All the simulated runs for the individual models were validated and there was no need for further runs to be performed. Thus, the output obtained from the initial runs was sufficient to perform the analysis. Therefore, Tables 5-9 and 5-10 were built comparing the actual production with that of the what-if scenarios for the HDA and HFA cells respectively are depicted below.

Table 5-9 SHDAIMPR scenario output parts comparision table

HOF Model	Simulated Avg. Parts Produced (Sim. Avg.)	Actual Production Output (Prod. Out.)	Difference (Sim. Avg.)-(Prod. Out.)
272AT	149	130	+19
472AT	124	110	+14
496AT	122	90	+32
672AT	119	90	+29
696AT	98	90	+8

Table 5-10 SHFAIMPR scenario output parts comparison table

HOF Model	Simulated Avg. Parts Produced (Sim. Avg.)	Actual Production Output (Prod. Out.)	Difference (Sim. Avg.)-(Prod. Out.)
272AT	110	80	+30
472AT	71	70	+1
496AT	72	67	+5
672AT	62	54	+8
696AT	68	54	+14

From observation of the two tables above, one can conclude that the HDA cell conveyor settings must be adjusted in order to obtain a higher production than the current levels. While for the HFA cell, apart from the model 272AT and 696AT, it is safe to say that the current belt's CIT settings are properly adjusted since there is no major different with the simulated production and the actual production of the cell. Another important aspect that comes out of the simulation of the zero CIT is the fact that the production per model varies significantly between the two cells. This has an implication in terms of the line balancing from the HDA and HFA cells, meaning that the HDA cell will produce a lot more than what the HFA cell can process. Therefore, the finished goods emanating from the HDA cell will have to wait until the resources of the HFA cell are available, in other words, there is no line balance. This unbalance of production could translate into overtime in order to keep up with the production, which is never desirable. Table 5-11 depicted below compares the production per model based on the zero CIT between the HDA and HFA cells.

Table 5-11 Production comparison between HDA and HFA cells with zero CIT table

HOF Model	HDA Avg. Parts Produced (HDA Out.)	HFA Avg. Parts Produced (HFA Out.)	Difference (HDA Out.)-(HFA Out.)
272AT	149	110	39
472AT	124	71	53
496AT	122	72	50
672AT	119	62	57
696AT	98	68	30

Table 5-11 clearly depicts a great difference in the capacity between the cells, which can be proven to be quite costly when taking in consideration that not only the lines within each cell must be balance, but the cells them-selves must be balanced as well. Another factor that will exemplify the difference between them, is the actual average flow time of the entities in both cells, leading into the next analysis.

Once again, as it was the case of the first analysis of the IMC belts simulations, calculations were made in regards to the mean flow time of the entities in each of the scenarios. By using the same parameters as before, the simulation accuracy level was set at $\varepsilon = 30$ seconds and a 95% confidence level, two tables, Table 5-12 and 5-13, were constructed pertaining to each cell where the information analysed is presented in a tabular form is depicted below.

Table 5-12 SHDAIMPR scenario mean flow time of entities based on HOF model table

HOF Model	Batch Size Qty	Number of observations	Average time in the system	Interval Estimation θ ± tα/2,fσ(θ)	
				LH	RH
272AT	560	149	5399.042	5376.547	5421.538
472AT	840	124	5400.654	5380.507	5420.802
496AT	840	122	5404.784	5389.181	5420.387
672AT	560	119	5399.239	5380.744	5417.734
696AT	840	98	5404.376	5369.457	5439.295

Table 5-13 SHFAIMPR scenario mean flow time of entities based on HOF model table

HOF Model	Batch Size Qty	Number of observations	Average time in the system	Interval Estimation θ ± tα/2,fσ(θ)	
				LH	RH
272AT	560	110	5400.425	5383.646	5417.204
472AT	840	71	5396.285	5343.607	5448.964
496AT	840	72	5389.029	5351.627	5426.432
672AT	560	62	5389.921	5357.440	5422.401
696AT	840	68	5396.522	5359.792	5433.251

In this case, the average flow time is directly related with the activities and not with the conveyor belts as it was the case in the SALHDA and SALHFA scenarios. The production in this case is controlled by the slowest operation, or the bottleneck since entities do not have to wait for the conveyor belt to move to carry them to the next workstation. Since there is no interference of the IMC belt, it is much easier to spot the bottleneck operations on the workstations pertaining to the individual HOF models. Hence, by inspecting both the queue lengths and the utilizations of the workstations, the bottleneck operations were identified as depicted in Tables 5-14 and 5-15 corresponding to the HDA and HFA cell respectively.

Table 5-14 SALHDA possible bottleneck operation identification table

Workstation range: HDA-04L to HDA-07L			Interval Estimation $\theta \pm t\alpha/2,f\sigma(\theta)$	
HOF Model	Possible bottleneck operation	Simulation average utilization	LH	RH
272AT	HDA-06L	0.474	0.456	0.491
472AT	HDA-05L	0.428	0.414	0.441
496AT	HDA-06L	0.811	0.784	0.838
672AT	HDA-05L	0.656	0.637	0.674
696AT	HDA-05L	0.523	0.500	0.546

Table 5-15 SHFAIMPR possible bottleneck operation identification table

Workstation range: HFA-02L to HFA-05L			Interval Estimation $\theta \pm t\alpha/2,f\sigma(\theta)$	
HOF Model	Possible bottleneck operation	Simulation average utilization	LH	RH
272AT	HFA-03L	0.990	0.977	1.000
472AT	HFA-04L	0.979	0.964	0.994
496AT	HFA-04L	1.000	1.000	1.000
672AT	HFA-04L	1.000	1.000	1.000
696AT	HFA-04L	0.985	0.949	1.000

By examining Table 5-14, which pertains to the HDA cell, one can detect that the utilization of the possible bottleneck operation still remains considerably low, since workstation HDA-03L is not counted in this analysis. The reason for such low utilization is then accounted for the fact that workstation HDA-03 as being the bottleneck and hence all the workstations after that are waiting for the parts to be processed at this workstation. Once again, this is a simple indication of the possible bottleneck operation, but the true bottleneck will be identified when the analysis of the simulation of the complete production area is performed. On the other hand, when it comes to the analysis of the utilizations of the workstations in the HFA cell, it was very hard to detect which workstation was in fact the bottleneck because the line is properly balanced. The utilizations of the workstations were all very close to 100% utilized, and the queue lengths in between the workstations were close to zero, hence indicating a real good distribution of tasks. By having the models of the zero CIT simulated and analysed, it was time to analyse the entire production area by eliminating the CIT and running the BASECASE model with the SHDAIMPR and SHFAIMPR scenarios integrated. This new scenario would be called SIMPRCON where the HOF production area would be simulated but with CIT equal to zero.

5.5 Output analysis of the "what-if" scenarios

Three additional scenarios modeling the entire HOF production area were created (SIMPRCON, SNOLINES and SNOLIMPC) to be compared with the BASECASE scenario in terms of both the mean flow time and the total parts produced. The intention of these scenarios was to determine if there is any improvement to the objective functions and thus allowing for alternative solutions to the current production process. The first scenario, SIMPRCON, simulates the current production with zero CIT, which is the theoretical maximum production capacity with the existing line selection rules (designated line to each HOF model). The second scenario, SNOLINES, will simulate with the current CIT settings but with a cyclic line selection rule in both the HDA and HFA cell, meaning that each model will be produced in both lines of each cell simultaneously. While the third scenario, SNOLIMPC, will be a simulation of the combination of both factors, the line selection rule and the zero CIT, where the best possible results are estimated to occur[13].

5.5.1 Analysis of the initial SIMPRCON scenario runs

The creation of the SIMPRCON scenario was created in order to compare the output in relation to the mean flow time and the total parts produced with other scenarios

[13] For a complete description of each scenario, please refer to Chapter 3: Simulation models.

pertaining to the simulation of the entire HOF production area. By eliminating the CIT, this was a theoretical way to know what the maximum production could be attained as well as the fastest way the product could be produced given the current line selection rule of designating a specific line to a particular HOF model. As it was the case of the BASECASE scenario, it was initially decided that this scenario would be mimicking a period of three weeks production. Therefore, the termination period was set at $T_E = 432{,}000$ seconds and it would have six initial runs, $R_0 = 6$. Statistics would be collected at every 12,000 seconds in order to apply the truncation method to eliminate the start-up period biased data. The truncation method applied in the calculations of the mean flow time was the same as in the case of the BASECASE scenario where the truncate average was calculated for the specific interval and then plotted in a graph for a visual inspection and detection of what truncation level to be performed. Figure 5:7 below depicts the plot of the truncate means of the average flow time pertaining to the SIMPRCON scenario.

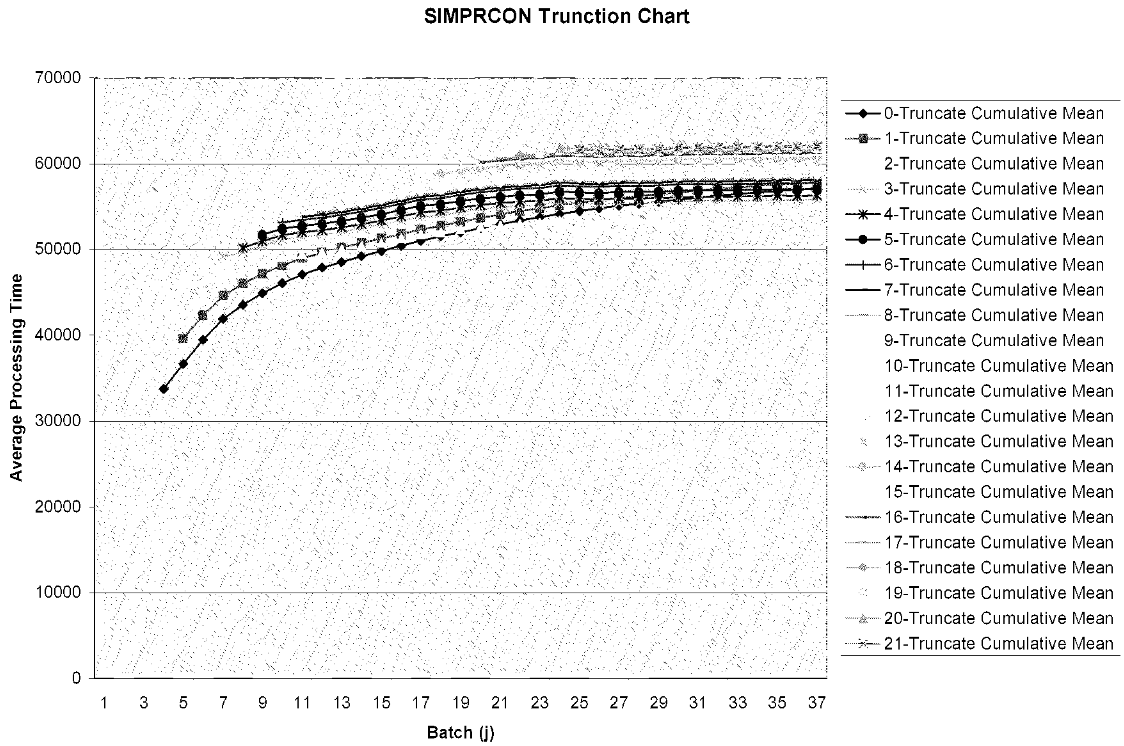

Figure 5:7 SIMPRCON scenario truncation chart

From a visual inspection of Figure 5:7, it was decided that a 10-truncate would be used in order to reduce the biased start-up data, Therefore, T_0 would be set at 144,000 seconds and the processing times would then be calculated based on the average of the observed data from 144,000 to $T_E = 432{,}000$ seconds. Based on the averages of the initial six runs, $R_0 = 6$, in the interval [144,000;432,000], with a 95% confidence interval and an accuracy level of $\varepsilon = 1{,}200$ seconds (20 minutes), the average processing time was calculated to be 60,728.951 seconds. Also, the calculated initial minimum number of runs $R_{\min} \geq \left(\frac{z_{\alpha/2} \times S_0}{\varepsilon} \right)^2$, was found to be 15, but when comparing with Inequality 4.2, it was found that the simulation should be simulated for a total of 24 runs in order for the output to be statistically sound. Therefore, the parameters for the new simulation were found to be $T_{0_{new}} = 576{,}000\,\text{seconds}$ and $T_{E_{new}} = 1{,}728{,}000\,\text{seconds}$.

Using the same output of the initial six runs, when analysing for the total number of parts, the same calculations for the parameter estimation had to be applied as before. In this case, as opposed to collecting and using the data at a given interval, the data was collected at the end of the simulation since what was intended was the total number of parts produced at the end of the three week period. From the output of the six runs, an average number of parts produced was calculated to be 11723 and since the accuracy level was at set at $\varepsilon = 300\,\text{parts}$ with a confidence level of 95%, the interval estimation based on Equation 5.1 would be between 10,000 and 13,446 parts. In order to validate the output, once the minimum number of runs was tested against inequality 4.2 and it was found that a new simulation should be performed with a termination period of $T_{E_{new}} = 1{,}656{,}000\,\text{seconds}$ and there was no need to clear statistics at any point since what was being sought out was the total number of parts. Once again, the termination period pertaining to the new simulation to calculate the total parts produced had to be matched up with the remaining analysis of the next scenarios in order to have a common termination period to be able to compare the total production. Therefore, a new simulation was only performed to validate the output for the calculations of the mean flow time as explained next.

5.5.2 Analysis of the solution runs of the SIMPRCON scenario

Once the new model to identify the mean flow time was simulated, the output was analysed. Once again six runs were simulated with a termination period of

$T_{E_{new}} = 1{,}728{,}000$ seconds, which produced a total of 253,122 and 244,077 parts in the in the HDA and HFA cell respectively. The breakdown of the production is depicted in Tables 5-16 and 5-17 below.

Table 5-16 Total parts produced per model in both HDA and HFA cells table

No. of parts produced in the PROCESSING solution simulation based on model		
HDA	MODEL	HFA
37520	272AT	35953
75904	472AT	73739
109945	496AT	107657
30240	672AT	29908
63455	696AT	61596
317064		308853

Table 5-17 Percentage of each model in comparison to total production table

% of parts produced in the PROCESSING solution simulation based on model		
HDA	MODEL	HFA
11.83	272AT	11.64
23.94	472AT	23.88
34.68	496AT	34.86
9.54	672AT	9.68
20.01	696AT	19.94

Since the first analysis is in regards to the mean flow time, the output of the new simulation produced an average value of 64849 seconds that an entity will take from the time being generated until it exits the system. This will be equivalent to 2.25 days (8 hours per day). Hence, any product being produced will most likely exit the system in 18.01 hours after it begins production. When comparing the mean flow time value with that of the BASECASE scenario, it represents a reduction in the mean flow time of 13.29%.

By using the same output obtained from the simulation, one can also determine which bottleneck operations are present in the HDA and HFA cells respectively when simulating with the zero CIT model. The identification of the bottleneck operation is a combination of both the high utilization as well as a high volume in the resource's queue. If a workstation presents both signs of being highly utilized and its queue has large number of entities waiting on average, then it is a clear indicator that it may indeed be a bottleneck operation when it comes to the mixed model simulation. Excluding both workstation HDA-01 and HDA-09 from the output, the workstation that presented the highest utilization and had the highest average queue length in the HDA cell was workstation HDA-11 with an average utilization of 0.944 and an average queue length of 235 parts. In the HFA cell, the workstation with the highest average utilization and queue length was HFA-04L with an average utilization of 0.721 and an average queue length of 24 parts. Since the analysis is being done in regards to the bottleneck operations, it is required also from this scenario to determine if the secondaries cell can keep up with the production of the primaries. Once again this is done by observing the queues emanating from the secondaries cell and the queues where the entities will wait to be assembled in workstations HDA-06. Figure 5:8 is a snapshot of the output report from the solution run of the SIMPRCON scenario depicting the average queue lengths of the workstations connecting the secondaries cell with the primaries production.

** FILE STATISTICS REPORT for scenario SIMPRCON **

File Number	Label or Input Location		Average Length	Standard Deviation	Maximum Length	Current Length	Average Wait Time
18	QUEUE	FINISHE	5.347	26.123	257	0	169.453
37	QUEUE	HDA_06L	98.042	131.426	560	363	6335.257
38	QUEUE	HDA_06S	108.094	108.720	433	0	6594.493

Figure 5:8 SIMPRCON queue lengths of files pertaining to the assembly of primaries with secondaries

By examining Figure 5:8, one can see that the production from the secondaries cell is not enough to fulfill the requirements of the assembly workstations. Files 37 and 38 are the queues pertaining to workstation HDA-06L and HDA-06S respectively and are the files waiting with entities produced from the primaries cell. Since the average queue lengths of both files are much greater than that of file 18, which is the file emanating from the secondaries cell, it is the indication required to determine that entities will wait for the entities of the secondaries cell. As opposed to the BASESCASE scenario, in this case, the secondaries cell will not keep up with the production of the primaries and hence, the purchasing of a new secondary winding machine would be a wise investment to make.

5.5.3 Output analysis of the initial SNOLINES scenario runs

The SNOLINES scenario was also created to establish a what-if scenario which deals primarily with the change of the line selection in both the HDA and HFA cells respectively. This is done to determine if there is any improvement on the mean flow time as well as the total parts produced. By having the current CIT of the belts, it is required to determine if the mean flow time will be improved since there will be an additional line producing on each cell. Hence, theoretically making the parts wait less time to be processed.

Once again, as it was the case of the previous scenarios pertaining to the simulation of the entire HOF production area, it was initially decided that this scenario would be mimicking a period of three weeks production. Hence, the termination period was set once again at $T_E = 432{,}000$ seconds and it would have six initial runs, $R_0 = 6$. Statistics would also be collected at every 12,000 seconds in order to apply the same truncation method to eliminate the start-up period biased data. Figure 5:9 below depicts the plot of the truncate means of the average flow time pertaining to the SNOLINES scenario.

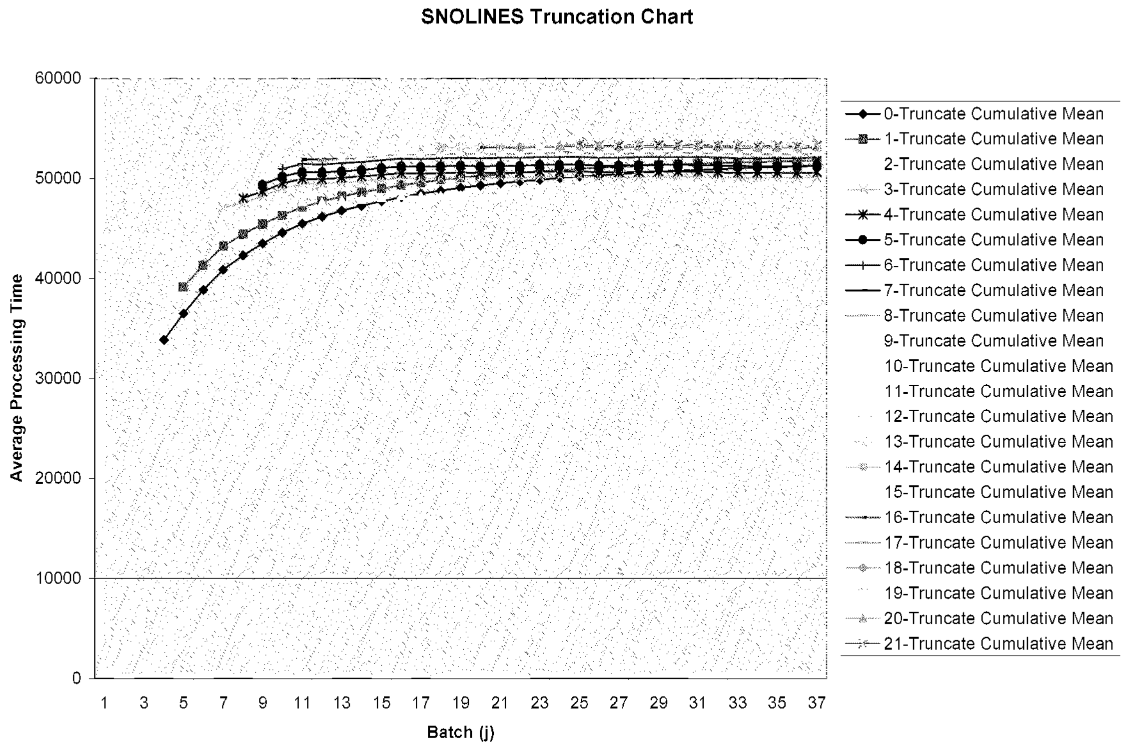

Figure 5:9 SNOLINES scenario truncation chart

From a visual inspection of Figure 5:9, it was decided that a 6-truncate would be used in order to reduce the biased start-up data. Thus, T_0 would be set at 96,000 seconds and the processing times would then be calculated based on the average of the observed data from 96,000 to $T_E = 432{,}000$ seconds. Based on the averages of the initial six runs, $R_0 = 6$, in the interval [96,000;432,000], with a 95% confidence interval and an accuracy level of $\varepsilon = 1{,}200$ seconds (20 minutes), the average processing time was calculated to be 52921.347 seconds. Also, the calculated initial minimum number of runs

$R_{\min} \geq \left(\frac{z_{\alpha/2} \times S_0}{\varepsilon} \right)^2$, was found to be 1, but when comparing with Inequality 4.2, it was found that the simulation should be simulated for a total of 5 runs in order for the output to be statistically sound. Therefore, since the calculated minimum number of runs was less than that already simulated, it was statistically safe to use the exiting output to perform the necessary analysis of the mean flow time. Therefore, based on the mean flow time calculated with these initial runs, this will be equivalent to 1.83 days (8 hours per day). Hence, any product being produced will most likely exit the system in 14.7 hours after it begins production. When comparing the mean flow time value with that of the BASECASE scenario, it represents a reduction in the mean flow time of 29.21%.

By using the same output obtained from the simulation, one can also determine which bottleneck operations are present in the HDA and HFA cells respectively when simulating with the cyclic line selection model. The identification of the bottleneck operation is a combination of both the high utilization as well as a high volume in the resource's queue. If a workstation presents both signs of being highly utilized and its queue has large number of entities waiting on average, then it is a clear indicator that it may indeed be a bottleneck operation when it comes to the mixed model simulation. Excluding both workstation HDA-01 and HDA-09 from the output, the workstation that presented the highest utilization and had the highest average queue length in the HDA cell was workstation HDA-11 with an average utilization of 0.88 and an average queue length of 114 parts. In the HFA cell, the workstation with the highest average utilization and queue length was HFA-05L with an average utilization of 0.641 and an average queue length of less than 1 part. Since the analysis is being done in regards to the bottleneck operations, it is required also from this scenario to determine if the secondaries cell can keep up with the production of the primaries. Once again this is done by observing the queues emanating from the secondaries cell and the queues where the entities will wait to be assembled in workstations HDA-06. Figure 5:10 is a snapshot of the output report from the solution run of the SNOLINES scenario depicting the average queue lengths of the workstations connecting the secondaries cell with the primaries production.

** FILE STATISTICS REPORT for scenario SNOLINES **

File Number	Label or Input Location		Average Length	Standard Deviation	Maximum Length	Current Length	Average Wait Time
18	QUEUE	FINISHE	0.210	2.802	62	0	7.201
37	QUEUE	HDA_06L	20.331	36.566	268	102	1392.698
38	QUEUE	HDA_06S	178.918	103.128	438	189	12259.459

Figure 5:10 SNOLINES queue lengths of files pertaining to the assembly of primaries with secondaries

By examining Figure 5:10, one can see once again that the production from the secondaries cell is not enough to fulfill the requirements of the assembly workstations. Files 37 and 38 are the queues pertaining to workstation HDA-06L and HDA-06S respectively and are the files waiting with entities produced from the primaries cell. Since the average queue lengths of both files are much greater than that of file 18, which is the file emanating from the secondaries cell, it is the indication required to determine that entities will wait for the entities of the secondaries cell. This scenario once again proves that by cycling the line selection, the secondaries will not keep up with the production of the primaries, and hence, it would be economically justified.

Using the same output of the initial six runs, when analysing for the total number of parts, the same calculations for the parameter estimation had to be applied as before.

In this case, as opposed to collecting and using the data at a given interval, the data was collected at the end of the simulation since what was intended was the total number of parts produced at the end of the three week period. From the output of the six runs, an average number of parts produced was calculated to be 11784 and since the accuracy level was at set at $\varepsilon = 300\,\text{parts}$ with a confidence level of 95%, the interval estimation based on Equation 5.1 would be between 8,762 and 14,806 parts. In order to validate the output, once the minimum number of runs was tested against inequality 4.2 and it was found that a new simulation should be performed with a termination period of $T_{E_{new}} = 4{,}464{,}000\,\text{seconds}$ and there was no need to clear statistics at any point since what was being sought out was the total number of parts. Once again, the termination period pertaining to the new simulation to calculate the total parts produced had to be matched up with the remaining and previous analysis of the next scenarios in order to have a common termination period to be able to compare the total production and apply the ANOVA technique explained in chapter 4.

5.5.4 Output analysis of the initial SNOLIMPC scenario runs

The last "what if" scenario remaining to be simulated was the SNOLIMPC where a combination of the cyclic line selection and zero CIT was modeled. As always, it was initially decided that this scenario would be mimicking a period of three weeks production. Hence, the termination period was set once again at $T_E = 432{,}000\,\text{seconds}$ and it would have six initial runs, $R_0 = 6$. Statistics would also be collected at every 12,000 seconds in order to apply the same truncation method to eliminate the start-up period biased data. Figure 5:11 below depicts the plot of the truncate means of the average flow time pertaining to the SNOLIMPC scenario.

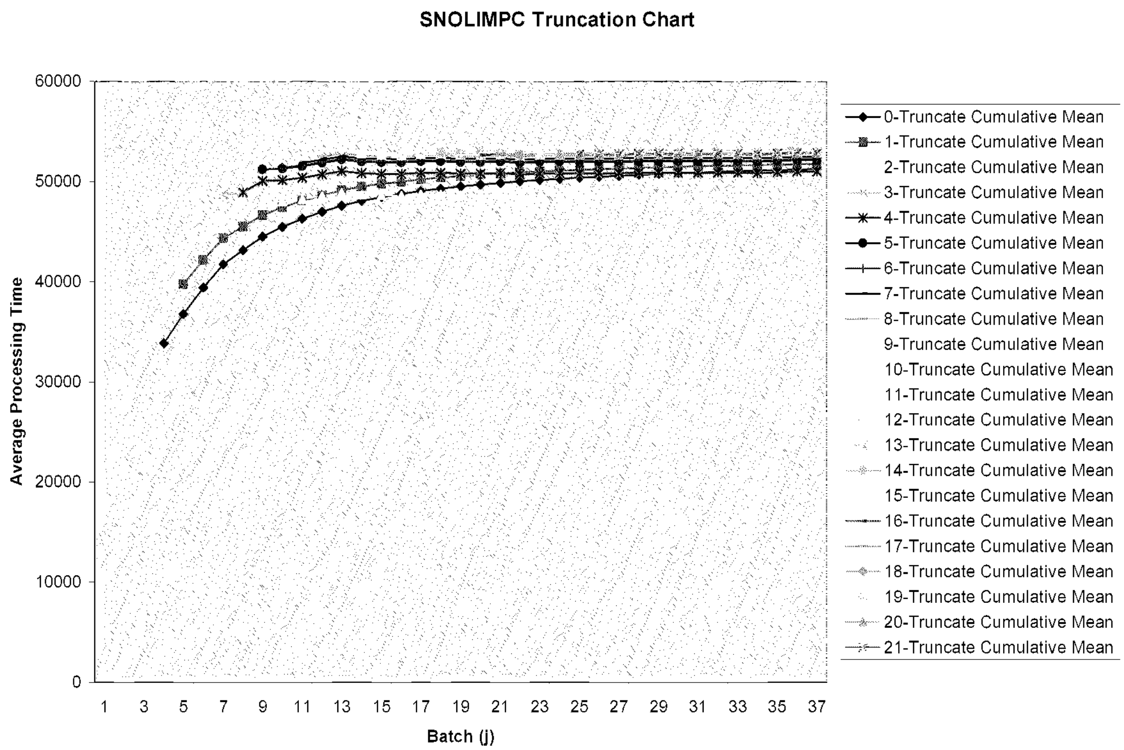

Figure 5:11 SNOLIMPC scenario truncation chart

From a visual inspection of Figure 5:11, it was once again, as in the analysis of the SNOLINES scenario, decided that a 6-truncate would be used in order to reduce the biased start-up data. Hence, T_0 would be set at 96,000 seconds and the processing times would then be calculated based on the average of the observed data from 96,000 to $T_E = 432{,}000$ seconds. Based on the averages of the initial six runs, $R_0 = 6$, in the interval [96,000;432,000], with a 95% confidence interval and an accuracy level of $\varepsilon = 1{,}200$ seconds (20 minutes), the average processing time was calculated to be 52,707.236 seconds. Also, the calculated initial minimum number of runs

$R_{\min} \geq \left(\dfrac{z_{\alpha/2} \times S_0}{\varepsilon} \right)^2$, was found to be 1, but when comparing with Inequality 4.2, it was found that the simulation should be simulated for a total of 5 runs in order for the output to be statistically sound. Therefore, since the calculated minimum number of runs was less than that already simulated, it was statistically safe to use the existing output to perform the necessary analysis of the mean flow time. Therefore, based on the mean flow time calculated with these initial runs, this will be equivalent to 1.83 days (8 hours per day). Hence, any product being produced will most likely exit the system in 14.64 hours after it begins production. When comparing the mean flow time value with that of the BASECASE scenario, it represents a reduction in the mean flow time of 29.5%, the highest reduction of all three “what if” scenarios, which was the prediction when the analysis were first initiated.

Since there is no need to have any additional runs simulated, it is statistically safe to analyse the existing data for the bottleneck operation identification as well as to determine if the secondaries production will keep up with the primaries and hence, to determine if it is economically feasible to purchase a second winding machine. Once again, determining which bottleneck operations are present in the HDA and HFA cells respectively when simulating with the cyclic line selection model as well as with the zero CIT, is a combination of both the high utilization as well as a high volume in the resource’s queue. Excluding once again both workstation HDA-01 and HDA-09 from the output, the workstation that presented the highest utilization and had the highest average queue length in the HDA cell was once again workstation HDA-11 with an average utilization of 0.89 and an average queue length of 173 parts. In the HFA cell, the workstation with the highest average utilization and queue length was HFA-04L with an average utilization of 0.705 and an average queue length of 4 parts. Since the analysis is once again being done in regards to the bottleneck operations, it is required also from this scenario to determine if the secondaries cell can keep up with the production of the primaries. Once again this is done by observing the queues emanating from the secondaries cell and the queues where the entities will wait to be assembled in workstations HDA-06. Figure 5:12 is a snapshot of the output report from the solution run of the SNOLINES scenario depicting the average queue lengths of the workstations connecting the secondaries cell with the primaries production.

** FILE STATISTICS REPORT for scenario SNOLIMPC **

File Number	Label or Input Location		Average Length	Standard Deviation	Maximum Length	Current Length	Average Wait Time
18	QUEUE	FINISHE	0.133	1.905	51	0	4.346
37	QUEUE	HDA_06L	38.046	65.672	410	35	2488.483
38	QUEUE	HDA_06S	202.929	120.628	660	191	13276.604

Figure 5:12 SNOLIMPC queue lengths of files pertaining to the assembly of primaries with secondaries

By examining Figure 5:12, one can see once again that the production from the secondaries cell is not enough to fulfill the requirements of the assembly workstations. Files 37 and 38 are the queues pertaining to workstation HDA-06L and HDA-06S respectively and are the files waiting with entities produced from the primaries cell. Since the average queue lengths of both files are much greater than that of file 18, which is the file emanating from the secondaries cell, it is the indication required to determine that entities will wait for the entities of the secondaries cell. This scenario once again proves that by cycling the line selection and having a zero CIT, the secondaries will not keep up with the production of the primaries, and hence, it would be economically justified. This could have been proved without resorting to the simulation report, since the previous scenarios where these factors were simulated independently also proved that the secondaries production could not keep up with the primaries. Hence, from first principles, this result would have been concluded as well.

Finally, the last analysis of the existing output is that of the total number of parts. The same calculations for the parameter estimation had to be applied as before. In this case, as opposed to collecting and using the data at a given interval, the data was collected at the end of the simulation since what was intended was the total number of parts produced at the end of the three week period. From the output of the six runs, an average number of parts produced was calculated to be 12076 and having the accuracy level was set at $\varepsilon = 300 \text{ parts}$ with a confidence level of 95%, the interval estimation based on Equation 5.1 would be between 10,250 and 13,896 parts. In order to validate the output, once the minimum number of runs was tested against inequality 4.2 and it was found that a new simulation should be performed with a termination period of $T_{E_{new}} = 1{,}728{,}000 \text{ seconds}$ and there was no need to clear statistics at any point since what was being sought out was the total number of parts. Since this was the last simulation to be performed, then the longest termination period of all four scenarios, (BASECASE, SIMPRCON, SNOLINES and SNOLIMPC) was selected in order to compare the production of them all. Therefore, the selected termination period was that of the SNOLINES scenario, being $T_{E_{new}} = 4{,}464{,}000 \text{ seconds}$.

5.6 ANOVA

Once all the scenarios were simulated with the proper statistical parameters, it was time to perform the ANOVA with replication analysis as explained previously in Chapter 4. Two testes were performed in order to determine if there is indeed a relationship between the two factors, line selection and belt's CIT and the objective functions. In the case of this thesis, the two objective functions tested were the mean flow time and the total parts produced. There was a need to determine alternative solutions to the current production scenario, which lead to the simulation of the what-if scenarios.

5.6.1 ANOVA pertaining to the mean flow time

The first analysis of variance performed had to do with the mean flow time. From the previous analysis of the output, the average flow time was plotted for the six solution runs of each scenario as depicted in Table 5-18 below.

Table 5-18 Mean Flow Time simulated in six runs of different factors table

		Conveyor Speed	
		Current CIT	Zero CIT
Line Selection	Designated	76370.009	64936.720
		82978.034	63061.858
		69848.421	64033.593
		69761.641	62738.255
		73481.418	68635.468
		76112.775	65689.958
	Cycling	53545.444	52096.916
		54252.549	51930.196
		51832.458	53570.175
		52488.239	51775.048
		52475.520	53084.162
		52933.871	53786.918

The ANOVA test was performed in order to determine if there was any variation between the levels, in this case the line selection and the conveyor speed and its factors. Then the three null hypothesis described in section 4.4.3 of Chapter 4 were tested by comparing the Fisher value calculated using formulas 4.17 to 4.19 with the critical value $F_{\gamma_1, \gamma_2, \gamma_3}$. If the calculated value is greater than that of the F-critical, then there is an indication that indeed there is interaction between the factors. Otherwise, there is no interaction and the null hypothesis fails to be accepted. Table 5-19 below depicts the calculations of the ANOVA in relation to the mean flow time.

Table 5-19 ANOVA calculations of the simulation models in regards to Mean Flow Time table

Anova: Two-Factor With Replication

SUMMARY	Current CIT	Zero CIT	Total
Designated			
Count	6	6	12
Sum	448552.298	389095.852	837648.15
Average	74758.71633	64849.30867	69804.0125
Variance	24540035	4673250.812	40059591.82
Cycling			
Count	6	6	12
Sum	317528.0811	316243.4163	633771.4975
Average	52921.34686	52707.23605	52814.29146
Variance	746754.7489	779541.5976	706273.8219
Total			
Count	12	12	
Sum	766080.3791	705339.2683	
Average	63840.0316	58778.27236	
Variance	141549642.3	42686704.01	

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	1731903727	1	1731903727	225.3646413	2.37086E-12	4.351250027
Columns	153728439.3	1	153728439.3	20.00397254	0.000233206	4.351250027
Interaction	140998171.9	1	140998171.9	18.34744157	0.000362668	4.351250027
Within	153697910.8	20	7684895.54			
Total	2180328249	23				

In the case of the mean flow time, all values were found to be greater than the F-critical. Thus, indicating that there is interaction between the factors, and therefore enabling one to conclude that the factors are statistically dependent from each other. In other words, the null hypotheses are rejected, and there is a conclusion that one factor influences more the outcome of the simulation than others.

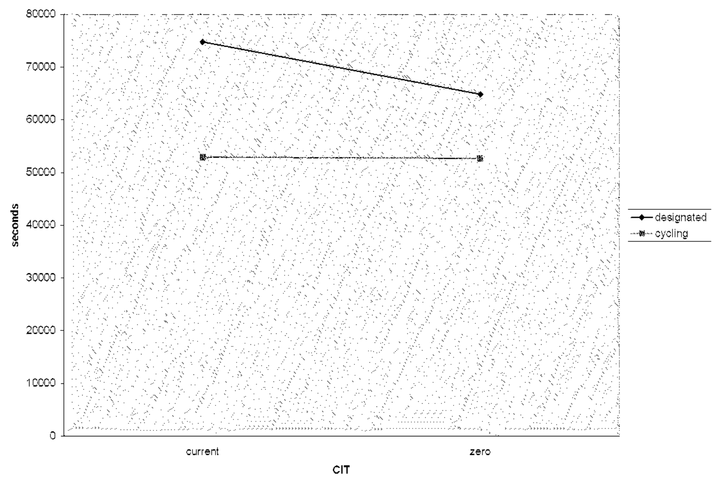

Figure 5:13 ANOVA Interaction graph between factors

Therefore, if the desire is to obtain a production with the lowest mean flow time, then the HOF production area should produce with a cyclic line selection and with a zero CIT.

5.6.2 ANOVA pertaining to the total parts produced

In regards to the total parts produced, there was a need to perform further simulation runs as explained previously in order to obtain statistically sound results. Once the runs were performed, the total number of parts produced from each scenario was also tabulated in order for the ANOVA test to be performed. Table 5-20 below depicts the total number of parts produced in each of the individual six runs pertaining to the independent scenarios.

Table 5-20 Total parts produced in six runs of different simulations table

		Conveyor Speed	
		Current CIT	Zero CIT
Line Selection	Designated	128516	138622
		131860	131241
		131320	129204
		131348	130287
		126210	133992
		131646	138319
	Cycling	128878	135393
		127677	130017
		134410	137580
		133743	129444
		137618	135532
		135700	128570

The ANOVA test was once again performed in order to determine if there was any variation between the levels. Then the three null hypothesis described in section 4.4.3 of Chapter 4 were tested by comparing the Fisher value calculated using formulas 4.17 to 4.19 with the critical value $F_{\gamma_1, \gamma_2, \gamma_3}$. The result of the ANOVA calculations is depicted in Table 5-21 below.

Table 5-21 ANOVA calculations of the simulation models in regards to the Total Parts Produced table

Anova: Two-Factor With Replication

SUMMARY	Current CIT	Zero CIT	Total
Designated			
Count	6	6	12
Sum	780900	801665	1582565
Average	130150	133610.8333	131880.4167
Variance	5231955.2	16701614.17	13236358.99
Cycling			
Count	6	6	12
Sum	798026	796536	1594562
Average	133004.3333	132756	132880.1667
Variance	15296234.67	14784996.4	13690105.79

Total		
Count	12	12
Sum	1578926	1598201
Average	131577.1667	133183.4167
Variance	11552964.15	14511388.45

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	5997000.375	1	5997000.375	0.461176459	0.504858445	4.351250027
Columns	15480234.38	1	15480234.38	1.19044843	0.288209766	4.351250027
Interaction	20636876.04	1	20636876.04	1.587000305	0.222258	4.351250027
Within	260074002.2	20	13003700.11			
Total	302188113	23				

In the case of the total parts produced, one can see from the calculations that the F value is smaller than the critical value. Hence, the null hypotheses are accepted, meaning that there is no difference between the scenarios and therefore, all scenarios will produce more or less the same number of parts.

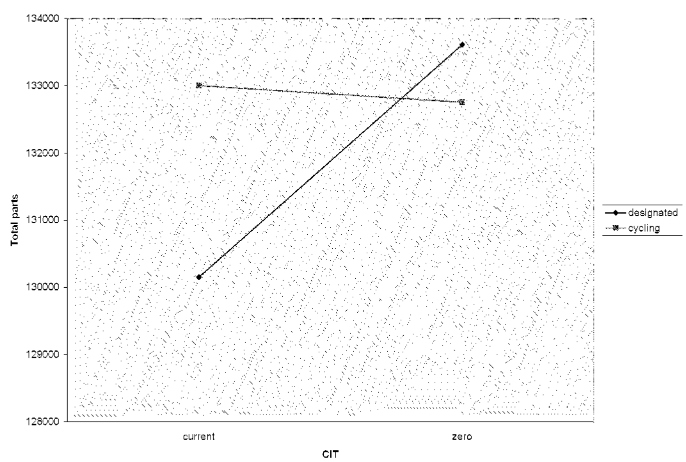

Figure 5:14 ANOVA Interaction Chart between blocks

CHAPTER 6 CONTRIBUTIONS AND FUTURE RESEARCH

6.1 Introduction

This chapter will be mainly focused on the contributions made throughout the process of the data collection, organization and scenario building, as well as the output analysis. At the end of the chapter, there is a section where possible future research will be discussed.

6.2 Overall contributions of the research project

As mentioned at the end of Chapter 2, three new tools were designed to improve both the productivity as well as the safety of all. From the early stages, data collection on processing times and process mapping, the research undertaken served as a training tool for the workers of the production area on the intentions and expectations of the study. An open information environment was created to allow for questions to be answered and also to create a comfort level for the production area personnel since their cooperation was extremely valuable. The most important information in regards to the "best-practices" lies with the people that actually perform the tasks. Hence, a solid relationship had to be created between the researchers and the shop personnel to "gain" access to the best methods used in order to create a solid process map in each workstation for each HOF model built. Since there was no data at the beginning of the research, the initial stages of the project were used to determine beforehand visible problematic areas that only an "outsider" could see by inspecting the different production cells, as well to become familiar with the whole production process. From these initial observations, and since the whole intent was to help increase productivity by determining how to reduce the mean flow time, the initial key elements observed were in regards to the setups of the individual workstations. Therefore, the introduction of the RT and Hook as well as the ASRs greatly improved some of the problems and contributed not only to the reduction of setup times but also to the company savings, as well as increasing the safety of the personnel.

Additional contributions of this project include those resulting from the data collection and from the data analysis. The modeling and analysis undertaken in this project has provided many benefits such as:

1. A comprehensive and scientific time study on a number of high-demand products that could be easily extended to other existing or future new products.
2. Extensive data collection that is greatly useful for process routings and line balancing tasks.
3. A set of simulation models that represent the existing system and a number of alternatives that could serve for both immediate needs and future problems.
    a. Production analysis in regards to mean flow time of entities via simulation
    b. Bottleneck identification via simulation.
    c. IMC belts simulation models which allow for adjustments and scenario testing prior to implementation.
4. Determined if primary cell and secondary cell were properly balanced, i.e., if secondary cores production could keep up with primary cores production.

5. Determined via simulation if purchasing of a second secondary winding machine was viable.

These contributions allowed for the result of spin-off projects which can be categorized as future research described in the next section.

6.4 Future research

Due to the size of the project, there are many other opportunities that could be explored as future research projects. One of the main projects that could spin-off from the output analysis of the simulation scenarios would be to devise a scheduling technique based on the SBP [1] to initiate the production of the HOF models. Instead of basing the production initialization on the human judgement of the lead-hand, a Kanban technique could be used to trigger a signal. This would greatly improve the schedule of known orders and, therefore, utilize the scheduling techniques widely used such as FIFO or LIFO and many other techniques based on the objective functions designated by the company objectives. As a wide perspective, an order could even be automatically scheduled by a computerized scheduling process and hence allow the order desk to instantly let the costumer know the lead time for their order based on the current production capacity and the mean flow time calculated by the simulation models pertaining to the different scenarios.

Another project as future research could be entirely based on the design of the workstations to reduce setups. One of the main objectives of any lean [39] manufacturing is to actually minimize setups and changeovers to the point of eliminating. If this is accomplished, many problems will be eliminated and a much better and lean production area can be accomplished. This would also involve the reduction of the material handling. Hence, relocation of certain storage spaces would be performed based on plant layout techniques.

Yet another project as future research would be on the actual process redesign. Finding new and improved techniques to produce the HOF ballasts in both the Dry and Final cells could greatly reduce and improve the mean flow time as well as costs of production. Some of the ideas proposed by the management include substituting the soldering of the wire terminals by clip-on terminals where the wire would be attached without the need to solder, hence, eliminating several steps. Also, a better and faster technique of impregnating the cores would greatly eliminate the biggest bottleneck operation of the HOF line. Instead of having the cores being submerged on the pitch resin and thinner, perhaps a coating polymer could do the same job but with much faster curing times. With all these ideas in place, the simulation models could assist in determining the effect of changes on productivity.

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APPENDIX A: SAMPLE OF INPUT MODELING AND DISTRIBUTION FITTING

A.1 Model 272AT distribution fitting for workstation HDA-01

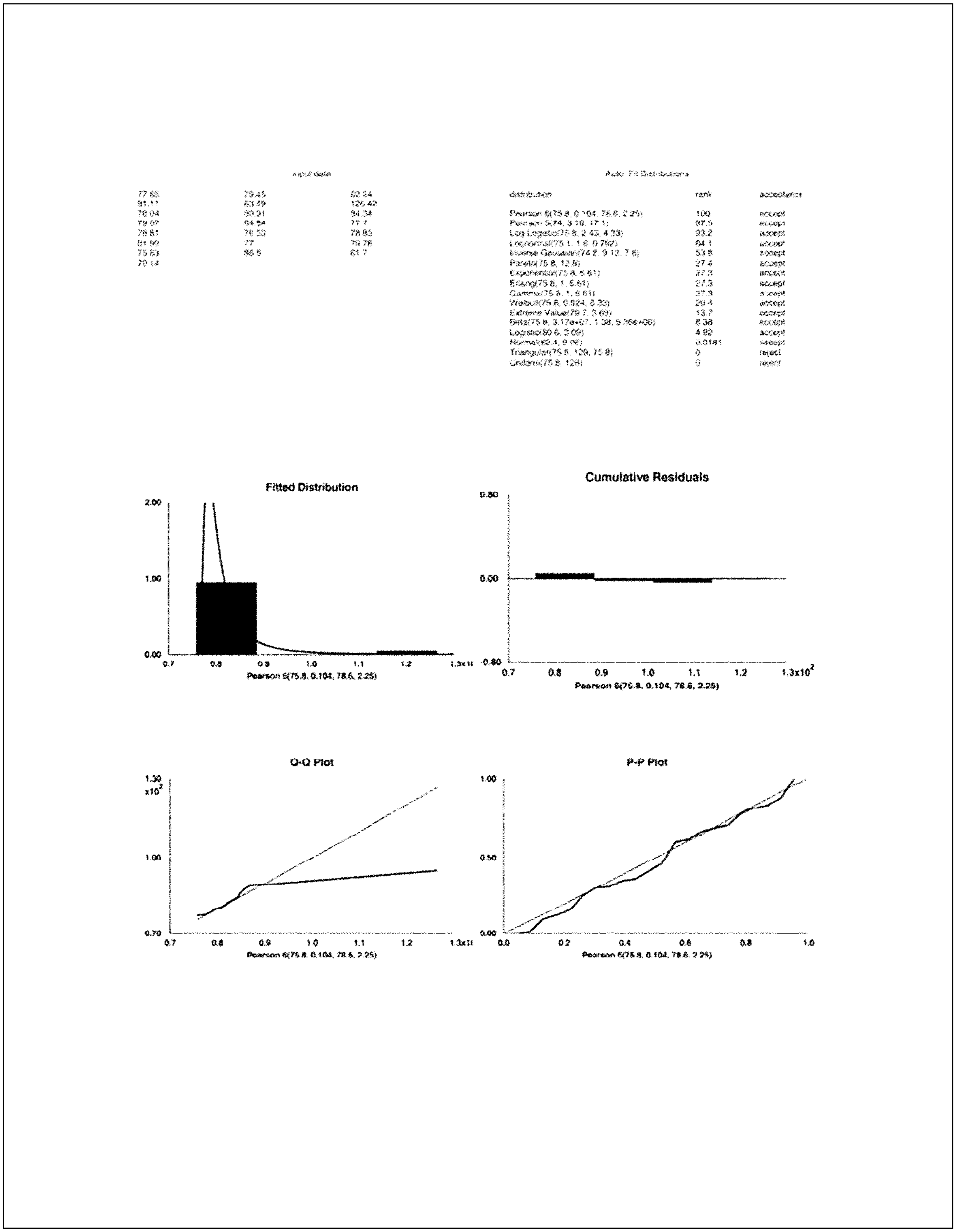

Figure A:1 Input modeling of the data pertaining to model 272AT of workstation HDA-01

A.2 Model 472AT distribution fitting for workstation HDA-01

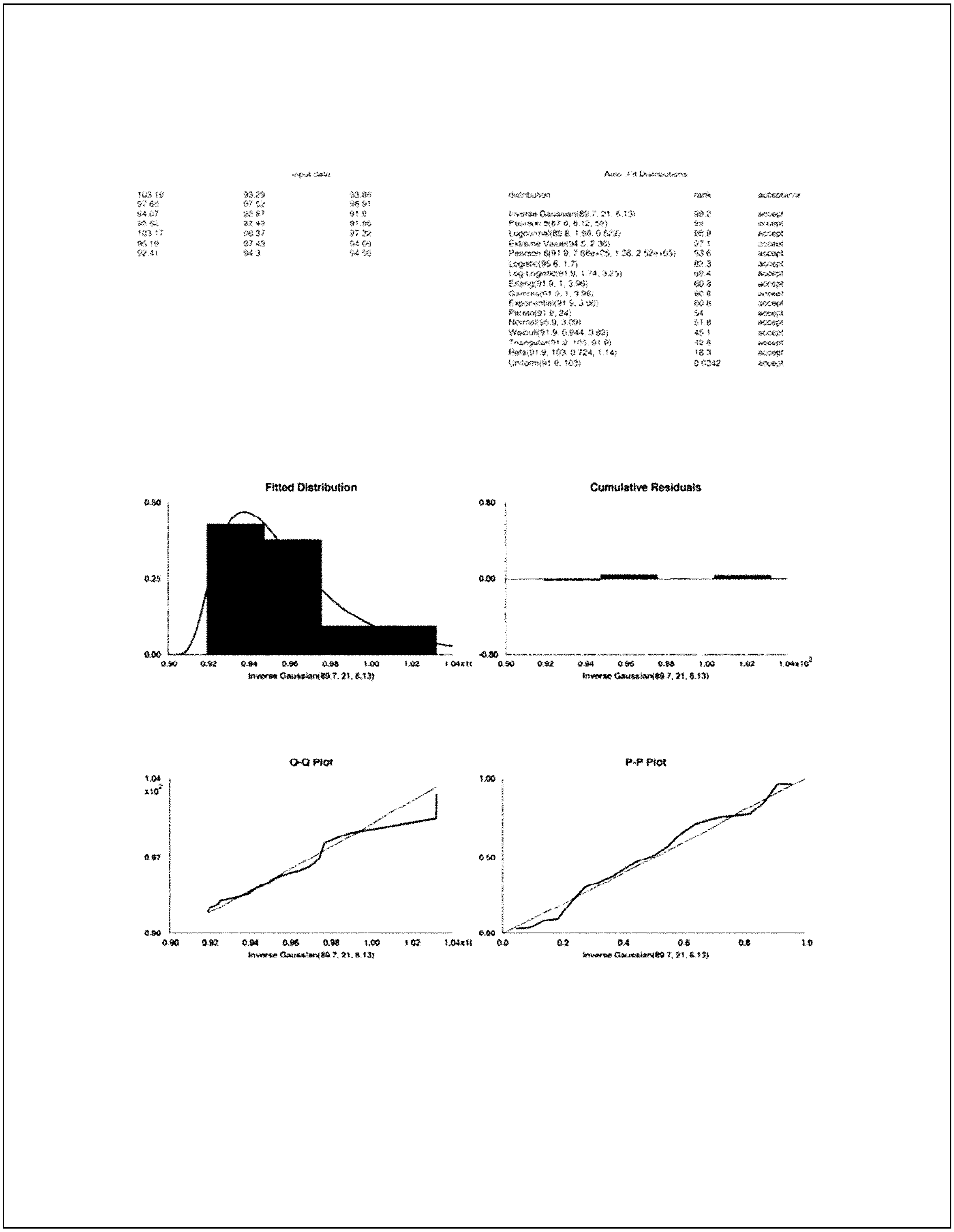

Figure A:2 Input modeling of the data pertaining to model 472AT of workstation HDA-01

A.3 Model 496AT distribution fitting for workstation HDA-01

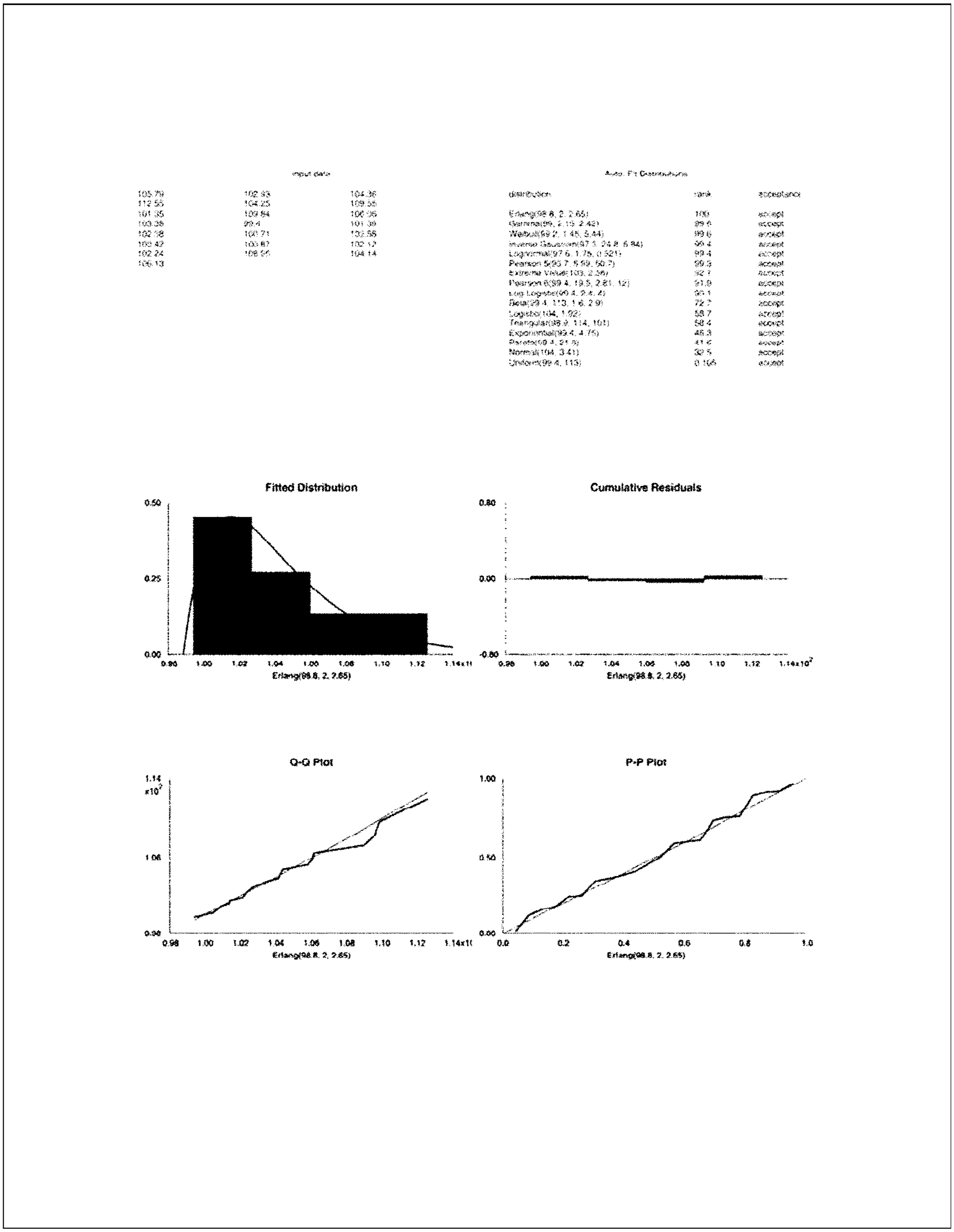

Figure A:3 Input modeling of the data pertaining to model 496AT of workstation HDA-01

A.4 Model 672AT distribution fitting for workstation HDA-01

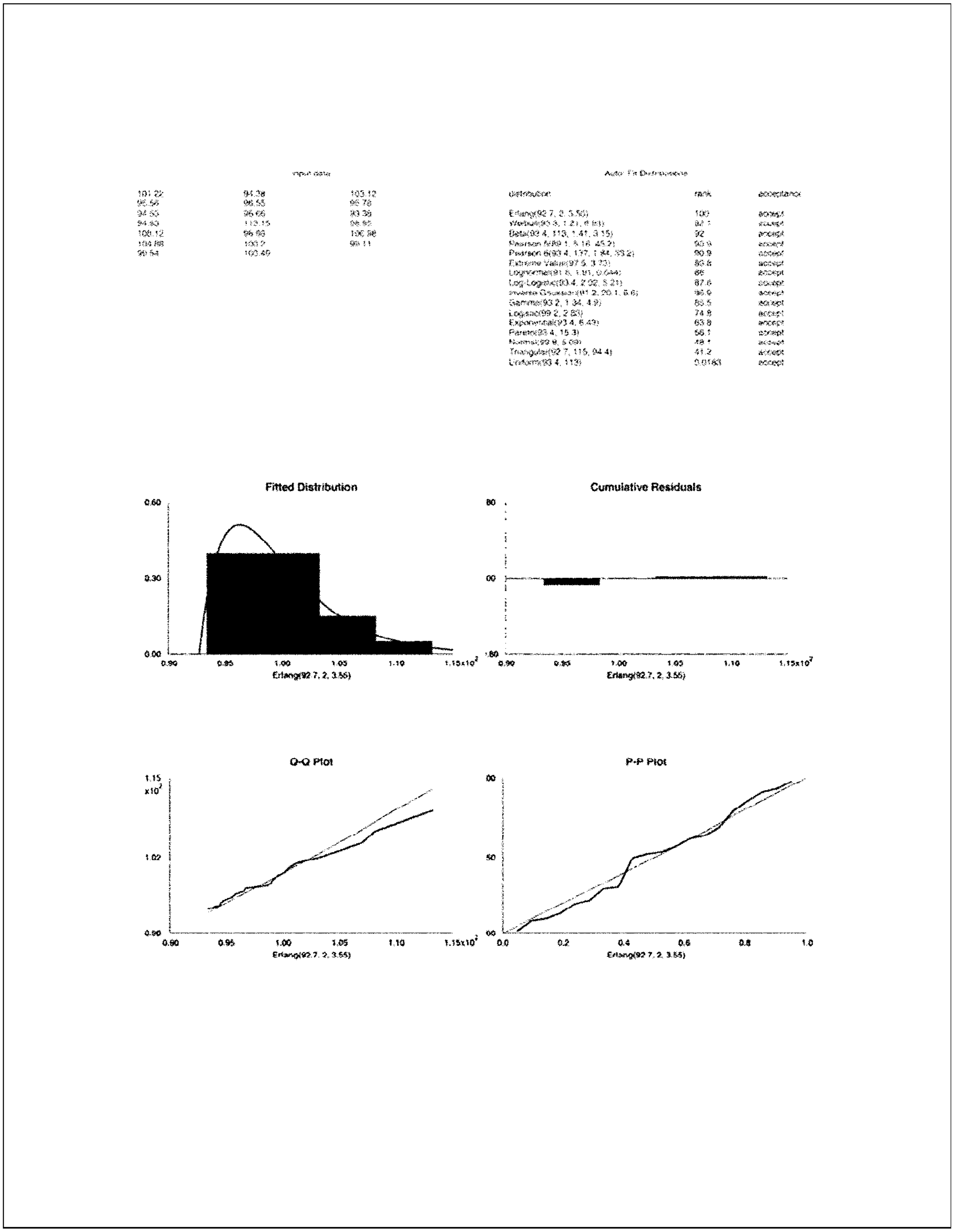

Figure A:4 Input modeling of the data pertaining to model 672AT of workstation HDA-01

A.5 Model 696AT distribution fitting for workstation HDA-01

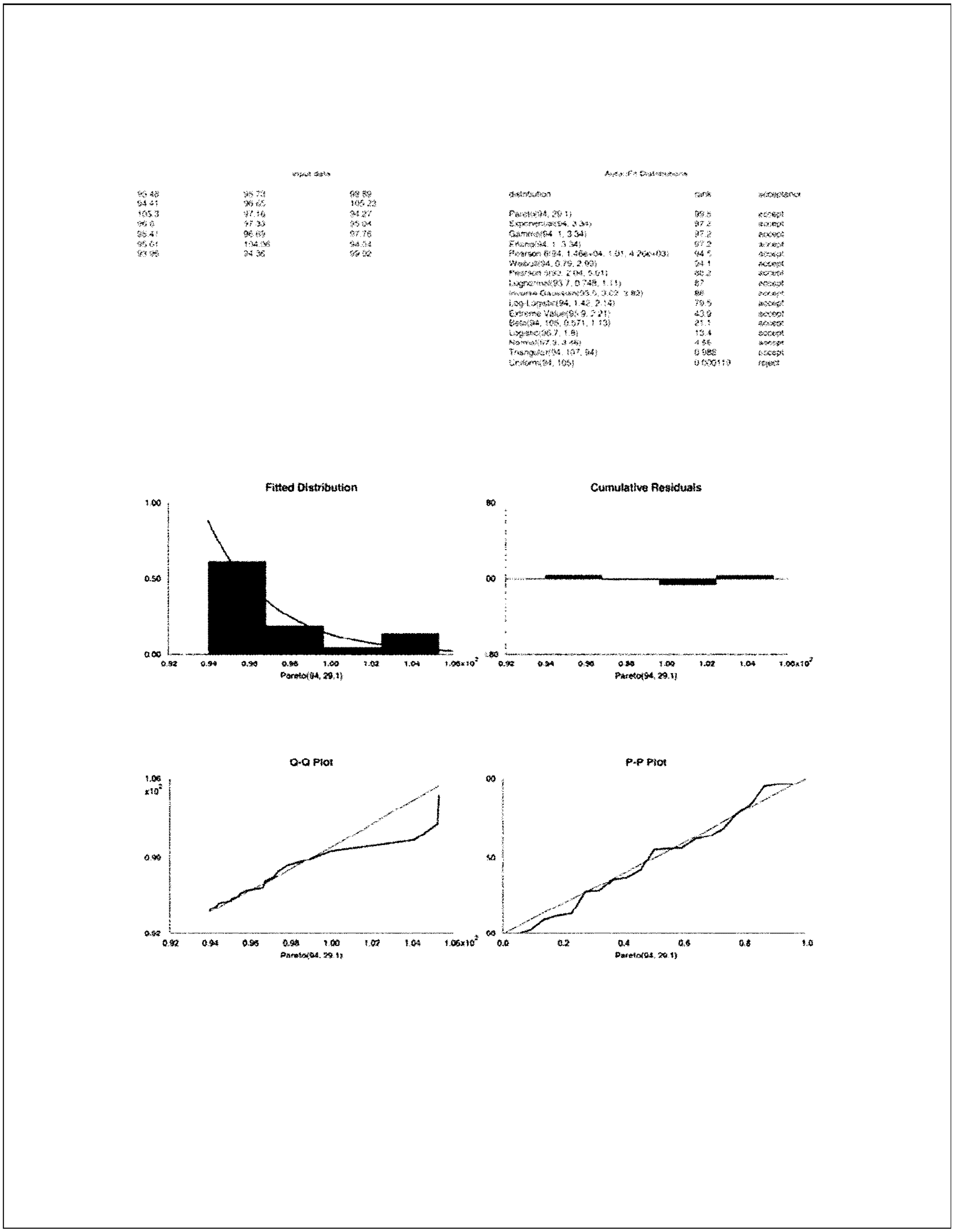

Figure A:5 Input modeling of the data pertaining to model 696AT of workstation HDA-01

APPENDIX B: WORKSTATION DISTRIBUTION BASED ON HOF MODEL (POST TRANSFORMATION)

Table B-1: Model 272AT workstations distributions

Model 272AT	
Workstation	Fitted Distribution
HDA-01	75.8 + 0.104 * VS.GAMA(0.104, 78.6, 1) / VS.GAMA(0.104, 2.25, 1)
HDA-02	VS.UNFRM(63.9, 77, 1)
HDA-03	19.2 + 3.77 * VS.BETA(1.14, 1.22, 1)
HDA-04	19.3 + VS.ERLNG(1.65, 3, 1)
HDA-05	17.9 + 6.51 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 4.96)
HDA-06	7.34 + VS.ERLNG(1.35, 3, 1)
HDA-07	5.87 + 1.4 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 4.05)
HDA-09	122 + 29.9 * VS.BETA(2.71, 1.57, 1)
HDA-10	16.1 + 16.5 * VS.BETA(0.653, 0.926, 1)
HDA-11	12.7 - 0.534 * Log((1 / VS.UNFRM(0, 1, 1)) - 1#)
HFA-01L	-323 + 442 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 66.3)
HFA-01S	5.69 + 128 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 9.72)
HFA-02	65.2 - 3.34 * Log((1 / VS.UNFRM(0, 1, 1)) - 1#)
HFA-03	60.3 / ((1# - VS.UNFRM(0, 1, 1)) ^ (1# / 14.8))
HFA-04	44.7 + 1# / VS.GAMA(0.00162, 33.9, 1)
HFA-05	26.5 + VS.ERLNG(1.87, 2, 1)
HFA-07	VS.TRIAG(18.7, 24.2, 27.4, 1)
HFA-08	6.94 + 7.34 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 7.76)

Table B-2: Model 472AT workstations distributions

Model 472AT	
Workstation	Fitted Distribution
HDA-01	87.6 + 1# / VS.GAMA(0.0169, 8.12, 1)
HDA-02	VS.RNORM(87.8, 4.1, 1)
HDA-03	22.8 + VS.GAMA(0.867, 3.43, 1)
HDA-04	26.4 + 1# / VS.GAMA(0.115, 4.32, 1)
HDA-05	31.7 + 4.59 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 2.74)
HDA-06	11.3 - 0.941 * Log(Log(1# / VS.UNFRM(0, 1, 1)))
HDA-07	4.69 + 1.48 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 4.98)
HDA-09	82.4 + 1# / VS.GAMA(0.0000354, 344, 1)
HDA-10	-4910# + VS.RLOGN(4920#, 0.717, 1)
HDA-11	11.3 + 10.6 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 3.27)
HFA-01L	113 + VS.GAMA(6.57, 3.53, 1)
HFA-01S	VS.TRIAG(116, 174, 174, 1)
HFA-02	VS.UNFRM(67.1, 97.9, 1)
HFA-03	63.5 - 2.76 * Log((1 / VS.UNFRM(0, 1, 1)) - 1#)
HFA-04	-121 + 1# / VS.GAMA(0.0000078, 636, 1)
HFA-05	-7830# + VS.RLOGN(7880#, 4.41, 1)
HFA-07	-71.1 + 102 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 73.1)
HFA-08	11.5 + VS.GAMA(1.16, 4.34, 1)

Table B-3: Model 496AT workstations distributions

Model 496AT	
Workstation	Fitted Distribution
HDA-01	98.8 + VS.ERLNG(2.65, 2, 1)
HDA-02	76.8 + VS.RLOGN(12.6, 10.9, 1)
HDA-03	25.6 + 8.63 * VS.BETA(0.826, 1.61, 1)
HDA-04	21.6 + 7.6 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 6.9)
HDA-05	16 + 1# / VS.GAMA(0.00215, 28.5, 1)
HDA-06	-136 + 160 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 83.2)
HDA-07	6.46 + 2.75 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 3.68)
HDA-09	82.4 + 1# / VS.GAMA(0.0000354, 344, 1)
HDA-10	11.1 + VS.RLOGN(6.77, 0.833, 1)
HDA-11	7.03 + 8.72 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 10.6)
HFA-01L	143 + 1# / VS.GAMA(0.00537, 6.49, 1)
HFA-01S	143 + 1# / VS.GAMA(0.00537, 6.49, 1)
HFA-02	-96.6 + 187 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 39.4)
HFA-03	60.1 + 28.5 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 7.49)
HFA-04	-12500# + VS.RLOGN(12600#, 9.76, 1)
HFA-05	31 + VS.ERLNG(3.62, 2, 1)
HFA-07	-4890# + VS.RLOGN(4920#, 2.88, 1)
HFA-08	17 - 0.911 * Log((1 / VS.UNFRM(0, 1, 1)) - 1#)

Table B-4: Model 672AT workstations distributions

Model 672AT	
Workstation	Fitted Distribution
HDA-01	92.7 + VS.ERLNG(3.55, 2, 1)
HDA-02	77.2 + 1# / VS.GAMA(0.00413, 12.4, 1)
HDA-03	-7840# + VS.RLOGN(7870#, 1.57, 1)
HDA-04	-1910# + 1930# * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 807)
HDA-05	59.1 - 2.78 * Log((1 / VS.UNFRM(0, 1, 1)) - 1#)
HDA-06	3.45 + 7.35 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 5.18)
HDA-07	4.52 + 2.75 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 4.65)
HDA-09	127 + 17.3 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 8.89)
HDA-10	15.7 + 1# / VS.GAMA(0.164, 3.7, 1)
HDA-11	13.1 + 40800000# * VS.GAMA(40800000#, 1.05, 1) / VS.GAMA(40800000#, 4890000#, 1)
HFA-01L	-402 + 644 * VS.BETA(37.2, 1.64, 1)
HFA-01S	216 + VS.GAMA(16.6, 3.09, 1)
HFA-02	-12500# + VS.RLOGN(12600#, 8.84, 1)
HFA-03	94.2 + VS.GAMA(4.06, 1.62, 1)
HFA-04	115 - 5.38 * Log((1 / VS.UNFRM(0, 1, 1)) - 1#)
HFA-05	36 + 8540000# * VS.GAMA(8540000#, 4.15, 1) / VS.GAMA(8540000#, 2670000#, 1)
HFA-07	35 + VS.ERLNG(2.96, 2, 1)
HFA-08	-7850# + VS.RLOGN(7870#, 1.66, 1)

Table B-5: Model 696AT workstations distributions

Model 696AT	
Workstation	Fitted Distribution
HDA-01	94 / ((1# - VS.UNFRM(0, 1, 1)) ^ (1# / 29.1))
HDA-02	69.2 + 1# / VS.GAMA(0.00105, 34.8, 1)
HDA-03	32.3 + VS.GAMA(1.89, 2.35, 1)
HDA-04	28 + VS.GAMA(1.37, 1.82, 1)
HDA-05	45.3 + 23.7 * VS.BETA(1.74, 1.6, 1)
HDA-06	-11.2 + 1# / VS.GAMA(0.000313, 116, 1)
HDA-07	6.18 + VS.ERLNG(0.4, 11, 1)
HDA-09	61.9 + 1# / VS.GAMA(0.00000872, 900, 1)
HDA-10	6.29 + VS.RLOGN(13.8, 1.66, 1)
HDA-11	16.4 - 1.05 * Log((1 / VS.UNFRM(0, 1, 1)) - 1#)
HFA-01L	177 - 8.5 * Log((1 / VS.UNFRM(0, 1, 1)) - 1#)
HFA-01S	177 - 8.5 * Log((1 / VS.UNFRM(0, 1, 1)) - 1#)
HFA-02	VS.RNORM(104, 11.8, 1)
HFA-03	41.9 + 1# / VS.GAMA(0.00062, 45.8, 1)
HFA-04	-161 + 1# / VS.GAMA(0.00000329, 1150#, 1)
HFA-05	VS.TRIAG(37.8, 53.9, 55.9, 1)
HFA-07	1.85 + VS.RLOGN(29.4, 2.29, 1)
HFA-08	VS.UNFRM(13.4, 20.7, 1)

APPENDIX C: SAMPLE VISUAL BASIC CODING PERTAINING TO THE DIFFERENT AREAS OF THE AWESIM® NETWORK

C.1 Model selection code

```
Private Sub ModelSelection(ent As VSENTITY)
  Dim RandNum As Double, Model_Number As String

  RandNum = VS.UNFRM(0, 1, 1)

    With ent
      Select Case RandNum
      Case 0 To 0.12: Model_Number = AT272
      Case 0.12 To 0.341:  Model_Number = AT472
      Case 0.341  To 0.656:  Model_Number = AT496
      Case 0.656 To 0.785:  Model_Number = AT672
      Case 0.785 To 1#:   Model_Number = AT696
      Case Else:  MsgBox "Assigning Models " & RandNum: Stop
      End Select
    End With

  ent.STRIB(1) = Model_Number
  'MsgBox "Model assigned " & Model_Number

End Sub
```

Figure C:1 VB code pertaining to the selection of models to be generated

C.2 Sample code of assigning attributes to the entities

```
Private Sub Assign_HDA01_Attrib(ent As VSENTITY)

 With ent
  Select Case ent.STRIB(1)

   Case AT148: .ATRIB(10) = 0
   Case AT224: .ATRIB(10) = 0
   Case AT272: .ATRIB(10) = 75.8 + 0.104 * VS.GAMA(0.104, 78.6, 1) / VS.GAMA(0.104, 2.25, 1)
   Case AT296: .ATRIB(10) = 82.1 - 1.47 * Log((1 / VS.UNFRM(0, 1, 1)) - 1#)
   Case AT348: .ATRIB(10) = 0
   Case AT372: .ATRIB(10) = 64.1 + 16.2 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 8.83)
   Case AT396: .ATRIB(10) = VS.TRIAG(90.9, 91.5, 101, 1)
   Case AT448: .ATRIB(10) = 40.1 + 38.6 * (1# / VS.UNFRM(0, 1, 1) - 1#) ^ (-1# / 20.4)
   Case AT472: .ATRIB(10) = 87.6 + 1# / VS.GAMA(0.0169, 8.12, 1)
   Case AT496: .ATRIB(10) = 98.8 + VS.ERLNG(2.65, 2, 1)
   Case AT572: .ATRIB(10) = 100 - 2.53 * Log((1 / VS.UNFRM(0, 1, 1)) - 1#)
   Case AT648: .ATRIB(10) = 0
   Case AT672: .ATRIB(10) = 92.7 + VS.ERLNG(3.55, 2, 1)
   Case AT696: .ATRIB(10) = 94 / ((1# - VS.UNFRM(0, 1, 1)) ^ (1# / 29.1))
   Case AT4120: .ATRIB(10) = 0

   Case Else
   MsgBox "AssignAttribs " & ent.STRIB(1)
   Stop

  End Select
 End With

 With ent
  Print #1, Tab(0); .STRIB(1);
  Print #1, Tab(20); Round(.ATRIB(10), 4);
 End With

End Sub
```

Figure C:2 VB code pertaining to the assigning of the entities attributes for workstation HDA-01

C.3 Coding of the IMC belt settings to detect attribute of entities

```
Private Function HDASmallConveyorIdleTimeSetting(ent As VSENTITY) As Double

'MsgBox "curetype(2) = " & CurEType(2) & " and curetype(4) = " & CurEType(4)

    If CurEType(2) = "" And CurEType(4) = "" Then
    ent.STRIB(3) = ""

    ElseIf CurEType(2) <> CurEType(4) And CurEType(4) = "" Then
    ent.STRIB(3) = CurEType(2)

    Else
    ent.STRIB(3) = CurEType(4)

    End If

    'MsgBox "Strib(3)= " & ent.STRIB(3)

      Select Case ent.STRIB(3)

        Case AT148: HDASmallConveyorIdleTimeSetting = 15.77
        Case AT224: HDASmallConveyorIdleTimeSetting = 15.77
        Case AT272: HDASmallConveyorIdleTimeSetting = 15.77
        Case AT296: HDASmallConveyorIdleTimeSetting = 15.77
        Case AT348: HDASmallConveyorIdleTimeSetting = 18.08
        Case AT372: HDASmallConveyorIdleTimeSetting = 18.08
        Case AT396: HDASmallConveyorIdleTimeSetting = 18.08
        Case AT448: HDASmallConveyorIdleTimeSetting = 20.81
        Case AT472: HDASmallConveyorIdleTimeSetting = 20.81
        Case AT496: HDASmallConveyorIdleTimeSetting = 28.08
        Case AT572: HDASmallConveyorIdleTimeSetting = 28.08
        Case AT648: HDASmallConveyorIdleTimeSetting = 28.08
        Case AT672: HDASmallConveyorIdleTimeSetting = 28.08
        Case AT696: HDASmallConveyorIdleTimeSetting = 28.08
        Case AT4120: HDASmallConveyorIdleTimeSetting = 28.08
        Case Else: HDASmallConveyorIdleTimeSetting = 0

      End Select

End Function
```

Figure C:3 VB code pertaining to the logic of setting the IMC belt settings

C.4 Line selection coding

```
Private Function HDALineSelection(ent As VSENTITY) As Long
Dim NuminLineOne As Integer
Dim NuminLineTwo As Integer
Dim RandNum As Double: RandNum = VS.UNFRM(0, 1, 1)
Dim i As Long

NuminLineOne = 0
NuminLineTwo = 0

   For i = 7 To 15 Step 2
     NuminLineOne = NuminLineOne + VS.NNQ(i)
   Next

   For i = 40 To 79
     NuminLineOne = NuminLineOne + VS.NNQ(i)
   Next

   For i = 60 To 99
     NuminLineOne = NuminLineOne + VS.NNACT(i)
   Next

     NuminLineOne = NuminLineOne + VS.NNQ(16) + VS.NNQ(37) + VS.NNQ(120) + VS.NNQ(121) +
VS.NNQ(140) + VS.NNQ(145) + VS.NNQ(146) + VS.NNQ(147) + VS.NNQ(160) + VS.NNACT(3) +
VS.NNACT(5) + VS.NNACT(9) + VS.NNACT(11) + VS.NNACT(13) + VS.NNACT(50) +
VS.NNACT(51) + VS.NNACT(52)


   For i = 6 To 14 Step 2
     NuminLineTwo = NuminLineTwo + VS.NNQ(i)
   Next

   For i = 80 To 108
     NuminLineTwo = NuminLineTwo + VS.NNQ(i)
   Next

   For i = 100 To 128
     NuminLineTwo = NuminLineTwo + VS.NNACT(i)
   Next

     NuminLineTwo = NuminLineTwo + VS.NNQ(17) + VS.NNQ(38) + VS.NNQ(123) + VS.NNQ(141) +
VS.NNQ(161) + VS.NNQ(148) + VS.NNQ(149) + VS.NNACT(4) + VS.NNACT(6) + VS.NNACT(10) +
VS.NNACT(12) + VS.NNACT(14) + VS.NNACT(55) + VS.NNACT(56)


   'MsgBox "There are " & NuminLineOne & " entities in line One and " & NuminLineTwo & " in line
Two"

     If ent.STRIB(1) = CurEType(9) Then
       HDALineSelection = 140 '// select line with queue 140

     ElseIf ent.STRIB(1) = CurEType(10) Then
       HDALineSelection = 141 '// select line with queue 141
```

```
    Else
      Select Case (NuminLineOne - NuminLineTwo)

      Case Is < 0
        HDALineSelection = 140

      Case Is = 0

        Select Case RandNum ' This will randomly select the line on a 50-50 chance
          Case Is < 0.5: HDALineSelection = 140 ' This will send entities to queue with file # 140
          Case 0.5: MsgBox "Random number came out to be 0.5 on the dot in line selector"
          Case Is > 0.5: HDALineSelection = 141 ' This will send entities to queue with file # 141
        End Select

      Case Else
        HDALineSelection = 141

      End Select

    End If

    'MsgBox "Sending Product " & ent.STRIB(1) & " to queue: " & HDALineSelection

End Function
```

Figure C:4 VB code pertaining to the logic of the line selection rule

APPENDIX D: AWESIM NETWORK (8 SECTIONS)

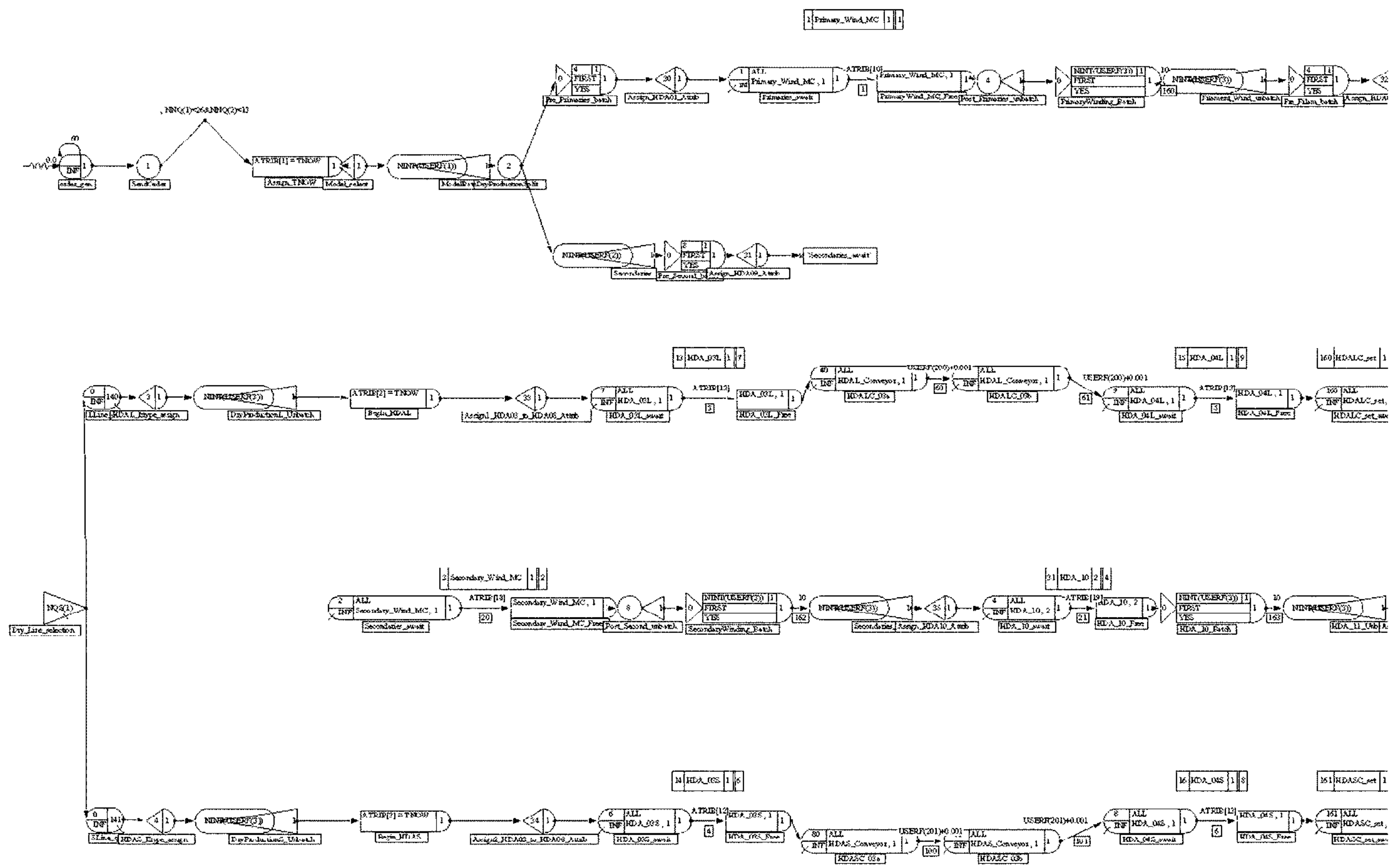

Figure D:1 Section 1 of BASECASE network

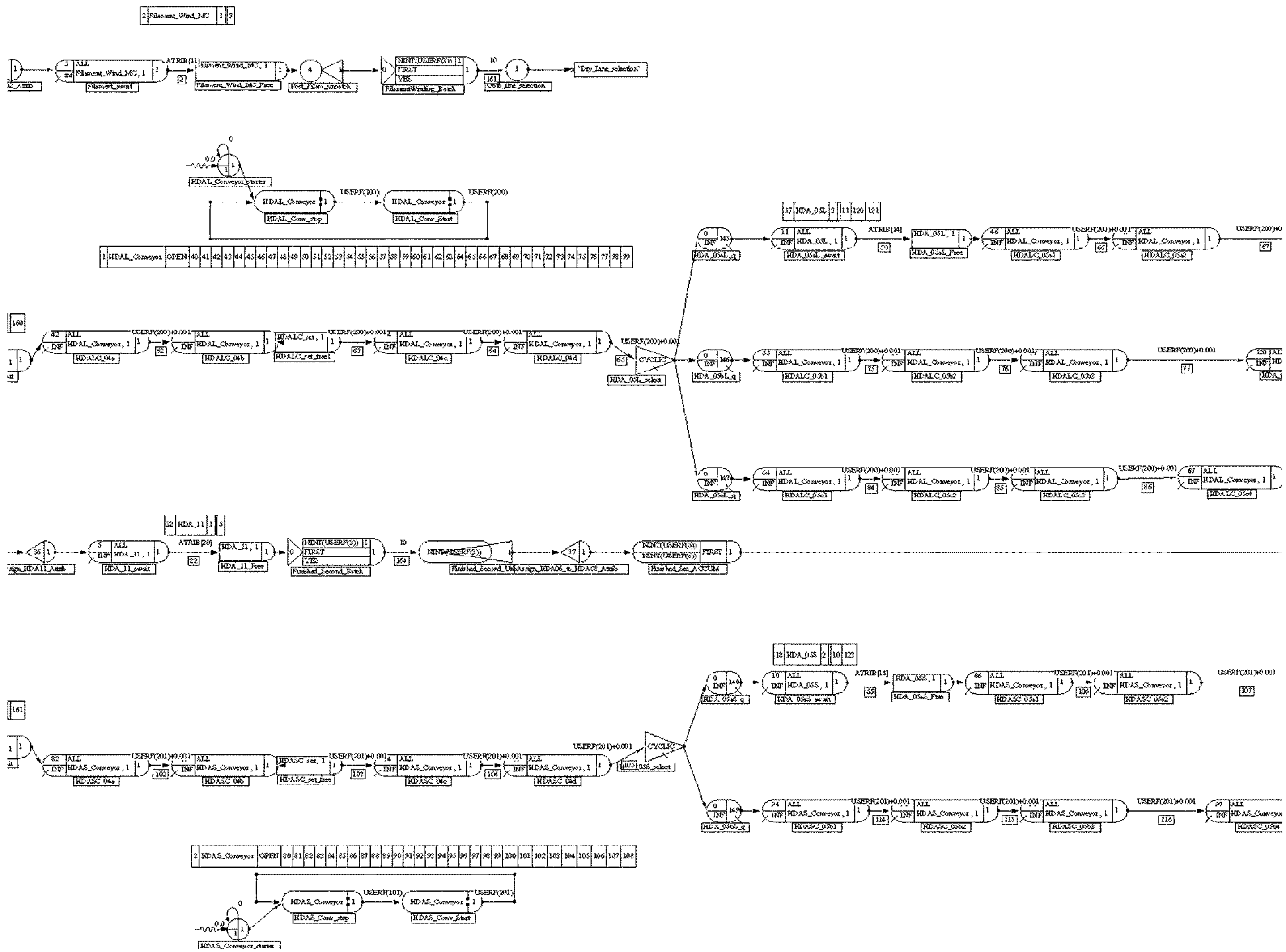

Figure D:2 Section 2 of BASECASE network

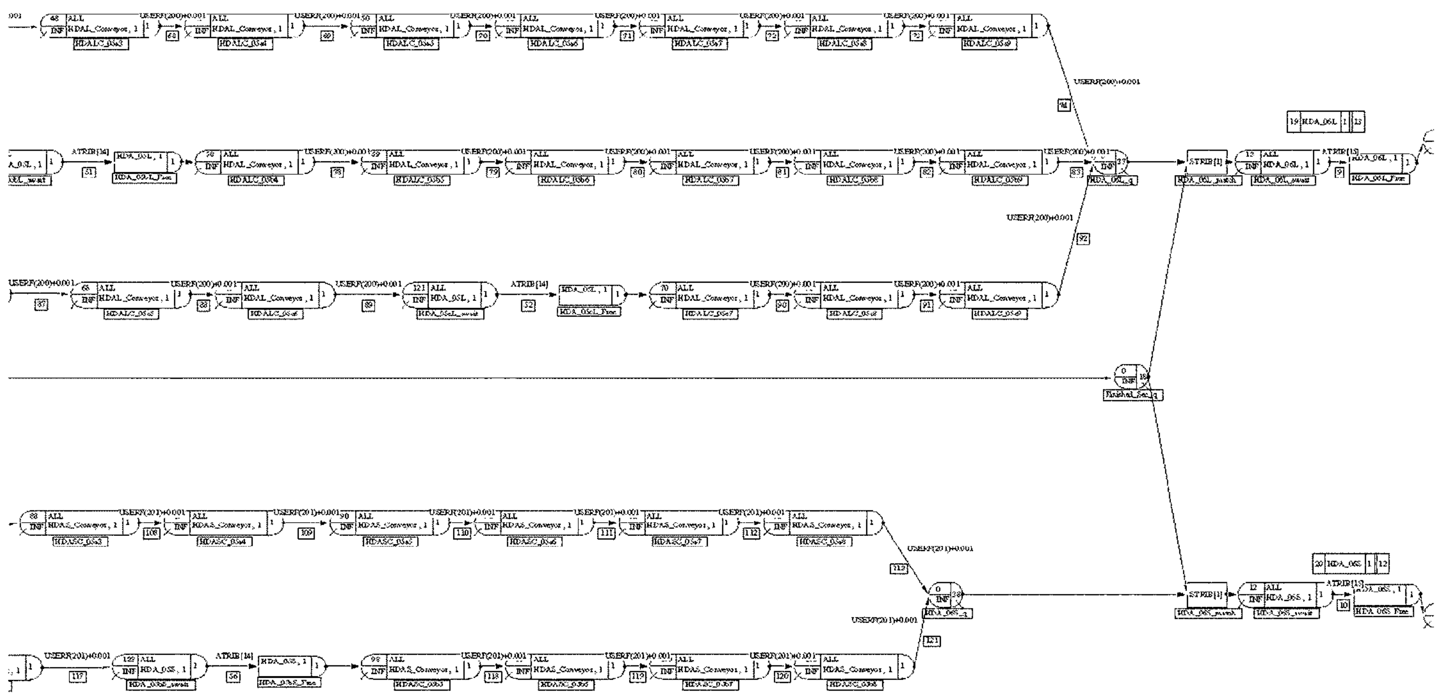

Figure D:3 Section 3 of BASECASE network

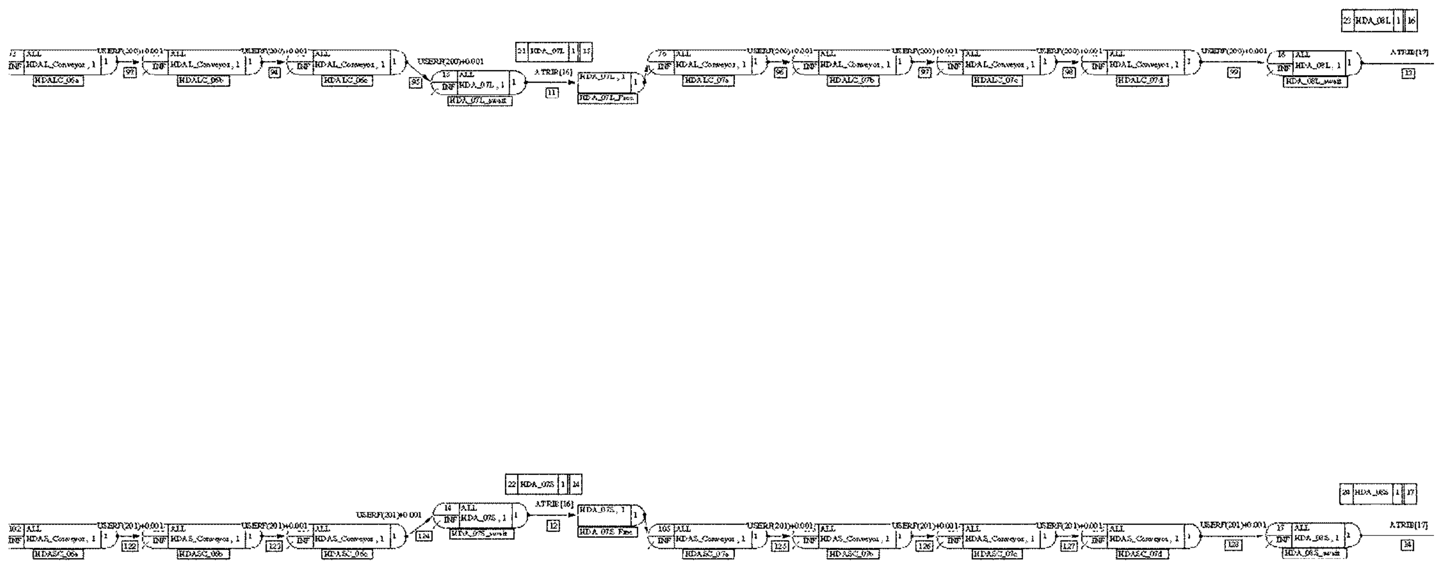

Figure D:4 Section 4 of BASECASE network

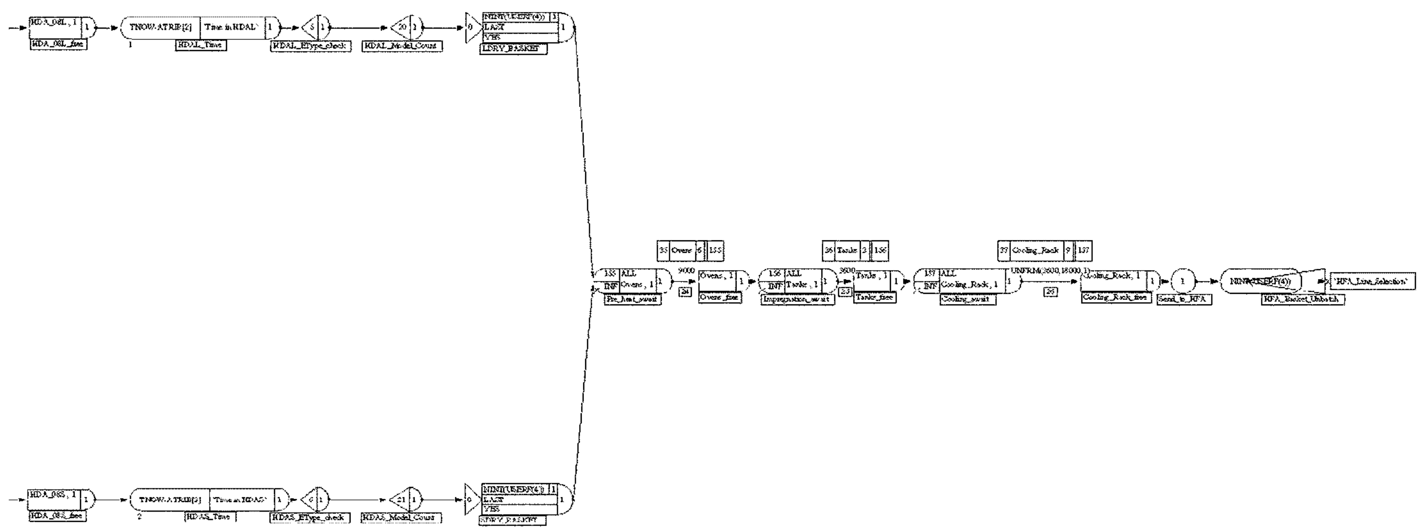

Figure D:5 Section 5 of BASECASE network

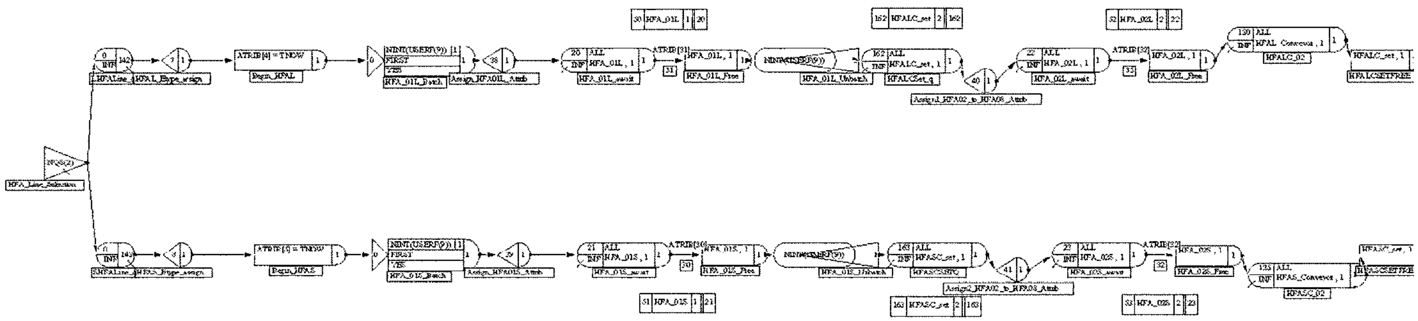

Figure D:6 Section 6 of BASECASE network

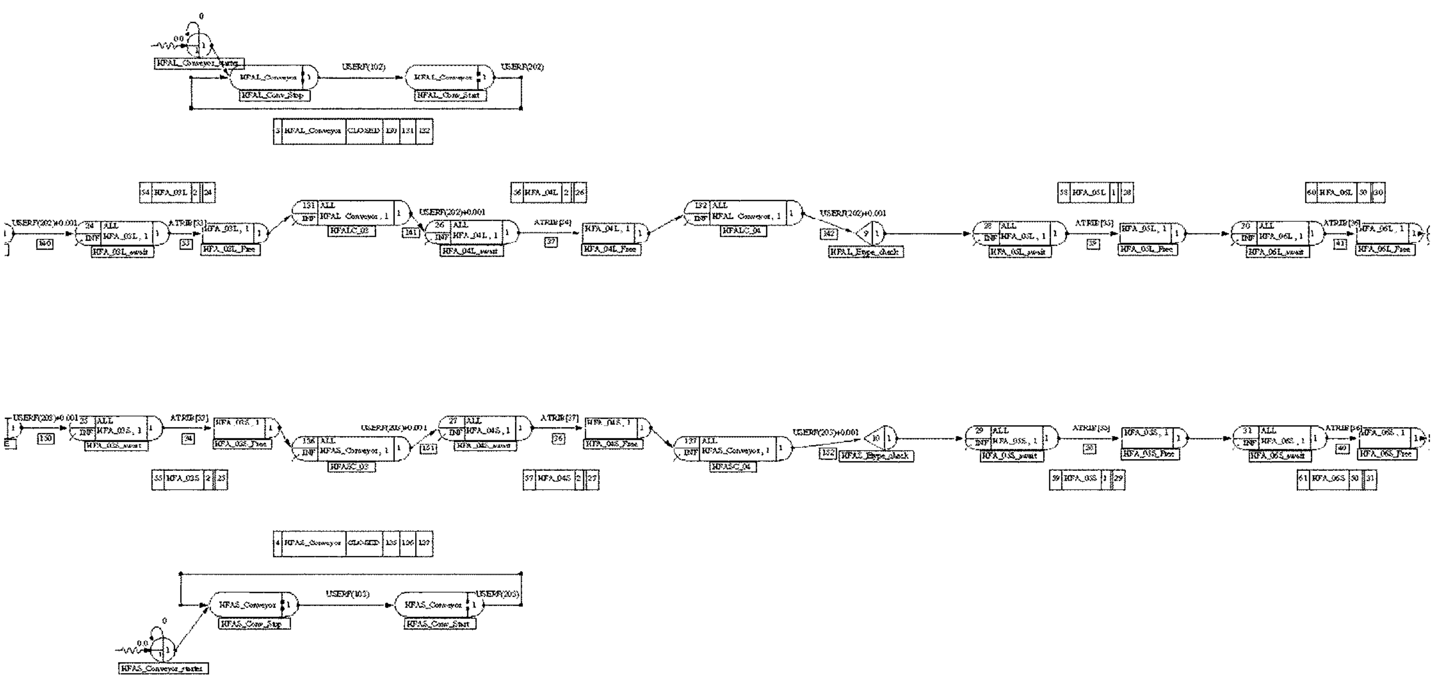

Figure D:7 Section 7 of BASECASE network

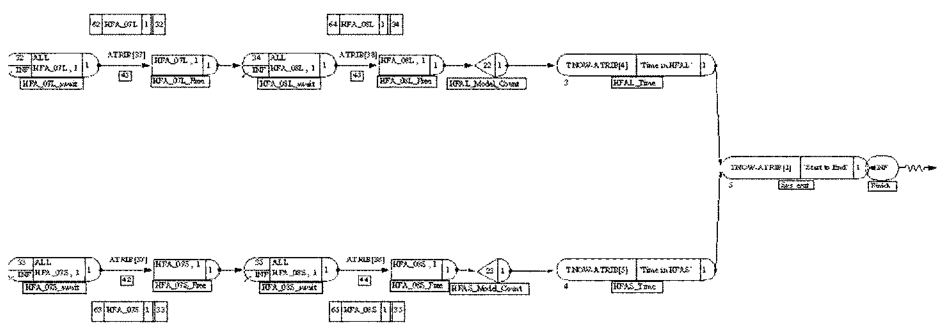

Figure D:8 Section 8 of BASECASE network

APPENDIX E: SAMPLE OF PARAMETER ESTIMATION CALCULATIONS PER SCENARIO

E.1 SALHDA scenario parameter estimation in regards to the mean flow time

Mean Flow Time

Model 272-AT

Mean Flow Time – Run 1	2	3	4	5	6	7	8	Average	Std. dev.	Sim Accuracy Seconds	Estimate of the min. number of runs 100(1-α)% Confidence Interval 95	Interval Estimation θ ± tα/2,fσ(θ) 100(1-α)% Confidence Interval 95 LH	RH
5400.182	5416.378	5416.804	5416.804	5417.017	5415.526	5417.656	5417.017	5414.673	5.887	30	0	5400.753	5428.593

Run length and new Time to clear statistics (100(1-α)% 95)

Ro =	To =	T = To + Te	Accuracy =	No. of Runs (R) =	New Run Length = (R/Ro)(To+Te)	New To = (R/Ro)(To)
8	3600	7200	30	3	2700	1350

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
0	#NUM!	#NUM!
1	#NUM!	#NUM!
2	12.7061503	6.21678272
3	4.302655725	0.712870934
4	3.182449291	0.389996489

Model 472-AT

Mean Flow Time – Run 1	2	3	4	5	6	7	8	Average	Std. dev.	Sim Accuracy Seconds	Estimate of the min. number of runs 100(1-α)% Confidence Interval 95	Interval Estimation θ ± tα/2,fσ(θ) 100(1-α)% Confidence Interval 95 LH	RH
5395.708	5384.086	5383.788	5383.193	5383.193	5383.491	5382.598	5383.788	5384.981	4.359	30	0	5374.673	5395.288

Run length and new Time to clear statistics (100(1-α)% 95)

Ro =	To =	T = To + Te	Accuracy =	No. of Runs (R) =	New Run Length = (R/Ro)(To+Te)	New To = (R/Ro)(To)
8	3600	7200	30	3	2700	1350

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
0	#NUM!	#NUM!
1	#NUM!	#NUM!
2	12.7061503	3.408533503
3	4.302655725	0.390852402
4	3.182449291	0.213827016

Model 496-AT

Mean Flow Time										Sim Accuracy	Estimate of the min. number of runs	Interval Estimation θ ± tα/2,fσ(θ)	
Run											100(1-α)% Confidence Interval	100(1-α)% Confidence Interval 95	
1	2	3	4	5	6	7	8	Average	Std. dev.	Seconds	95	LH	RH
5392.81	5383.557	5382.223	5380.89	5381.779	5383.112	5380.89	5381.779	5383.380	3.926	30	0	5374.097	5392.663

Run length and new Time to clear statistics

Ro =	To =	T = To + Te	Accuracy =	No. of Runs (R) =	New Run Length = (R/Ro)(To+Te)	New To = (R/Ro)(To)
8	3600	7200	30	3	2700	1350

100(1-α)% 95

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
0	#NUM!	#NUM!
1	#NUM!	#NUM!
2	12.7061503	2.764915861
3	4.302655725	0.317049548

Model 672-AT

Mean Flow Time										Sim Accuracy	Estimate of the min. number of runs	Interval Estimation θ ± tα/2,fσ(θ)	
Run											100(1-α)% Confidence Interval	100(1-α)% Confidence Interval 95	
1	2	3	4	5	6	7	8	Average	Std. dev.	Seconds	95	LH	RH
5381.779	5380.001	5380.001	5379.557	5380.001	5380.001	5380.001	5380.001	5380.168	0.669	30	0	5378.585	5381.750

Run length and new Time to clear statistics

Ro =	To =	T = To + Te	Accuracy =	No. of Runs (R) =	New Run Length = (R/Ro)(To+Te)	New To = (R/Ro)(To)
8	3600	7200	30	2	1800	900

100(1-α)% 95

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
0	#NUM!	#NUM!
1	#NUM!	#NUM!
2	12.7061503	0.080363731
3	4.302655725	0.009215212

Model 696-AT

Mean Flow Time Run 1	2	3	4	5	6	7	8	Average	Std. dev.	Sim Accuracy Seconds	Estimate of the min. number of runs 100(1-α)% Confidence Interval 95	Interval Estimation θ ± tα/2,fσ(θ) 100(1-α)% Confidence Interval 95 LH	RH
5391.921	5380.001	5380.001	5380.001	5380.001	5380.001	5380.001	5380.001	5381.491	4.214	30	0	5371.526	5391.456

100(1-α)%

95

Run length and new Time to clear statistics

Ro =	To =	T = To + Te	Accuracy =	No. of Runs (R) =	New Run Length = (R/Ro)(To+Te)	New To = (R/Ro)(To)
8	3600	7200	30	3	2700	1350

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
0	#NUM!	#NUM!
1	#NUM!	#NUM!
2	12.7061503	3.186016283
3	4.302655725	0.365336623

E.2 SALHFA scenario calculations in regards to number of parts produced

PARTS

Model 272-AT

Total parts produced											Estimate of the min. number of runs	Interval Estimation θ ± tα/2,fσ(θ) 100(1-α)% Confidence Interval	
Run										Sim Accuracy	100(1-α)% Confidence Interval	95	
1	2	3	4	5	6	7	8	Average	Std. dev.	Parts	95	LH	RH
81	80	80	80	80	80	80	80	80.125	0.354	2	0	79.289	80.961

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
0	#NUM!	#NUM!
1	#NUM!	#NUM!
2	12.7061503	5.045195483
3	4.302655725	0.578526447

Run length and new Time to clear statistics					100(1-α)% 95	
Ro =	To =	T = To + Te	Accuracy =	No. of Runs (R) =	New Run Length = (R/Ro)(To+Te)	New To = (R/Ro)(To)
8	3600	7200	2	3	2700	1350

Model 472-AT

Total parts produced											Estimate of the min. number of runs	Interval Estimation θ ± tα/2,fσ(θ) 100(1-α)% Confidence Interval	
Run										Sim Accuracy	100(1-α)% Confidence Interval	95	
1	2	3	4	5	6	7	8	Average	Std. dev.	Parts	95	LH	RH
70	71	69	71	70	70	71	71	70.375	0.744	2	0	68.616	72.134

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
0	#NUM!	#NUM!
1	#NUM!	#NUM!
2	12.7061503	22.34300857
3	4.302655725	2.562045692

Run length and new Time to clear statistics					100(1-α)% 95	
Ro =	To =	T = To + Te	Accuracy =	No. of Runs (R) =	New Run Length = (R/Ro)(To+Te)	New To = (R/Ro)(To)
8	3600	7200	2	3	2700	1350

Model 496-AT

												Interval Estimation θ ± tα/2,fσ(θ)	
		Total parts produced									Estimate of the min. number of runs	100(1-α)% Confidence Interval	
		Run								Sim Accuracy	100(1-α)% Confidence Interval	95	
1	2	3	4	5	6	7	8	Average	Std. dev.	Parts	95	LH	RH
66	67	66	65	66	69	67	68	66.750	1.282	2	1	63.719	69.781

Run length and new Time to clear statistics					100(1-α)%	
					95	
Ro =	To =	T = To + Te	Accuracy =	No. of Runs (R) =	New Run Length = (R/Ro)(To+Te)	New To = (R/Ro)(To)
8	3600	7200	2	5	4500	2250

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
1	#NUM!	#NUM!
2	12.7061503	66.3082835
3	4.302655725	7.60349044
4	3.182449291	4.159707504
5	2.776450856	3.166064735

Model 672-AT

												Interval Estimation θ ± tα/2,fσ(θ)	
		Total parts produced									Estimate of the min. number of runs	100(1-α)% Confidence Interval	
		Run								Sim Accuracy	100(1-α)% Confidence Interval	95	
1	2	3	4	5	6	7	8	Average	Std. dev.	Parts	95	LH	RH
54	53	54	54	54	54	55	54	54.000	0.535	2	0	52.736	55.264

Run length and new Time to clear statistics					100(1-α)%	
					95	
Ro =	To =	T = To + Te	Accuracy =	No. of Runs (R) =	New Run Length = (R/Ro)(To+Te)	New To = (R/Ro)(To)
8	3600	7200	2	3	2700	1350

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
0	#NUM!	#NUM!
1	#NUM!	#NUM!
2	12.7061503	11.53187539
3	4.302655725	1.322346163

Model 696-AT

Total parts produced – Run 1	2	3	4	5	6	7	8	Average	Std. dev.	Sim Accuracy Parts	Estimate of the min. number of runs 100(1-α)% Confidence Interval 95	Interval Estimation θ ± tα/2,fσ(θ) 100(1-α)% Confidence Interval 95 LH	RH
54	54	54	54	54	54	54	54	54.000	0.000	2	0	54.000	54.000

100(1-α)%

95

Run length and new Time to clear statistics

Ro =	To =	T = To + Te	Accuracy =	No. of Runs (R) =	New Run Length = (R/Ro)(To+Te)	New To = (R/Ro)(To)
8	3600	7200	2	2	1800	900

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
0	#NUM!	#NUM!
1	#NUM!	#NUM!
2	12.7061503	0
3	4.302655725	0

D.3 BASECASE scenario calculations in regards to truncation method

Average Processing Time

Batch (*j*)	Simulation Interval (sec.)	Run C1355547	C1402721	C1556671	C806622	C9684360	CJAN03	Average	0-Truncate Cumulative Mean	1-Truncate Cumulative Mean	2-Truncate Cumulative Mean	3-Truncate Cumulative Mean	4-Truncate Cumulative Mean	5-Truncate Cumulative Mean	6-Truncate Cumulative Mean
	0-12000	-	-	-	-	-	-	-							
	12001-24000	-	-	-	-	-	-	-							
1	24001-36000	32010.185	34049.679	33233.588	33328.175	33737.808	33629.101	33331.423	33331.423						
2	36001-48000	37871.627	40032.939	38355.466	39316.018	38672.132	39559.798	38967.997	36149.710	38967.997					
3	48001-60000	44997.629	46069.506	42682.623	45043.619	46131.782	42933.619	44643.130	38980.850	41805.563	44643.130				
4	60001-72000	51408.403	47971.043	45872.591	48063.094	51395.994	46341.511	48508.773	41362.830	44039.966	46575.951	48508.773			
5	72001-84000	54404.331	50532.329	47885.344	52709.345	53792.815	51292.083	51769.375	43444.139	45972.318	48206.252	50139.074	51769.375		
6	84001-96000	55814.300	50879.534	54360.856	54014.673	54029.760	51261.479	53393.434	45102.355	47456.541	49018.282	50951.103	52581.404	53393.434	
7	96001-108000	58711.155	53934.679	54021.765	54791.806	55309.865	51802.808	54762.013	46482.306	48674.120	49702.571	51635.393	53265.694	54077.723	54762.013
8	108001-120000	61627.133	53619.751	54553.548	56066.828	56815.212	54517.539	56200.002	47697.018	49749.246	50421.566	52354.387	53984.688	54796.718	55481.007
9	120001-132000	61872.071	53930.735	57732.930	57332.156	59959.585	55274.440	57683.653	48806.644	50741.047	51163.391	53096.213	54726.514	55538.543	56222.833
10	132001-144000	62652.146	54382.940	58336.250	59284.843	59413.778	56653.831	58453.965	49771.376	51598.038	51548.547	53481.369	55111.670	55923.699	56607.989
11	144001-156000	64411.329	55572.049	58194.633	61400.968	60756.359	59098.824	59905.694	50692.678	52428.803	52274.412	54207.233	55837.534	56649.564	57333.853
12	156001-168000	66324.999	57360.541	58478.379	62218.417	61459.459	61258.939	61183.456	51566.909	53224.681	52913.293	54846.114	56476.415	57288.445	57972.734
13	168001-180000	65801.364	58875.915	58957.726	62361.083	61169.242	62782.672	61658.000	52343.147	53927.457	53150.565	55083.387	56713.687	57525.717	58210.007
14	180001-192000	67040.316	59801.425	59234.856	65854.468	60763.766	62598.755	62548.931	53072.132	54590.648	53596.030	55528.852	57159.153	57971.182	58655.472
15	192000-204000	67032.594	61096.897	59351.849	66329.984	61980.739	63361.524	63192.265	53746.807	55205.049	53917.697	55850.519	57480.820	58292.849	58977.139
16	204001-216000	67088.124	62197.262	60460.053	66534.634	62592.657	64350.615	63870.558	54379.542	55782.749	54256.844	56189.665	57819.966	58631.996	59316.285
17	216001-228000	67490.046	63791.425	60121.156	67354.937	63059.495	64431.611	64374.778	54967.497	56319.751	54508.954	56441.776	58072.076	58884.106	59568.396
18	228001-240000	68893.742	65311.622	60064.433	67717.041	63627.074	64010.521	64937.406	55521.380	56826.672	54790.268	56723.089	58353.390	59165.420	59849.709
19	240001-252000	68524.591	64994.471	60513.839	67588.872	64984.915	64036.48	65107.195	56025.897	57286.701	54875.162	56807.984	58438.285	59250.314	59934.604
20	252001-264000	68525.046	65308.698	60578.366	67898.095	66818.056	64147.153	65545.902	56501.897	57721.396	55094.516	57027.338	58657.638	59469.668	60153.958
21	264001-276000	69266.469	65946.507	62408.107	68781.484	67412.757	64403.73	66369.842	56971.799	58153.818	55506.486	57439.308	59069.608	59881.638	60565.928
22	276001-288000	70032.346	66252.35	62628.832	68397.705	67603.925	64802.28	66619.573	57410.335	58556.949	55631.351	57564.173	59194.474	60006.503	60690.793
23	288001-300000	70495.527	66734.69	63203.112	68425.57	67412.04	64993.428	66877.395	57821.946	58935.151	55760.262	57693.084	59323.385	60135.414	60819.704
24	300001-312000	70853.606	66845.698	63513.328	69069.619	67710.86	65515.537	67251.441	58214.842	59296.729	55947.285	57880.107	59510.408	60322.438	61006.727
25	312001-324000	70556.185	67001.994	63222.46	69582.731	68827.522	65740.481	67488.562	58585.790	59638.056	56065.846	57998.667	59628.968	60440.998	61125.288
26	324001-336000	70067.423	67909.585	63430.364	69959.671	69335.217	66212.943	67819.201	58940.922	59965.301	56231.165	58163.987	59794.288	60606.317	61290.607
27	336001-348000	69903.162	67964.885	63269.835	69764.318	69039.804	66097.365	67673.228	59264.340	60261.760	56158.179	58091.000	59721.301	60533.331	61217.621
28	348001-360000	70470.571	67988.797	63380.973	69831.758	69118.234	65616.886	67734.537	59566.847	60538.530	56188.833	58121.655	59751.956	60563.985	61248.275
29	360001-372000	70557.285	68367.559	63584.794	70145.625	69191.548	65485.004	67888.636	59853.806	60801.033	56265.883	58198.704	59829.005	60641.035	61325.324
30	372001-384000	70113.127	68002	63885.366	70690.854	69361.348	65858.993	67985.281	60124.855	61048.766	56314.206	58247.027	59877.328	60689.358	61373.647
31	384001-396000	69911.947	68341.503	64116.222	71038.621	69374.061	66219.02	68166.896	60384.275	61286.037	56405.013	58337.834	59968.135	60780.165	61464.454
32	396001-408000	69546.106	68162.55	64209.532	70535.267	69769.84	65936.766	68026.677	60623.100	61503.477	56334.903	58267.725	59898.026	60710.055	61394.345
33	408001-420000	69435.792	68015.89	64649.736	70564.182	69749.411	65998.966	68068.996	60848.734	61708.650	56356.063	58288.884	59919.185	60731.215	61415.505
34	420001-432000	69260.236	68075.126	64825.357	71061.688	69916.595	65734.091	68145.516	61063.345	61903.706	56394.323	58327.144	59957.445	60769.475	61453.764

14-Truncate Average Waiting Time in Replication *r*

Run C1355547	C1402721	C1556671	C806622	C9684360	CJAN03	Average	Std. dev.	Sim Accuracy Seconds
69525.860	66695.401	62740.309	69207.509	67626.598	65241.677	66839.559	2562.057	1200

Estimate of the min. number of runs

100(1-α)% Confidence Interval	95
	12

Interval Estimation θ ± tα/2,fσ(θ)

100(1-α)% Confidence Interval 95

LH	RH
60253.592	73425.526

Run length and new Time to clear statistics

Ro =	To =	T = To + Te	Accuracy =	100(1-α)% 95 No. of Runs (R) =	New Run Length = (R/Ro)(To+Te)	New To = (R/Ro)(To)
6	204000	432000	1200	20	1440000	680000

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
12	2.200986273	22.08258243
13	2.178812792	21.63988882
14	2.16036824	21.27505836
15	2.144788596	20.96931172
16	2.131450856	20.70932004
17	2.119904821	20.48556361
18	2.109818524	20.29109081
19	2.100923666	20.12035962
20	2.093024705	19.96934873
21	2.085962478	19.83481603