Simulation based scheduling of a dynamic and stochastic flexible manufacturing system

by

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Signatures have been redacted for privacy

TABLE OF CONTENTS

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ABSTRACT

Scheduling of a manufacturing system is a complicated task because of its dynamic and stochastic nature. Also, there are numerous possible combinations that can be considered which make scheduling time consuming. Developing a system that generates schedules based in dynamic and stochastic parameters, and using simulation for performance evaluation can help overcome aforementioned problems.

In the following research heuristics have been developed to solve batch size and sequencing problem for an assembly line using simulation with an objective to increase throughput. A simulation model is developed in Arena to study the behavior of assembly line and to evaluate the performance of the heuristics.

CHAPTER 1

INTRODUCTION TO SIMULATION AND SIMULATION BASED SCHEDULING

1.1 Introduction

Simulation is one of the most potent tools available to decision-makers responsible for the design and operation of complex processes and systems. It makes possible the study, analysis and evaluation of situations that would not be otherwise possible. In an increasingly competitive world, simulation has become an indispensable problem solving methodology for engineers, designers and managers.

Scheduling of a manufacturing system is a complicated task because of its dynamic and stochastic nature. Also, there are numerous possible combinations that can be considered which make scheduling time consuming. Developing a system that generates schedules based on dynamic and stochastic parameters, and using simulation for performance evaluation can help overcome aforementioned problems.

In this thesis, heuristics have been developed to solve batch size and sequencing problem for an assembly line using simulation with an objective to increase throughput. A simulation model is developed in Arena (Kelton et al, 2002) to study the behavior of assembly line and to evaluate the performance of the heuristics.

The rest of this chapter explains briefly the simulation of manufacturing systems and the main steps of simulation study followed by an introduction to simulation optimization and simulation based scheduling. Next chapter discusses the methodology followed for the study and simulation of assembly line and optimization of the queuing logic to improve throughput. Chapter 3 gives the description and the background for the simulation based scheduling of the assembly line followed by the methodology, experiments, algorithms and the testing of algorithms. Chapter 4 gives conclusions and the future work.

1.2 Simulation of manufacturing systems

Shannon (1998) defines simulation as *the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and /or evaluating various strategies for the operation of the system.* Thus it is critical that the model be designed in such a way that the model behavior mimics the response behavior of the real system to events that take place over time.

Here the term's *model* and *system* are key components of the definition of simulation. By a *model,* Shannon (1998) means a representation of a group of objects or ideas in some form other than that of the entity itself. By a *system* he means a group or collection of interrelated elements that cooperate to accomplish some stated objective. One of the real strengths of simulation is the fact that we can simulate systems that already exist as well as those that are capable of being brought into existence, i.e. those in the preliminary or planning stage of development.

Manufacturing systems is one of the largest application areas for simulation modeling, with the first uses dating back to at least the early 1960's. Law and McComas (1998) present an overview of the use of simulation in the design and analysis of manufacturing systems. Detailed discussions of simulation of manufacturing systems may be found in Banks, Carson, and Nelson (1996) and Law and Kelton (1991). A discussion of the steps that can be used for the simulation of manufacturing systems is given in Law and McComas (1990).

1.3 Structure of a simulation study

Simulation study incorporates the following main steps (Banks et.al., 2001):

- Problem formulation
- Setting the objectives and overall project plan
- Model conceptualisation
- Data collection
- Validating the conceptual model
- Model translation
- Verification, validation and accreditation

- Experimental design
- Production runs
- Output analysis
- Documentation, implementation and reporting

Main steps of a simulation study are described below:

1. *Problem identification and definition:* A problem to be solved should be identified and defined. Sadowski and Grabau (2000) cautions that the biggest mistake is made at the outset of a simulation study. If the wrong problem has been picked by an organization to be explored with simulation, there is a high risk of failure even before first mouse click.

2. *Setting objectives and overall project plan.* Objectives of the study should be specified very clearly. The overall plan for reaching these objectives includes identifying involved people, resources available, used methodology, parameters to be varied and alternatives to be tested, calendar planning, etc.

3. *Building a conceptual model:* The system to be studied is distinguished from its environment. Decisions about the level of detail to be included are made. The main elements of the system are evaluated and their relations identified. Various parameters and variables are defined and assumptions made.

4. *Data collection:* Collecting data on the appropriate elements of the system of interest is one of the initial and pivotal steps in successful input modeling. Even a very well developed model cannot give close-to-reality results, if its input data differ from what is present in reality. Statistical considerations should be taken into account, when describing random factors, e.g., random variables. (Groumpos and Merkuryev, 2002).

5. *Validating the conceptual model.* Here the simulation team comes together in order to discuss decisions made about the conceptual model and descriptions of input data. For instance, types of probability distributions, used to describe random input variables, have to be discussed. (Groumpos and Merkuryev, 2002).

6. *Model translation* means implementing the conceptual model in the form of a corresponding software program. The resulted program is actually what is called "a simulation model". A choice between using general software tools and special simulation tools (e.g., simulation languages (like GPSS/H (Schriber, 1991)) or systems (like Arena (Kelton et al, 2002))) should be made at this stage. (Groumpos and Merkuryev, 2002).

7. *Verification, validation and accreditation of the simulation models:* Balci (1998) presents 15 guiding principles for conducting model verification, validation and accreditation. He describes

Model Verification as substantiating that the model is transformed from one form into another, as intended, with sufficient accuracy. Model verification deals with building the model *right*. The accuracy of transforming a problem formulation into a model specification or the accuracy of converting a model representation from a micro flowchart form into an executable computer program is evaluated in model verification.

Model Validation is substantiating that the model, within its domain of applicability, behaves with satisfactory accuracy consistent with the modeling and simulation objectives. Model validation deals with building the *right* model. An activity of accuracy assessment can be labeled as verification or validation based on an answer to the following question: In assessing the accuracy, is the model behavior compared with respect to the corresponding system behavior through mental or computer execution? If the answer is "yes" then model validation is conducted; otherwise, it implies that the transformational accuracy is judged implying model verification.

Model Testing is ascertaining whether inaccuracies or errors exist in the model. In model testing, the model is subjected to test data or test cases to determine if it functions properly. "Test failed" implies the failure of the model, not the test. A test is devised and testing is conducted to perform either validation or verification or both. Some tests are devised to evaluate the behavioral accuracy (i.e., validity) of the model, and some tests are intended to judge the accuracy of model transformation from one form into another (verification).

Accreditation is "the official certification that a model or simulation is acceptable for use for a specific purpose."

Sargent (2000) also discusses verification, validation, and accreditation of simulation models. The different approaches to deciding model validity are presented; how model verification and validation relate to the model development process are discussed; various validation techniques are defined; conceptual model validity, model verification, operational validity, and data validity are described; ways to document results are given; a recommended procedure is presented; and accreditation is also briefly discussed.

Robinson (1997) discusses various forms of verification and validation depending upon the phase of the simulation study. He also discusses the difficulties in verification and validation and series of methods for verification and validation are described.

8. *Design experiments:* This means planning experiments with the simulation model. Choosing values of model parameters to be investigated or tuned, deciding about alternatives to be compared by simulation, etc. It is performed in the same way, as it would be done, planning experiments with a real system

(e.g., using a full factorial design or fractional factorial design). Typical questions to be answered at this stage are the following: How many simulation runs should be performed for each experiment? Which kind of model behaviour should be evaluated: transient or steady state? In the last case, how shall we deal with the warm-up period? Do we need to take into account correlation in simulation results? Then the simulation experiments are performed. (Groumpos and Merkuryev, 2002).

9. *Make production runs:* If necessary, additional experiments are performed (e.g., if it is necessary to achieve a higher preciseness of simulation results: to get narrower confidence intervals for evaluated values, etc.) (Groumpos and Merkuryev, 2002).

10. *Output analysis:* At this stage we interpret the results of the simulation study and make decisions based on those results. Goldsman and Tokol (2000) give the statistical analysis of output from discrete-event computer simulations. They discuss problems involving terminating simulations, the initialization of simulations, steady-state point and confidence interval estimation for various system parameters, and comparison among competing system designs. Their purpose is to give practical methods to perform statistical analysis of output from discrete-event computer simulations. Sanchez (2001) also gives brief overview of several of the basic output analysis techniques for evaluating stochastic

dynamic simulations. The author discusses how to avoid common pitfalls that may lead to erroneous results and faulty conclusions.

11. Document, present and implement results: Since simulation models are most often used for more than one application, it is very important to document assumptions that went into the model and the computer program. Finally, the study whose results are not implemented is most likely a failure and the results from a highly credible model are much likely to be used. (Law and Kelton, 1991)

1.4 Simulation Optimization: Introduction and literature review

Carson and Maria (1997) define Simulation Optimization as the process of finding the best-input variable values from among all possibilities without explicitly evaluating each possibility. The objective of simulation optimization is to minimize the resources spent while maximizing the information obtained in a simulation experiment.

Jacobson, Schruben, Swisher and Hyden (2000) give the survey of techniques and procedures of simulation optimization. Swisher et al. (2000) provides a more comprehensive review of this topic while Jacobson and Schruben (1989) covers the literature preceding 1988. Several excellent surveys have been written on this topic. Ólafsson and Kim (2002) present introduction to simulation optimization and many known techniques to solve these problems. Fu (2001) gives introduction to simulation optimization, presents motivating and illustrative examples, summarizes most of the major approaches and briefly describes some software implementations. Azadivar (1999) provides a survey of issues specific to simulation optimization. Andradottir (1998a,b) also presents a review of simulation optimization techniques, focusing on both gradient estimation techniques (for continuous input parameters) and random search methods (for discrete input parameters). Carson and Maria (1997) present a general summary of simulation optimization. Fu (1994a,b) provides a comprehensive review of simulation optimization and simulation gradient estimation techniques. Vysypkov et al. (1994) classify and analyze different situations in simulation model optimization and suggest appropriate search algorithms. Gaivoronski (1992) offers a survey of recent results on the optimization of stochastic discrete event dynamic systems.

Safizadeh (1990) contributes a general survey of simulation optimization techniques and procedures. Park (1990) provides an overview of simulation optimization techniques, including a discussion of methods appropriate to uni-modal and multi-modal objective functions. Glynn (1989) discusses research issues associated with optimizing simulated systems, including convergence rates for different gradient estimators and stochastic approximation (SA) algorithms.

1.5 Scheduling using simulation of Flexible Manufacturing Systems: Introduction and literature review

Byrkett et al. (1988) defines Flexible Manufacturing System (FMS) as a manufacturing system in which groups of numerically controlled machines (machine centers) and a Material Handling System (MHS) work together under computer control. O'Keefe and Kasirahan (1992) defines FMS as a group of workstations connected together by a MHS producing or assembling a number of different part types under the central control of a computer. Kaltwasser et al. (1986) stated that FMSs are highly automated production systems, able to produce a great variety of different parts by using the same equipment and same control system.

Chan and Chan (2004) give a comprehensive survey and future trend of simulation study on FMS scheduling. Over the last three decades, scheduling of FMSs has attracted a lot of interest of academic and industrial sectors. The scheduling problems in FMS relate to the execution of production orders and include raw part input sequencing, machine and vehicle scheduling, monitoring system performance and taking corrective actions. Dispatching algorithms are widely used for scheduling in industrial practice. The algorithms are based on various dispatching rules that prioritize the products for assignment to machines and automated guided vehicles.

They have classified scheduling problems as follows:

(1) Parts dispatching problems: To select a part from a queue.

(2) Machine selection problems: To select the next machine to process a part.

(3) AGV scheduling problems: To select AGV for transportation or the routing of AGV.

(4) Operation (process) selection problems: To select the next operation of a part to be processed.

(5) Others: Since FMS is a very complex system.

Chan and Chan (2004) also review simulation of FMS scheduling studies based on three scheduling approaches:

1. Single criterion scheduling problems:

In a single criterion scheduling problem, only one performance measure is evaluated against various scheduling rules. The objective is usually to maximize or minimize the selected criterion. Stecke and Solberg (1981) carried out a simulation study of an FMS at the Caterpillar Tractor Company to show the impact of several machine-sequencing rules on the performance of the FMS under different loading objectives. The model contained 10 machines with two carts to transport parts. They concluded that scheduling rules have significant effect on the performance of the FMS and some rules that were known to be superior in a conventional job shop performed poorly in the FMS. They also demonstrated that the set of best performing scheduling rules varied with the performance measures. It means that there was no single scheduling rule that outperforms the others for all performance measures.

Spano et al. (1993) reviewed the work done on the design of FMSs in the areas of facilities design, MHS design, control system design, and scheduling. Rachamadugu and Stecke (1994) classified and reviewed the existing FMSs scheduling procedures. Their classification was based on some key factors such as the FMS type, the mode of system operation, the nature of the demands placed on the system, the scheduling environment, and the responsiveness of the system subjected to disturbance. They also discussed the choice of appropriate scheduling criteria.

Basnet and Mize (1994) reviewed the literature concerning the operations aspect of FMS. They described scheduling methodology under six different categories: mathematical programming, multi-criteria decision-making, heuristic oriented, control theoretic, simulation and artificial intelligence. They concluded that discrete event simulation technique has a great potential to make major contributions to FMS operation and stressed that simulation can be used to model FMSs quite comprehensively.

Gupta et al. (1990) extended the review to cover simulation approaches to the FMS scheduling problems as well as analytical ones. They pursued two objectives:

(1) Developing a framework within which the current literature on dispatching rules can be discussed.

(2) Comparing the developed list of dispatching rules and performance criteria from the surveyed literature.

Buzacott and Yao (1986) presented a comprehensive review of the analytical models developed for the design and scheduling of FMS. They strongly advocated analytical methods as giving better insight into the system performance than simulation models. Chan and Chan (2004) give an extensive summary table of publications on scheduling problems in single criterion environment. They conclude that 28 out of the 40 (that is 70%) of published papers dealt with part dispatching scheduling problems. Very few of them considered machine selection, AGV scheduling, and operation (process) selection problems. On the other hand, 23 researches (more than 50%) employed less than four performance measures. This is probably due to the fact that in a single criterion environment, the more performance measures (e.g. flow time, utilization, throughput, etc.), the more complex the system to be considered. They also conclude that the investigation on FMS scheduling problems in the single criterion environment was most popular from the late 1980s to the early 1990s and that one of the shortcomings of these researches is that no single rule can be found as the best rule in different models.

2. Multi-criteria scheduling approaches:

Mutli-criteria decision-making is employed in a multi-criteria environment such that different criteria are considered at the same time in order to find the pseudo optimal solution, rather than finding the best solution for particular criterion. Lee and Jung (1989) developed a formulation for part selection and allocation problems using goal programming. Their model considered the goal of meeting production requirements, balancing of machine utilization and minimization of throughput time of parts. Decision-makers to satisfy their goals and their prioritization could use this kind of goal programming.

Gupta et al. (1991) explored the applicability of multi-criteria approaches to the production scheduling problems of an FMS and reviewed the pertinent literature on scheduling of FMS involving multiple objectives and also discussed following issues:

(1) FMS scheduling problems within the context of a general decision making process.
(2) An overview of multi-criteria decision making approaches and its feasibility to FMS scheduling problems.
(3) The literature of FMS scheduling involving multiple objectives.
(4) The major findings.

The major advantages of multi-criteria decision making technique is that it does not need holistic judgments, thus, it can accommodate the multidimensionality of value and allow the decision makers to evaluate several alternatives with different impacts. It also coincides with one practice of modern decision makers, who prefer to be presented with a range of feasible alternatives rather than one best solution. The aim is to select alternative(s) on the basis of their preference order. The preference order is constructed based on the alternatives' values on the attributes considered. Usually, a function, which is a mathematical representation of the attributes, is constructed to evaluate alternatives by considering different attributes. The implications of the results can provide valuable insights and decision opportunities for major decision-making.

Chan and Chan (2004) again give a comprehensive summary table on multi-criteria scheduling problems in FMS. They again conclude that part dispatching scheduling problem was the most frequently encountered. However, this time the number of performance measures was generally higher than that in a single criterion environment. Seventy percent of the listed papers employed more than three performance measures.

CHAPTER 2

SIMULATION OF THE ASSEMBLY LINE

2.1. Background

The assembly line assembles a family of variable frequency drives. It is highly automated with eleven stations, uses an automated conveyor system, and produces four drive sizes with many different variations. There are throughput problems faced by the assembly line and since the product is in the early stages of its life cycle, improving throughput is critical to future growth to meet the demand objectives. Thus, the assembly line was simulated using Arena (Kelton et al, 2002) with an objective to improve throughput.

This chapter explains the steps used to model assembly line for simulation study and increasing the throughput of assembly line through identification and elimination of bottlenecks caused by the material handling system before proceeding to the scheduling of line.

Many options for improving the material handling system were explored. Throughput was taken as a performance measure and was defined as total number of drives produced in one day comprising of two shifts. In particular, the following options and variations of these options were considered and modeled in Arena (Kelton et al, 2002):

- Optimization of the logic of central conveyor
- Reconfiguration of functional test stations to allow parallel flow
- Recirculation of the pallets
- Elimination of the conveyor and shifting to manual material handling system.

2.2. The assembly line

The assembly line assembles four types of drives or frames, A, B, C and D. The drives are transported from one station to another on pallets through automatic conveyor system. The first station on which a drive is processed is manual assembly station 1 followed by manual assembly station 2 and so on as shown in the figure 2.1. The queuing logics for flash test stations and functional test stations are explained in section 2.3.3. Before the last processing station, packaging, drive is taken off the pallet and the pallet is transported on the conveyor to the first processing station. There are total 48 pallets available.

Manual assembly station 1, manual assembly station 2, soldering, strap station, HIM assembly, verification test and packaging are manual stations and require operators while hipot, flash and functional test stations are automatic and do not require operators.

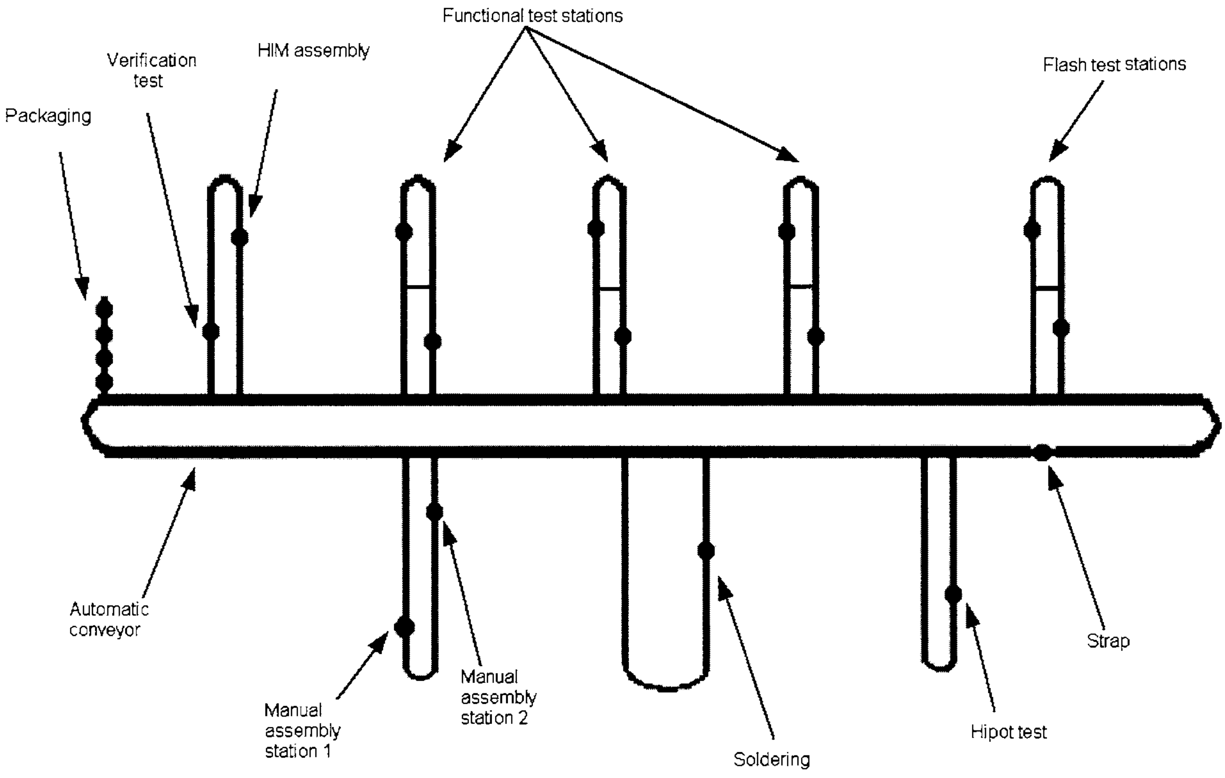


Figure 2.1: Assembly line

2.3. Steps of simulation study

Following steps were taken for simulation, modeling and analysis of the line (Banks et.al., 2001):

- Determine the scope and details for the simulation model
- Collect data
- Define conceptual model and validate that model
- Implement the model in Arena

- Validate the Arena model
- Design experiments to be conducted
- Output analysis
- Recommend solutions

2.3.1. Scope and details for the simulation model

The main objectives at this point were:

- To understand working of the assembly line.
- To understand day today problems faced by that line.
- To understand the operator movement on the assembly line.

2.3.2. Collect data

Although a lot of information including demand per day, processing times of the test stations etc. was available; processing times of the manual stations was not available. The processing times for different drives at the manual stations were collected and Expert Fit (Law and Vincent, 1995) was used to fit random distributions to represent the process times for different drives types. The distributions are summarized in appendix I.

2.3.3. Conceptual model and validation of that model

Some key facts about the assembly line:

- Total stations: 11
- Total operators: 7
- Total pallets: 48
- Breaks:
    - 1 half hour break (12:00pm - 12:30pm)
    - 2 fifteen minutes (9:00am - 9:15am and 2:00pm - 2:15pm)
    - 2 five minutes breaks

Manual processing stations: Operations at assembly station 1, assembly station 2, soldering, strapping, HIM assembly and packaging are done manually. The distributions for the processing times of these stations are summarized in appendix I.

Automatic processing stations: Operations at hipot test, flash test, functional test and verification test are automatic and the processing times for these operations are summarized in appendix II.

Trouble shooting distribution at hipot test, flash test, functional test and verification test: A triangular distribution (conservative estimate) with mean 15, minimum value of 5 and maximum value of 1 hour was assumed.

Flash station queuing logic:

- The first frame will go to the 2nd station.
- Second frame will go to the 2nd station and wait in the queue.
- The next frame will go to the 1st station and the next one will enter the queue of the 1st station.

Figure 2.2: Flash test station queue logic

Functional station queuing logic:

- There are three loops with two stations each.
- Within the loops the logic is same as the flash test stations.
- Frames will go to the first loop after the flash test loop and then the second loop and then the third loop.
- If all the six stations in the three loops are busy, the frames will queue up at the third loop.

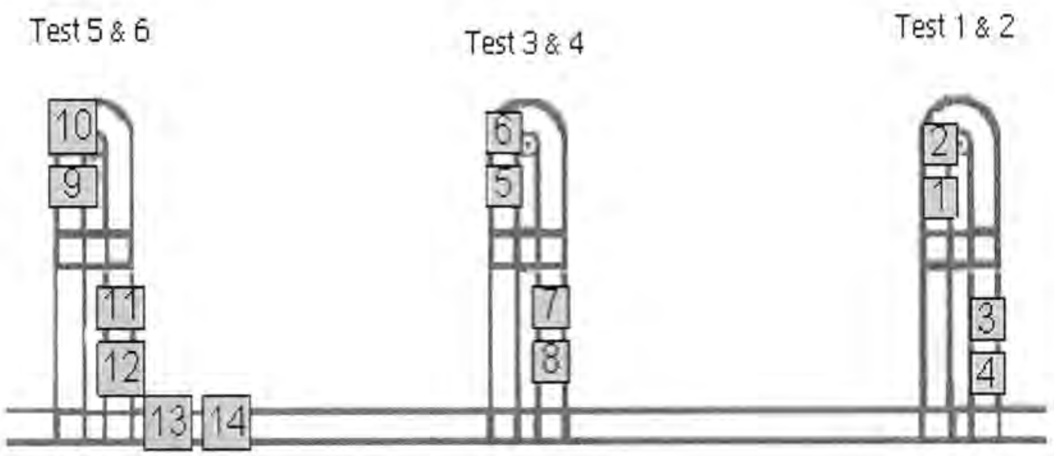


Figure 2.3: Functional test station queue logic

Additional assumptions:

- There are no breakdowns, no operator absenteeism.
- Raw material is always available.
- Frames are assembled in batches varying from 1 to 22 with most likely batch size being 10.
- Set time for the first two assembly stations was taken to be constant and added to the processing times.

Validation of conceptual model was done by presenting it to the company personnel and taking their feedback.

2.3.4. Modeling in Arena 5.0

Assembly line was modeled in Arena 5.0. Arena is a general-purpose discrete event simulation program that used flowchart approach to show the movement of entities. Different modules contain different logics and constricts; for example creating entities, processing on resources, transporting etc. Some of the important modules used in the modeling are described below:

Create: Entities were created with Random (expo) 2 min. This distribution was taken so that the drives do not have to wait when the pallets are available, hence giving maximum efficiency.

Assign: Assign module was used for giving the probability of different drives. Drives A, B, C and D were given the probabilities 0.2475, 0.3782, 0.2215 and 0.1628 respectively, based on the average daily demand for different months. Assign module was also used for assigning different pictures and colors of different drives during animation.

Process: This module was used to represent different stations like soldering, strap, hipot, manual assembly stations etc. Process time distributions for different drives for different processes were assigned in this module.

Resource: Resource module was used to define resources like pallets, operators and machines etc.

Schedule: Schedule module was used to give the daily schedule defining the time for breaks and work for machines and operators.

Seize: Seize module was used to seize pallets and operators and to limit their number to 48 and 7 respectively.

Enter and Leave: These modules were used to transfer entities from one station to another using conveyor.

Sequence: Sequence module was used to assign the process path followed by drives.

Conveyor: Conveyor module was used to simulate the actual automatic conveyor running at a speed of 0.5 feet/sec.

Segment: Segment module was used to give the length of the conveyor from one process station to the next process station.

Run parameters: Following run parameters were used for simulation:

- Number of replications = 10
- Warm–up period: Warm-up period of one shift was given. Warm up period is defined as the start-up period of a simulation run where an initially empty system is processing entities at a rate that is different from the one observed when the system has reached a steady state. Data collected during the warm-up period is discarded if steady state performance measures are desired.
- Simulation was performed for 2 shifts so that the throughput for one day can be considered as our performance measure.

2.3.5. Validation of the model

The model was validated by testing on familiar day-to-day scenarios. A queue forms at the functional test stations and the HIM assembly and there is no queue at the 1st and the 2nd manual assembly stations when only frame A and frame B are being produced. Also, when frame C and frame D are being produced, there is no queue at the functional test station, instead there is a queue at the 1st manual assembly station. The Arena model produced similar results. Also, the utilizations and the queues at all the stations were as expected and as observed.

2.3.6. Experimental design

Following options were designed considering the main objective of simulation, which is to increase the throughput of the assembly line:

1. Current configuration.
2. Various queue logics at functional test stations.
3. Reconfiguring the functional test stations to parallel: This would be more efficient with respect to flow of pallets but this will take up more space floor and hence longer distances.
4. Reconfiguring both flash and functional test stations to parallel.
5. Pallets re-circulate rather than queue: Queue is commonly observed at the functional test stations. Allowing re-circulation will eliminate that queue.
6. Increase the number of pallets in the system: This could eliminate the idle time when all pallets are circulating in the system.
7. Eliminate automatic conveyor and move to manual material handling system.

2.3.7. Output analysis

Simulation experiments were run for all the different configurations of the assembly line and the throughput comparison is shown below.

Table 2.1: Throughput comparisons:

Configuration	Throughput (drives/day)
Current	265
Recirculation of pallets	275 (4% increase)
Queue logic: Option 1	274 (3% increase)
Queue logic: Option 2	279 (5% increase)
Queue logic: Option 3	280 (6% increase)
Queue logic: Option 4	295 (11% increase)
Mixed series/parallel	282 (6% increase)
All tests in parallel	296 (12% increase)
Increase to 60 pallets (25%)	291 (10% increase)
No Conveyor	256 (3% decrease)

Explanation of the results:

To explain this improvement in the throughput let us consider the utilizations of the functional test stations in the current model:

Table 2.2: Utilization comparison at the loops

	Utilization	Difference
First loop	0.81	
Station 1	0.67	0.27
Station 2	0.94	
Second loop	0.63	
Station 3	0.45	0.36
Station 4	0.81	
Third loop	0.41	
Station 5	0.3	0.22
Station 6	0.52	

The above results show that the test stations are highly unbalanced. Improving the balance between these utilizations will increase the throughput. This can be achieved by increasing the load at second and third loop. Filling the stations 5 and 6 first and then stations 3 and 4 and then stations 1 and 2 will improve the balance between different loops. Based on this idea the following queuing logic was devised:

- Option 1: Queue one drive at second station in each loop starting with furthest away loop: This logic makes a balance between no queuing and the current method of queuing.
- Option 2: Queue one drive at both stations in each loop, starting with furthest away loop.
- Option 3: Not queuing at the test stations will balance the load between the stations in the loops.
- Option 4: Queue at second station in first loop only, start with furthest away loop: this logic also used the idea of back filling and makes a balance between no queuing and queuing at second station. Figure 2.4 illustrates this queue logic.

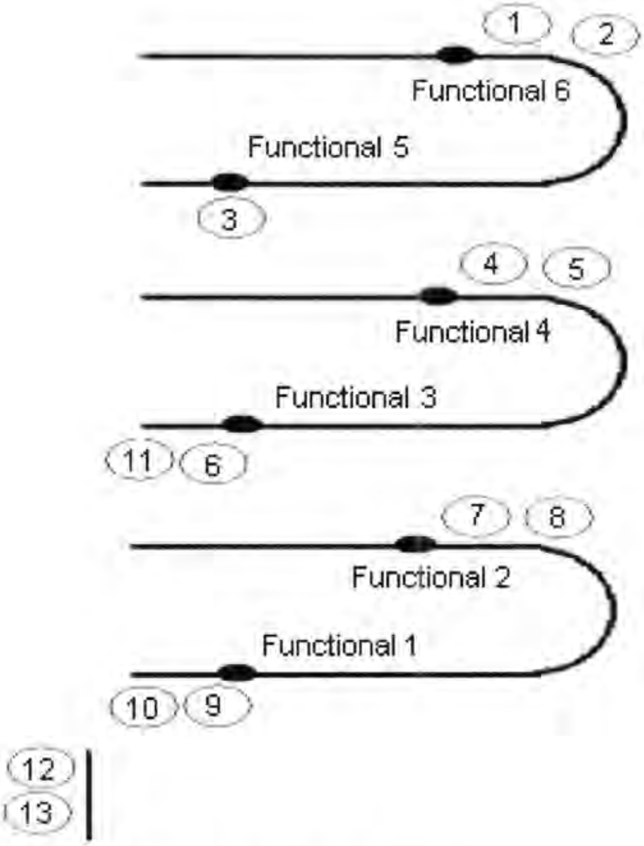


Figure 2.4: Queue logic 4

Utilization comparison for the different configurations is shown in table 2.3. The results show that the utilization at the functional test stations is uneven and can be improved by using the idea of backfilling (starting with the furthest away loop) and correcting the queue length at the stations. Queue logic 4 as described in figure 2.4 gives us the best results comparable to configuring the test stations in parallel, which will require a lot of restructuring and space.

Table 2.3: Utilization comparison

Configuration	Functional Test Utilization
Current	0.67, 0.94, 0.45, 0.81, 0.30, 0.52
Recirculation of pallets	0.71, 0.94, 0.51, 0.86, 0.26, 0.54
Queue logic: Option 1	0.42, 0.67, 0.56, 0.83, 0.67, 0.91
Queue logic: Option 2	0.39, 0.67, 0.52, 0.84, 0.61, 0.91
Queue logic: Option 3	0.64, 0.65, 0.75, 0.71, 0.80, 0.76
Queue logic: Option 4	0.53, 0.82, 0.65, 0.65, 0.73, 0.70
Mixed series/parallel	0.69
All tests in parallel	0.71
Increase to 60 pallets	0.70, 0.95, 0.49, 0.83, 0.43, 0.61

Identification of Bottleneck(s):

Table 2.4: Utilizations at different stations

Station	Utilization	Comments
Manual station 1	80%	Bottleneck
Manual station 2	65%	
Soldering	79%	Bottleneck
Hi-Pot	15%	
Strapping	37%	
Flash test	53% average	
Functional test	71% average	Third highest utilization
Functional test station 2	94%	Bottleneck
HIM	31%	
Verification	47%	
Packing	57%	

The utilization of various stations in the current model is given in table 2.4. Functional test station 2 is the most heavily loaded station on the line and thus the bottleneck station for the line. On average, the functional test stations are slightly less loaded than manual station 1 and the soldering station, which should hence also be considered as bottleneck stations.

CHAPTER 3

SIMULATION BASED SCHEDULING OF A DYNAMIC AND STOCHASTIC FLEXIBLE MANUFACTURING SYSTEM

3.1 Background and problem definition

Scheduling of a manufacturing environment is a complicated task mainly because of the dynamic and stochastic nature of manufacturing facilities, a large number of possible combinations that can be considered and because scheduling is time consuming and there is not always enough time to develop and evaluate more than one schedule. Developing a system that generates schedules based in dynamic and stochastic parameters, and using simulation for performance evaluation can help overcome aforementioned problems. The objective of this study was to maximize the throughput while meeting the demand. Finding an optimal sequence as well as batch size is a N-P hard problem and thus some heuristics are needed to solve this problem efficiently. Chan and Chan (2004) present a comprehensive survey of simulation study on flexible manufacturing systems (FMS) scheduling from 1980 till date. Only 4% (2 out of 50) of the papers surveyed had throughput as a performance measure. Thus, a lot of work needs to be done in this area.

The first step of the study was to define the decision variables, the objective and the constraints of the problem.

Decision variables:

- The sequence in which the drives are assembled.
- The optimal batch size for different drives.

Objective: To maximize throughput

Constraints:

- Meet the demand

3.2 Modeling and experimentation

One of the assumptions made in the simulation model was that there was a constant set up time for each drive at the manual assembly station 1 and manual assembly station 2. This assumption was relaxed and the model was modified to account for set up time for a batch of one type of drives at both the manual assembly stations. Appendix III gives the set up times assumed for the simulation model.

3.2.1 Sequencing problem

There are four types of drives and hence total of 3! = 6 different sequences that can be generated. One important observation was that the drives A and B and the drives C and D have similar processing times and thus behave similarly in terms of utilization and queue formation at the bottleneck stations. To test this observation, utilizations at the bottleneck stations (manual assembly station 1, soldering station, and functional test station) were compared and the results are attached in appendix

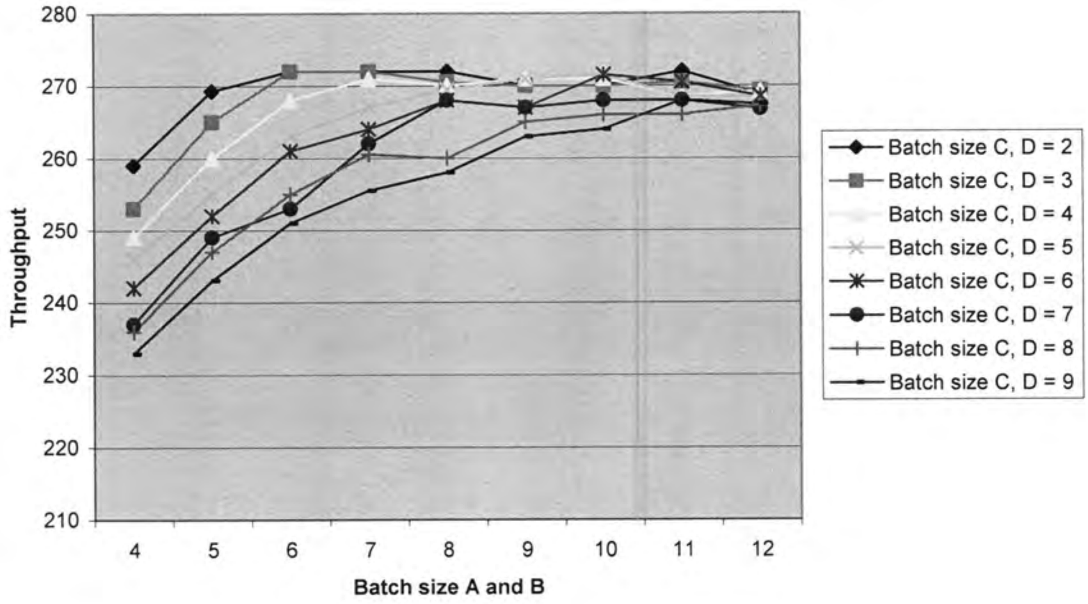
IV. Additional test runs were made by choosing two sequences ACBD and ADBC. The results attached in appendix V show that both the sequences give statistically same results for a given batch size. Now the sequencing problem was reduced down to two sequences: ACBD and ABCD. By taking different batch sizes for the sequence ABCD, system was simulated to see how it behaves. The results are attached in appendix VI. The results show that sequence ACBD gives same results than sequence ABCD. The sequence ACBD was now taken as a benchmark for further study.

3.2.2 Batch size problem

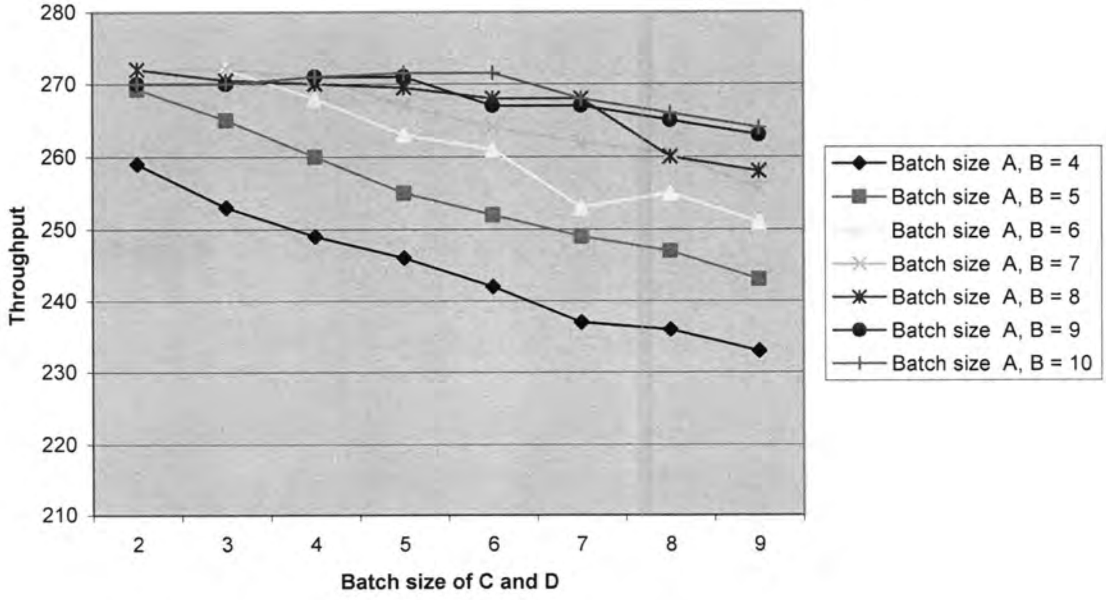
After solving the problem for sequencing, the only decision variable left was batch size for different drives. To solve this problem, simulation model was modified to generate the sequence (ACBD) of drives. Many simulation experiments were run by changing the batch size and some of the simulations even required 5000 replications to bring the half width (95% confidence level that the throughput is throughput ± half width) of throughput in the range of 3 to 4. The results are attached in appendix VII.

From the results, two very important conclusions can be drawn:

- With the increase in the batch size of A and B, throughput increases up to a certain point. The following line chart shows this trend.


Throughput increases with the batch size of A and B

- With the increase in the batch size of C and D, throughput decreases. The following line chart shows this trend.


Throughput decreases with the batch size of C and D

Thus, these results indicate that to get the best results for throughput, batch size of A and B should be as high as possible and batch size of C and D should be as low as possible.

Another observation from the results is that there is no unique batch size that gives the best throughput. There are many different batch sizes that give the best results. The following table summarizes the batch sizes that appear to give us the best results. Batch sizes of A and B >11 and batch sizes of C and D > 7 have not been considered because they were giving statistically same results.

Table 3.1: Batch sizes that give best results

A, B	**C, D**	**A, B**	**C, D**	**A, B**	**C, D**	**A, B**	**C, D**	**A, B**	**C, D**
5	2	6	3	7	4	8	5	10	6
6	2	7	3	8	4	9	5	11	6
7	2	8	3	9	4	10	5		
8	2	9	3	10	4	11	5		
9	2	10	3	11	4				
10	2	11	3						
11	2								

3.3 Algorithms

After solving both the sequencing and the batch size problems, the question was how to generate a schedule on a particular day when demand is given. The average daily demand data for several months is attached in appendix VIII. The following algorithms were written to fulfill daily demand.

3.3.1 Algorithm to define batch sizes

```
Take demand ratio (A+B)/(C+D) = R1/R2 for a given demand
Find the corresponding ratio from the table I and define batch sizes
Such that batch size A and B <= 11 and batch size C and D <= 6
If there is no corresponding ratio,
    If
        Batch size R1 >11,
        Divide R1 and R2 by 2
            If
            R1 and R2 are decimals,
            Take higher integer for R1 and lower integer for R2
        Define batch sizes from the table 3.1
    Else
        Multiply R1 and R2 by 2
        Define batch sizes from the table 3.1
If there is no corresponding ratio,
    Subtract 1 from R2 Or Add 1 to R1
    Define batch sizes from the table 3.1.
```

3.3.2 Algorithm to define the sequence

Divide demand of B by demand of A (if demand of B is higher than A else divide demand of A by demand of B) and take the lower integer.

Define that number as n. Similarly take the demand ratio for C and D. Define that number as m. The demand data shows that the demand ratio for C and D is always one while the demand ratio for A and B can vary from 2 to 5.

Based on n and m define the sequence as follows:

```
If the sent number of batches of B < n
        Send a batch of B
Else
        Send A
        Set sent number of batches for A and B to zero
If the sent number of batches of C < m
        Send a batch of C
Else
        Send D
        Set sent number of batches for C and D to zero.
```

3.4 Testing of the algorithms

To test the algorithms, the simulation model was modified such that by taking the inputs of demand ratio and batch sizes, it would automatically generate the required sequences and the batches. Three test runs were made to test the algorithms using the following methodology:

- Three sample demands were taken and the corresponding sequences and the batch sizes were found using the algorithms.
- Simulations were run for the total throughput and the throughput of each drive.
- Neighborhood (neighborhood was obtained by changing the batch size of the drives by 1 unit, taken one drive at a time.) of the solutions from the algorithms was searched.
- The output of the solution from the algorithms was compared with the output of
    - Different batch sizes that meet the demand.
    - Single batch equaling the demand in the sequence BCAD.
    - Single batch equaling the demand in the sequence BACD.

Following tables give the test results:

Table 3.2: Test 1 results with demand of A=27, B = 73, C = 36, D = 24

Demand Ratio (A+B/C+D) = R1/R2 10:6
Batch size obtained by applying algorithm: A, B = 10 & C, D = 6

m = 3, n = 1
Sequence obtained by applying algorithm: BCBDBCAD

Batch size									
A	B	C	D	Total TH	Half width	TH A	TH B	TH C	TH D
10	10	6	6	269	5.18	41	127	51	50
Comparison with the batch sizes in the neighborhood									
5	5	3	3	266	3.63	42	124	50	50
10	10	3	3	272	6.3	52.6	157	31	32
6	6	4	4	265	4.31	39	120.4	53	52.5
10	10	6	5	267	5.8	43	130	50.5	43.5
Comparison with random batch sizes that meet the demand									
6	6	6	6	260	3.26	33	96.5	66	65
4	4	3	3	257	2.29	37.5	110	55	54.5
4	4	4	4	250	2.09	32.5	92	62	63

Sequence	Comparison when batch size = demand									
	A	B	C	D	Total TH	Half width	TH A	TH B	TH C	TH D
BCAD	27	73	36	24	268	4.97	49	114	65	39
BACD	27	73	36	24	261	4.14	49	129.5	46.5	36.5

Table 3.3: Test 2 results with demand of A=30, B = 103, C = 37, D = 24

Demand Ratio (A+B/C+D) = 13:6
Batch size obtained by applying algorithm: A, B = 7 & C, D = 3

m = 3, n = 1
Sequence obtained by applying algorithm: BCBDBCAD

Batch size									
A	B	C	D	Total TH	Half width	TH A	TH B	TH C	TH D
7	7	3	3	271	5.82	48	141	41	41
Comparison with the batch sizes in the neighborhood									
13	13	6	6	267	5.89	43	140.5	42	42
7	7	4	4	270	4.99	42	130	50	48
6	6	3	3	267	5.5	45.5	132	44.5	45
Comparison with random batch sizes that meet the demand									
4	4	3	3	257	2.29	37.5	110	55	54.5
5	5	4	4	262.5	3.03	36.5	108.5	59	58.5
4	4	4	4	250	2.09	32.5	92	62	63

Sequence	Comparison when batch size = demand									
	A	B	C	D	Total TH	Half width	TH A	TH B	TH C	TH D
BCAD	30	103	37	24	262	4.89	49	125	46	42
BACD	30	103	37	24	255	4.53	48.5	110	54	42

Table 3.4: Test 3 results with demand of A=31, B = 132, C = 40, D = 32

Demand Ratio (A+B/C+D) = 9:4
Batch size obtained by applying algorithm: A, B = 9 & C, D = 4

m = 4, n = 1
Sequence obtained by applying algorithm: BCBDBCBDACBD

Batch size									
A	B	C	D	Total TH	Half width	TH A	TH B	TH C	TH D
9	9	4	4	269.5	5.96	36.5	150	41	41.5
Comparison with the batch sizes in the neighborhood									
9	9	5	4	270	6.06	34	146	50.5	40
8	8	5	5	268.5	4.19	30.5	123	57	58.5
7	7	4	3	269	5.5	37	142	51.5	39
Comparison with random batch sizes that meet the demand									
3	3	2	2	243	1.89	29	117	49	49

Sequence	Comparison when batch size = demand									
	A	B	C	D	Total TH	Half width	TH A	TH B	TH C	TH D
BCAD	31	132	40	32	265	4.9	50	126	46.5	42
BACD	31	132	40	32	265.5	3.82	28	144	63	30

Analysis of the results:

An important inference of the three test results is that the throughput obtained by defining the batch sizes and the sequence using the algorithms is statistically no worse than any other throughput, and better than many. When the neighborhood was searched for better solutions, statistically, no better solutions were found. When the results were compared with any random batch sizes that satisfied the demand, the performance of the batch sizes given by the algorithms was better. The test results show that demand can be satisfied through various combinations of batch sizes. And more than one of these combinations, possibly will give best results for throughput.

CHAPTER 4

CONCLUSIONS AND FUTURE WORK

4.1 Conclusions of the simulation study

This study illustrates the application of simulation in the manufacturing environment to improve utilization and remove the bottlenecks. A detailed simulation model of the assembly line was developed to determine how the throughput could be improved with minimal investment. Many different options were considered and simulated and examination of the simulation results reveals the following:

- Utilization balancing: Utilization of functional test stations is currently uneven and can be improved by the idea of backfilling and by allowing correct amount of queuing.
- Bottleneck detection: Functional Test Station 2 is the most heavily loaded station on the line. On average, the functional test stations are slightly less loaded than Manual Station 1 and Soldering Station, which should hence also be considered bottleneck.
- Throughput improvement: Significant improvement can be obtained through changing queuing logic that is inexpensive and a high return alternative.

4.2 Conclusions of the simulation based scheduling study

This research demonstrates the use of simulation to solve the complex problem of scheduling in a flexible manufacturing environment. Simulation model is used to understand the behavior of the assembly line for different sequences and different batch sizes. Based on the simulation results, heuristics have been developed to solve the scheduling problem. Once the solution is found using the heuristics, the performance of the solution can be evaluated using the simulation model in minimal time. This helps to get the solution and its performance inexpensively so that it can be applied in the rapidly changing day-to-day manufacturing environment.

For this particular study undertaken, following deductions could be made:

- For a particular demand, throughput depends on the sequence and the batch size of drives.
- Sequence ACBD, ADBC and ABCD will give us same results for same batch sizes.
- To get the best results for throughput, batch size of A and B should be as high as possible and batch size of C and D should be as low as possible.
- The developed heuristics for sequencing and batch sizing will give statistically no worse results than any other batch sizes and better results than many.

The benefit of the scheduling system is not only limited to the fact that any given schedule is better than any human can achieve. It also paves a way for continuous improvement. If the same business rules are applied consistently and continuously, and every schedule, every time is not dependent on the ability or personal preferences of any individual, it provides a basis for continuous improvement and is the major factor in the success of the organization.

4.3 Future work

The objective of our simulation based scheduling study was to maximize throughput. Another area that has a lot of scope for research is scheduling based simulation to maximize profits. As seen from the test results attached in appendix X, demand can be fulfilled in a number of ways with different product mixes. Following are the throughput results from test 2.

Table 4.1: Product mix comparison for same throughput

Batch size									
A	B	C	D	Total TH	Half width	TH A	TH B	TH C	TH D
7	7	3	3	271	5.82	48	141	41	41
7	7	4	4	270	4.99	42	130	50	48

From the above table it is clear that by changing the batch sizes, we can get same total throughput and an entirely different product mix. Thus, this study should be further extended to develop heuristics with an additional objective to maximize profits.

There has been a lot of research in scheduling with an objective to minimize inventory costs. One important conclusion drawn from that research is that higher the setup costs bigger the batch size for that product. In our research when the objective was to maximize the throughput, a contrary conclusion can be drawn. For higher setup cost products C and D, we need a smaller batch size and for lower setup cost products A and B we need a bigger batch size. Thus, research should be done to understand how the objective of minimizing the inventory costs affects the throughput and the objective of maximizing throughput affects the inventory costs.

APPENDIX I: EXPERT FIT DISTRIBUTIONS FOR MANUAL STATIONS

	Frame A			Frame B		
Processing station	**Distribution**	**Parameter**	**Values (sec)**	**Distribution**	**Parameter**	**Values (sec)**
Assembly station 1	Weibull(K)	Location	60	Log-Logistic(K)	Location	40
		Scale	23.1167		Scale	33.04865
		Shape	3.12005		Shape	2.99215
Assembly station 2	Log-Logistic(K)	Location	50	Log-Logistic(K)	Location	45
		Scale	40.39128		Scale	33.48815
		Shape	5.34851		Shape	3.79121
Soldering station	Log-Logistic(K)	Location	50	Log-Logistic(K)	Location	60
		Scale	42.27365		Scale	33.67733
		Shape	4.84282		Shape	4.83384
Strap station	Pearson Type 5	Location	0	Weibull(K)	Location	20
		Scale	340.0488		Scale	59.50343
		Shape	5.53208		Shape	1.53744
HIM assembly	Log-Logistic(K)	Location	25	Pearson Type 5(K)	Location	25
		Scale	23.09886		Scale	29.73783
		Shape	2.01541		Shape	2.00884
	Frame C			**Frame D**		
Assembly station 1	Log-Logistic(K)	Location	80	Rayleigh(K)	Location	180
		Scale	109.4299		Scale	97.32708
		Shape	4.88614			
Assembly station 2	Log-Logistic(K)	Location	90	Log-Logistic(K)	Location	50
		Scale	50.75401		Scale	107.9418
		Shape	5.29007		Shape	3.54202
Soldering station	Log-Laplace(K)	Location	90	Weibull(K)	Location	200
		Scale	91		Scale	125.4246
		Shape	2.74517		Shape	2.30104
Strap station	Inverted Weibull(K)	Location	30	Gamma(K)	Location	25
		Scale	27.14946		Scale	12.3986
		Shape	2.63535		Shape	2.70768
HIM assembly	Weibull(E)	Location	33.9888	Log-Logistic(K)	Location	25
		Scale	15.37212		Scale	47.0645
		Shape	0.52184		Shape	2.8074
	For all frames					
Packaging	Weibull(E)	Location	51.9964			
		Scale	64.0994			
		Shape	0.94462			

APPENDIX II: PROCESSING TIMES FOR AUTOMATIC TEST STATIONS

	Hipot test	Flash test	Functional test	Verification test
Frame A	30	244.2	796.8	82.2
Frame B	28.2	187.8	790.2	114
Frame C	30	229.2	780	61.2
Frame D	34.8	229.8	799.8	75

Time in seconds

APPENDIX III: SET UP TIMES FOR MANUAL STATIONS

Station	Drive type	Setup times (sec)
Manual assembly station 1	Frame A	tria(90, 120, 150)
	Frame B	tria(50, 80, 110)
	Frame C	tria(180, 210,270)
	Frame D	tria(180, 210,270)
Manual assembly station 2	Frame A	tria(90, 120,150)
	Frame B	tria(60, 90, 120)
	Frame C	tria(150, 180,210)
	Frame D	tria(150, 180,210)

APPENDIX IV: STATION UTILIZATION FOR FRAMES

Station	Frame A	Frame B	Frame C	Frame D
Manual station 1	0.4563	0.438	0.9316	0.9279
Manual station 2	0.4971	0.4508	0.6733	0.6075
Soldering	0.4601	0.4762	0.8149	0.9206
Hipot	0.1338	0.1296	0.115	0.0963
Strap	0.3575	0.3635	0.2829	0.1726
Flash test 1	0.3705	0.1685	0.1346	0.0165
Flash test 2	0.7399	0.7094	0.7571	0.6273
Functional test 1	0.4209	0.4265	0.1945	0.0261
Functional test 2	0.7539	0.7915	0.6884	0.3263
Functional test 3	0.5652	0.5741	0.5002	0.4286
Functional test 4	0.5993	0.6008	0.5272	0.4998
Functional test 5	0.6562	0.6548	0.5897	0.545
Functional test 6	0.6749	0.6744	0.6154	0.5692
Average for functional test	0.611733	0.62035	0.519233	0.399167
Him assembly	0.2839	0.2525	0.2469	0.2406
Verification	0.406	0.585	0.2509	0.2379
Packaging	0.546	0.5621	0.4639	0.3425
Throughput	268	278	223	166
Half width for throughput	<7.75	<5.97	<2.47	<1.84
Replications	200	200	20	20

APPENDIX V: COMPARISON OF THROUGHPUT FOR SEQUENCES ACBD AND ADBC FOR SAME BATCH SIZE

Batch size		Sequence		Sequence	
		ACBD		ADBC	
A, B	C, D	Throughput	Half width	Throughput	Half width
5	3	265	3.78	264.5	3.97
5	5	255	2.44	258	2.49
5	7	249	2.13	250	2.04
5	9	243	1.96	244	1.91
7	3	272	3.86	270	5.63
7	5	267	4.4	265.5	4.58
7	8	260.5	3.1	260	3.13
7	10	253	2.94	254	2.28
9	3	270	4.59	275	6.12
9	5	271	5.25	270.5	5.58
9	7	267	4.75	266.5	4.38
9	9	263	3.77	262.5	3.8
11	3	270.5	6.28	269	6.33
11	5	268.5	3.85	268	5.67
11	7	268	3.78	267.5	5.08
11	9	268	4.3	264	4.39

APPENDIX VI: SIMULATION RESULTS FOR THE SEQUENCE ABCD

A, B	C, D	Throughput	Half width	A, B	C, D	Throughput	Half width
3	2	240	1.76	5	3	261	3.89
3	3	235	1.76	5	5	256	2.73
3	5	230	1.63	5	7	249	1.96
3	7	228	1.35				
3	9	225	1.45				
5	2	270	4.31	5	4	257	3.4
7	2	269	5.37	7	4	269	4.86
9	2	266	6.5	9	4	266	5.69
11	2	267	6.27	11	4	266	5.86
5	6	253	2.33	5	8	247	2.1
7	6	261	4.12	7	8	260	2.67
9	6	267	4.76	9	8	263	4.13
11	6	266	5.18	11	8	263	3.96
5	2, 2	270	4.31	5	2, 2	270	4.32
5	2, 3	264	4.28	5	3, 2	267	4.27
5	2, 4	261	3.31	5	5, 2	264	4.01
5	2, 5	257	2.85	5	7, 2	264	3.97
5	2, 7	248	2.64				

APPENDIX VII: SIMULATION RESULTS FOR THE SEQUENCE ACBD

A, B	C, D	Throughput	Half width	A, B	C, D	Throughput	Half width	A, B	C, D	Throughput	Half width
4	2	259	2.76	5	2	269.3	3.17	6	2	272	4.01
4	3	253	2.68	5	3	265	3.78	6	3	272	7.16
4	4	249	2.25	5	4	260	3.35	6	4	268	3.96
4	5	246	1.74	5	5	255	2.44	6	5	263	3.45
4	6	242	1.96	5	6	252	2.61	6	6	261	2.76
4	8	237	1.62	5	7	249	2.13	6	7	253	2.9
4	9	236	1.64	5	8	247	2.11	6	8	255	2.45
4	10	233	1.44	5	9	243	1.96	6	9	251	2.03
7	2	272	4.39	8	2	272	4.64	9	2	270	4.67
7	3	272	3.86	8	3	270.5	4.41	9	3	270	4.59
7	4	271	3.53	8	4	270	3.86	9	4	271	5.73
7	5	267	4.4	8	5	269.5	4.86	9	5	271	5.25
7	6	264	3.89	8	6	268	4.48	9	6	267	5.03
7	7	262	3.8	8	7	268	3.79	9	7	267	4.75
7	8	260.5	3.1	8	8	260	3.85	9	8	265	4.35
7	9	255.5	2.79	8	9	258	3.29	9	9	263	3.77
7	10	253	2.94	8	10	255	3.09	9	10	262	3.37
10	2	270	4.7	11	2	272	6.48	12	2	268.8	4.3
10	3	270	4.53	11	3	270.5	6.28	12	3	269.3	4.28
10	4	271	6.38	11	4	268.5	6.05	12	4	269.2	4.04
10	5	271.5	5.87	11	5	268.5	3.85	12	5	268.4	4.34
10	6	271.5	5.33	11	6	270.5	3.98	12	6	268.5	3.9
10	7	268	4.95	11	7	268	3.78	12	7	266.8	3.5
10	8	266	3.2	11	8	266	5.7	12	8	267.2	3.38
10	9	264	3.06	11	9	268	4.3	12	9	267.4	3.27
10	11	261	2.46	11	10	265	2.84	12	10	265.8	2.85
								12	11	263.2	2.63

APPENDIX VIII: AVERAGE DAILY DEMAND FOR DIFFERENT MONTHS

Frame A	Frame B	Frame C	Frame D	A+B = R1	C+D = R2	Ratio (A+B)/(C+D) = R1:R2	
27	73	36	24	100	60	1.67	5:03
30	103	37	24	133	62	2.16	13:06
31	132	40	32	163	73	2.24	9:04
33	80	40	29	112	69	1.63	13:08
42	121	42	29	163	71	2.28	16:07
47	68	45	32	115	77	1.49	3:02
40	84	42	29	125	71	1.75	7:04
35	74	44	26	109	69	1.58	11:07
38	77	38	28	115	66	1.74	7:04
39	81	37	32	120	69	1.74	7:04
36	60	41	33	96	74	1.29	9:07
30	52	24	26	82	51	1.62	13:08
36	64	35	28	100	63	1.60	8:05

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