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Rochester Institute of Technology

**ANALYSIS OF PRODUCTION CONTROL METHODS FOR SEMICONDUCTOR
RESEARCH AND DEVELOPMENT FABs USING SIMULATION**

A Thesis

**Submitted in partial fulfillment of the
requirements for the degree of
Master of Science in Industrial Engineering**

in the

**Department of Industrial & Systems Engineering
Kate Gleason College of Engineering**

by

Vikram Ramamurthi

B.E., Instrumentation Engineering, University of Mumbai, 2002

December, 2004

DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING
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CERTIFICATE OF APPROVAL

M.S. DEGREE THESIS

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ABSTRACT

The importance of semiconductor device fabrication has been rising steadily over many years. Integrated circuit technology and innovation depends on successful research and development (R&D). R&D establishes the direction for prevailing technology in electronics and computers. To be a leader in the semiconductor industry, a company must bring technology to the market as soon as its application is deemed feasible. Using suitable production control methods for wafer fabrication in R&D fabs ensures reduction in cycle times and planned inventories, which in turn help to more quickly, transfer the new technology to the production fabs, where products are made on a commercial scale. This helps to minimize the time to market. The complex behavior of research fabs produces varying results when conventional production control methodologies are applied. Simulation modeling allows the study of the behavior of the research fab by providing statistical reports on performance measures. The goal of this research is to investigate production control methods in semiconductor R&D fabs. A representative R&D fab is modeled, where an appropriate production load is applied to the fab by using a representative product load. Simulation models are run with different levels of production volume, lot priorities, primary and secondary dispatching strategies and due date tightness as treatment combinations in a formally designed experiment. Fab performance is evaluated based on four performance measures, which include percent on time delivery, average cycle time, standard deviation of cycle time and average work-in-process. Statistical analyses are used to determine the best performing dispatching rules for given fab operating scenarios. Results indicate that the optimal combination of dispatching rules is dependent on specific fab characteristics. However, several dispatching rules are found to be robust across performance measures. A simulation study of the Semiconductor & Microsystems Fabrication Laboratory (SMFL) at the Rochester Institute of Technology (RIT) is used to verify the results.

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1 INTRODUCTION

Silicon replaced germanium in the early 1960s as the dominant material for semiconductor device fabrication. Many factors went in favor of the use of silicon wafers for fabrication. Silicon can be oxidized easily to form silicon dioxide (SiO_2), which acts as a barrier for the diffusion steps needed in integrated circuit (IC) fabrication. Most importantly, silicon is abundantly available in nature, which makes it an inexpensive raw material (May & Sze, 2003). The exceptional qualities of this raw material have opened the doors to radical technology that has changed the world. The use of computers, calculators, cell phones, transistors and other indispensable smart devices has become possible due to semiconductor technology.

Integrated circuits are fabricated on silicon wafers in semiconductor manufacturing facilities, also called fabs. Technology and product development are key to the success of semiconductor manufacturers. Thus, most of the industry leaders have both production fabs, where products are made for sale to the public, and research and development (R&D) fabs, where new technologies and products are designed and tested. Although production fabs and R&D fabs may have similar tool sets, semiconductor production fabs operate differently than R&D facilities. These differences arise from the scales of production, lot prioritization, material handling techniques and performance parameters. Production fabs aim at increasing throughput for maximizing profits whereas R&D fabs concentrate on developing new technology and minimizing time to market.

Production fabs in general are characterized by a low product mix, high production volumes, established products with standardized routings and established processes. On the other hand, R&D fabs are characterized by large product mix with unique and/or non-standard routes, prioritization of research activities, random engineering holds and mandatory testing procedures.

While a significant body of research exists for designing, analyzing and improving the performance of production fabs, very little has been done to study the performance of R&D fabs. This research will focus on performance improvement of R&D fabs in terms of productivity, cycle time and due date performance. In general, this research will involve conducting simulation experiments on models of R&D fabs to determine factors that significantly effect fab performance. Furthermore, this research will investigate prioritization policies that are encountered in R&D fabs.

In the next sub-sections, the background on semiconductor manufacturing is discussed along with the role of R&D fabs and their production control strategies. Finally, the role of simulation as an analysis tool is discussed.

1.1 An Overview on Semiconductor Manufacturing

In 1965, Gordon Moore, founder of Intel made his famous observation in his original paper which the press called Moore's Law. In this observation, Moore concluded that the observed trend of exponential growth in the number of transistors in an integrated circuit would continue. This means that the number of transistors on a chip would double every couple of years (Jaeger, 2002). Figure 1.1 shows the evolution of microprocessors beginning with the world's first single chip microprocessor, Intel 4004 in 1970. With advent in technology, the number of transistors on the chips began to increase and this increase corresponded with the observation made by Moore. The Intel Itanium 2 processor introduced in 2003 has 410,000,000 transistors in an integrated circuit. Moore's Law is expected to hold well into the future. Semiconductor manufacturing, which is the pace setter for Moore's Law, involves four basic steps as shown in Figure 1.2.

Figure 1.1: Realization of Moore's Law (<http://www.intel.com/research/silicon/mooreslaw.htm>)

Figure1.2: Semiconductor Manufacturing Steps

The raw material, quartzite is distilled and reduced to form polycrystalline silicon and eventually single crystal silicon, in the form of ingots, using either the “Czochralski crystal growth” or the “Float Zone” method. The ingots are ground, polished and sawed according to the desired orientations to form silicon wafers (Wolf, Stanley, Tauber, & Richard, 1986). Wafer fabrication is a process of integrating circuits on a silicon die. The first integrated circuits were fabricated at Texas instruments and Fairchild Semiconductor in the early 1960s. Simple logic

gates and amplifier circuits were built using transistors and resistors. These were the first steps, which opened up the gates for bigger and better technology to follow. The level of integration on wafers has been doubling every two years and modern technology allows for integration of up to billions of components on a 20-mm x 20-mm die (Jaeger, 2002). Larger wafer diameters allow for simultaneous production of a large number of integrated-circuit dies. Clean room facilities these days are including tools in their layout that process wafers with a diameter of 300 mm. Layers of integrated circuits are built on the silicon wafer in the wafer fabrication step. The integrated circuit is then assembled and packaged for use. Automatic test equipment (ATE) and test programs electrically test the assembled devices before shipment to the customer (Wolf et al., 1986).

A great amount of research has gone into optimizing the wafer fabrication process since it is the most expensive phase of semiconductor manufacturing. This stage involves the addition of layers of circuits on the silicon wafer through a sequence of 300-600 intricate steps. The process flow is highly reentrant, where many of the processing steps are repeated for every layer. Different sequences of steps are required for different circuits and some steps can include sub-operations on different tools. Processing steps also vary in the quantity of wafers that are processed at one time. These quantities can be single wafers, wafer lots or batches of wafer lots. Typically a lot consists of 24-48 wafers, while a batch consists of 6 lots.

These characteristics of semiconductor manufacturing make it different from traditional manufacturing. Due to the reentrant nature of the flow, wafers at different stages of production queue up in front of the same tool a number of times. The smoothness of flow is hindered by this reentrant flow. Typical reentrant flow in a semiconductor manufacturing facility is shown in Figure 1.3.

1.2 The Semiconductor Industry and R&D

The invention of the transistor in 1947 served to make semiconductors, the leaders of the electronics revolution (Busch, 1999). An article on the top 100 R&D spenders in the IEEE Spectrum publication ranks International Business Machines Corp., U.S. and Intel Corp., U.S., major players in the semiconductors and semiconductor equipment sector, in the top 15 (Hira, 2003). The semiconductor industry ranks behind only the automotive and communications industries in annual R&D spending. In 2001, the industry spent \$14.2 billion on R&D (Wolfe, 2002). This makes it a strategic industry that is vital to the financial and state security welfare and whose existence has a bearing on the economy with important forward and backward relationships through the presence of encouraging externalities. The technological progress of the semiconductor industry seen increase in productivity of fab products but has also motivated gains in industries linked to it (Green, 1996). Semiconductors form the backbone of the information age and are the roots of innovation in all electronic applications and defense mechanisms. Hence, the well being of a country's semiconductor industry is a necessary condition for competing in high technology (Busch, 1999).

The semiconductor industry is distinguished by big capital investment in R&D, learning curves and constant enhancement. The industry falls into the category of high technology because a high proportion of R&D costs as a percentage of sales and also because a high number of the employees are scientists and engineers (Green, 1996).

Figure 1.3: Sub-Micron CMOS Process at RIT

Productivity is seen as an economic parameter that manifests the increase in efficiencies and outputs on the basis of present inputs. Progress in productivity has been made possible by technological advances via R&D. R&D has been the biggest contributor to growth in productivity and plays a very important role in determining economic strength. Improvements in manufacturing methodologies, materials and tools are technological advances that improve productivity. This advance is essential since in the simplest terms companies can be competitive by maximizing output. It also is a big provider to growth in national income and productivity.

1.3 High Priority Wafer Lots

High priority lots in semiconductor research fabs are commonly referred to as '*hot lots*'. Their presence in the work in process inventory has positive and negative effects. Hot lots give the management a clearer picture on delivery lead times but on the flipside, they disrupt the process flow on the fab floor (Ehteshami, Petrakian, & Shabe, 1992). Hot lots are introduced into the system to meet marketing and business needs. These include decreasing manufacturing cycle time for the lots to decrease product delivery time and expediting the development time of a new process or product. Although hot lots have the same routes and step process times as other lots of the same product type, they get priority over regular lots for processing, which results in altered average cycle time and throughput (Narahari & Khan, 1997 and Fronckowiak, Peikert, & Nishinohara, 1996).

1.4 The Role of Industrial Engineers in the Semiconductor Industry

The semiconductor industry is a capital and technology driven industry. The R&D, manufacture and marketing of a single chip estimates to more than \$50 million. According to the National Technology Roadmap for Semiconductors, equipment in a semiconductor manufacturing facility is close to 90% of the factory capital costs. Tools on an average cost between \$500,000 to \$2,000,000.

It hence becomes essential to output products to the world market as soon as possible to recover invested funds and increase profits (Green, 1996). This is the only way for semiconductor companies to be competitive and gain on the learning curves.

In comparison to discrete manufacturing facilities, the unique challenges that semiconductor fabrication processes face are:

- Large number of process steps;
- Complex and reentrant process flows;
- Intermixture of lots and single wafers in tool queues;
- Batching of different lots having common processing recipes and times;
- Different rework routes for every product; and
- Regular use of metrology tools for parameter measurement and to judge the health of the wafer (Thompson, 1996).

Apart from implementing changes in the products and the fabrication procedures, improvement in productivity is achieved by increasing utilization of resources on the fab floor, reducing cycle times and effectively managing the work-in-process (WIP). This approach to increasing productivity can be achieved by the effective utilization of industrial engineering practices. The role played by industrial engineers (IEs) today, in this respect is very limited. Even though the importance of industrial engineering to this field has been realized, there still is room for industrial engineers to play a bigger role. (Padillo & Meyersdorf, 1998)

1.4.1 Process Improvements in Semiconductor Fabs

A number of product and process developments have been made in recent times. These can be categorized as technology dependent. Improvement in the operation of the fab is system

dependent and is the domain of IE. Technological advances in semiconductor manufacturing include feature size reduction, wafer size increase and better yield.

- Feature size reduction - Chips can now hold transistors that are 0.35 micron wide. These measure less than half the width of a strand of human hair. It is estimated that in another ten years the feature size will go down to 0.14 micron.
- Wafer size increase - With the use of wafers measuring 300 mm in diameter, more chips can be accommodated per wafer.
- Yield improvement – Yield is defined as the percentage of good die to the total number of die on a finished wafer.

Operational improvements have been historically proven to account for 7 to 10% of annual productivity rate. Most of the operational improvements have come from technology dependent developments like equipment performance, quality of raw materials and technological advances. (Padillo et al., 1998)

Optimizing the process flow on the fab floor can offset the increase in operational costs attributed to these technological advances. System dependent problems relating to flow and capacity that have consequences on performance and efficiencies will have to be tackled. IEs use diagnostic tools to evaluate policies and existing practices on issues concerning:

- Resource scheduling;
- Resource utilization;
- Fab floor layout;
- WIP; and
- Process routings and times.

Industrial engineers play a vital role in maintaining a semiconductor firm's competitiveness in this age of short product life cycles and complex procedures. An industrial engineer effectively uses his skills to bridge the gap between production targets and actual performance levels (Padillo et al., 1998).

1.4.2 The Use of System Simulation

Diagnostic tools used by decision makers range from classical and traditional methods to modern computer software including system simulation, queuing theory, mathematical programming and heuristics, statistical process control and computer-aided design (CAD). Computer tools are used to account for fab floor constraints for planning and scheduling systems when crucial decisions are made. The planning process gets intricate when new constraints are introduced into the system due to design evolution.

The smooth running of the system depends on high machine utilization and short cycle times to ensure product line flexibility and good throughput rates. Process flows and data in semiconductor manufacturing systems are getting intricate by the day. The presence of too many interdependent variables in the various manufacturing disciplines of design, engineering and management become too cumbersome to handle. Many decisions made affect the future running of the system since they have a long-term effect. So, it makes it really unsafe to leave these decisions to instinct. These decisions can be modeled using simulation software and evaluated for feasibility. The best way to going about comprehending the concerned manufacturing system is to understand the layout and process flow from the simulation model.

In essence, semiconductor manufacturing facilities use simulation software in three main areas:

- Dispatch rule testing;

- Forecasting plan, schedule and “what-if” situations; and
- Integrating the simulation software with Manufacturing Execution System software for real-time dispatching (Thompson, 1996).

Leading names in semiconductor manufacturing employ industrial engineers to use simulation software for the above purposes.

1.5 Summary of Introduction

The wafer fabrication process in semiconductor fabs is highly complex and reentrant. In semiconductor R&D fabs, large product mixes with unique and/or non-standard routes, prioritization of research activities, random engineering holds and mandatory testing procedures characterize this process. Since semiconductor R&D fabs feed technology to the production fabs, it is important to minimize the time-to-market for this technology. Industrial engineers effectively use their skills to bridge the gap between production targets and actual performance levels. For this purpose, industrial engineers use system simulation to comprehend the manufacturing system to understand the layout and process flow.

2 PROBLEM STATEMENT

To gain a large share of the market, a semiconductor company needs to minimize time to market to make its technology commercially available faster than its competitors. This is essential for a company to maximize profits (Johal, 1998). Minimizing time to market can be achieved by shorter cycle times in the various stages of new product development, which include the concept design, the detailed design and the production of prototypes. This thesis investigates production control methods in semiconductor R&D fabs. The appropriate use of which, will enable a faster transfer of technology to the production fabs. This in turn reduces the time to make the product commercially available.

The product and process development phase is one of the most complex and expensive steps in semiconductor manufacturing. With advent in technology, Very Large Scale Integration (VLSI) allows for more and more chips to be integrated into the wafer. A significant reinvestment of revenue goes into supporting R&D fabs to maintain these technological advances in the semiconductor industry. R&D fabs operate differently than production fabs. A research fab may host several processes and products at varying WIP levels and priorities. Hindrances to process flow like random stoppages, tool reservations and lot prioritization are inherent characteristics of R&D fabs.

Past research on productivity improvement in semiconductor fabs has focused on the working of production fabs and the effective application of cycle time reduction strategies to these fabs. Very little research has gone into improving productivity of R&D fabs and decreasing cycle times for faster transfer of technology to the production fabs. This thesis investigates methods to increase productivity and quantify the performance of semiconductor R&D fabs considering cycle time and throughput along with the influence of hot lots or high priority lots

using system simulation with a focus on employing production control. The objectives of this research are to:

- Construct a simulation model of a representative R&D fab;
- Conduct a series of experiments to understand the relationship between WIP, throughput and cycle time in R&D fabs;
- Conduct an experiment to evaluate the effects of WIP, tool redundancy and levels of technical (repair) support on productivity;
- Conduct an experiment to compare alternative dispatching rules in R&D fabs with priority-designated lots based on productivity; and
- Perform a case study for the Semiconductor and Microsystems Fabrication Laboratory (SMFL) at the Rochester Institute of Technology (RIT) to validate experiments and to aid in improving productivity of the fab;

To comprehend the workings of research fabs, a simulation model of a representative R&D fab is built with no lot priorities using a representative load to approximate production. This model is simulated to investigate factors affecting the productivity of R&D fabs. These factors are lab shifts, scheduling policies, resource allocations, and technical support capabilities, among others. Bottleneck situations identified during this simulation run will help identifying tools and/or resources that operate with the maximum utilizations.

A relationship between WIP, throughput and cycle time is investigated to determine the capacity of the R&D fab. To achieve this, the simulation model is run with varying levels of WIP. Cycle time and throughput figures from each of these runs are recorded and separately graphed to determine the capacity of the fab.

Levels set on the WIP, redundancy of the bottleneck tools in the fab and technical support capabilities will be part of formally designed experiments. The results from each run will indicate fab performance in cycle time and throughput metrics.

Wafer lots are assigned priorities for the next set of experiments. The lots have three classifications of priorities; H, M and L, where H is high priority, M is medium priority and L is low priority. The model will then be simulated with a combination of different primary and secondary dispatching rules with different lot prioritization proportions in effect. Dispatching rules like Priority, FIFO, Critical Ratio, Highest X-Theoretical Ratio First and Least Balance Ahead are used as primary and secondary rules. This covers the four classifications of dispatching strategies that are based on processing time, due dates, strategies based on neither processing time nor due date and finally a combination of the three strategies (Sha & Hsu, 2004). This helps compare the use of employing different dispatching rules. Statistical analyses will be used to compare the performance of the different dispatching rules. Fab performance is reflected by the behavior of the performance measures, which are percent on time delivery, average cycle time, standard deviation of cycle time and average WIP.

The results from these experiments are verified by running experiments on simulation models of the Semiconductor and Microsystems Fabrication Laboratory (SMFL) at the Rochester Institute of Technology (RIT) for validation purposes. The culmination of these objectives aids in selecting the appropriate production control policies with regard to changing operational factors in R&D fabs. This helps increase the productivity of these fabs and in turn shorten the time to market.

3 LITERATURE REVIEW

Literature reviewed on past research has been classified into two sub-sections. Past research on R&D fabs and production fabs has been reviewed separately.

3.1 Past Research on Improvements in R&D Fab Productivity

Janakiram (1996) discusses a theory of constraints (TOC) related to cycle time reduction. His work involves identifying constraint equipments, evaluating constraints based on physical and procedural types and effectively implementing the listed TOC methods for cycle time reduction. His work cites training, dedication by management and committed team effort as essentials for cycle time reduction. Cycle time reduction techniques involve reducing process waste, effective scheduling of resources, using tested WIP management strategies and employing cross-functional work-teams. Some of the benefits of compressing cycle time apart from increased productivity are better utilization of resources, schedule reliability, decreased costs, adaptability to market needs and conditions. The main obstacles faced in a semiconductor research facility are changing levels of the product-mix and production volumes, random delays, the R&D outlook, test steps and reentrant flow. The biggest hindrance is the presence of any kind of variation. The constraints in such an R&D setup, if not monitored and managed properly, can lead to misleading results.

Tullis, Mehrotra and Zuanich (1990) discuss the use of discrete event simulation at HP's Silicon Processing Laboratory (SPL), which is an R&D fab. ManSim, a simulation software package was used to create discrete event simulation models of the flow of lots. The overall fab load was controlled either by varying lot starts or defining maximum WIP levels. Random delays were modeled between some recipe steps. Equipment breakdown (MTBF), repair times (MTTR) and preventive maintenance events were also included in the model. Operators were categorized

into work areas, shifts and skills. Mean Cycle Time (MCT) versus WIP graphs were plotted for the base model, a model with full staffing, a model without unscheduled maintenance events and a combination of the full staffing model and the model without unscheduled maintenance. It was observed that the MCT did not change significantly between any of the dispatching rules used. The dispatching rules employed were FIFO, SIPT (shortest processing time at next station), SRPT (shortest remaining processing time), LLNQ (least lots in next queue), CR and SLACK. The predicted cycle time was observed to be within 15% of a small sample of observed lot cycle times.

Pierce and Yost (1996) investigate metrics on cycle time in an R&D semiconductor wafer fab. Multiples of theoretical cycle time, breakdown analysis of cycle time queue and holding time of equipment were studied and analyzed. A relationship is established between discipline cycle time and overall fab performance. The study also concludes that day-to-day fab cycle time is related to the same day of the week and not with the previous or the following day.

Liao, Chang, Pei and Chang (1996) present a paper on the development of a daily scheduling tool for an R&D fab. The daily scheduling function is set up such that the right amount of wafer lots get processed at the right time, meeting the delivery schedule and hence reduce fabrication cycle times. The scheduling methodology consists of three parts viz. an efficient algorithm, fast rescheduling and periodic rescheduling. The daily scheduling tool, Electronic Researcher and Service Organization Fab Scheduler (ERSOFS) gives due consideration to high variety, low volume, cyclic process flow, engineering splitting and merging of wafer lots which are inherent to R&D fabs. The solution methodology is based on Lagrangian relaxation and network flow techniques. This methodology is developed, implemented and validated. Tests have proven that ERSOFS generates high quality schedules efficiently. Fast and

smooth adjustments of schedules by the rescheduling function of the ERSOFS help cope with the production uncertainties in an R&D fab. It is concluded that ERSOFS can also be used in large fabs due to the nature of the algorithm.

Shiu et al. (1996) present a paper on the working of FASE, a computer-aided scheduling environment developed for semiconductor manufacturing. It is an extended version of an optimization-based scheduler for an R&D pilot line to a production fab. FASE combines optimization-based scheduling methodologies, equi-variability graph technique, queuing analysis and GUI technique into a decision aid. It consists of a mid-term and daily scheduler, a machine variability analyzer, a what-if analysis tool and a user-friendly GUI. The objective is to generate daily production schedule with a look-ahead capacity. FASE's variability analyzer can be used for bottleneck identification, trade-off among cycle time, utilization and variability and a what-if analysis. This tool supports what-is analyses of capacity variation, machine allocation policy, output schedule and wafer start schedule.

Lu, Ramaswamy and Kumar (1994) test a new set of scheduling rules called Fluctuation Smoothing policies using simulation. 11,000 simulations were conducted on three R&D fab lines and one production line. The fluctuation smoothing policies were developed as a special subclass of least slack (LS) policies, which give lots in queue with the least slack, the highest priority. This class of scheduling policies attempts to reduce various fluctuations in the queuing network. The class consists of 3 least slack policies. The Fluctuation Smoothing for Variance of Lateness (FSVL) policy reduces variance of lateness, the Fluctuation Smoothing Policy for Variance of Cycle Time (FSVCT) reduces the variance of cycle time and the Fluctuation Smoothing Policy for Mean Cycle Time (FSMCT) reduces the mean cycle time and also leads to a small variance of cycle time. These policies and other dispatching rules like FIFO and SRPT were tested on the

fab models. A 22.4% reduction in the mean queuing time and a 52% reduction the standard deviation of cycle time were reported over the baseline FIFO policy.

3.2 Past Research on Improvements in Production Fab Productivity

Wein (1988) assesses the impact that scheduling has on the performance of semiconductor wafer fabs. The data gathering for the simulation model was done at HP's Technology Research Center Silicon fab (TRC), an R&D fab in Palo Alto, California. The model excludes the engineering hold –times encountered at this fab as the focus was on the analysis of production facility environments. In the simulation model, coded in SIMAN, lots entering the fab visit 24 different stations with a total of 172 operations. Three versions of the simulation model with three fab configurations are used. Fab 1 and Fab 2 are 1- & 2-bottleneck systems respectively. Fab 3 has four stations with high utilizations (near 90%) and several other moderately utilized stations (between 60 and 77%). The fabs are run using different combinations of input rules and lot sequencing rules. The input rules include Poisson processes, constant interarrival times, closed loop inputs and workload regulating inputs. The lot sequencing rules include FIFO and SRPT. For each rule tested, 20 independent runs are made, each representing 3 ½ years of fab operation. The runs do not include warm-up periods for steady-state specific analysis. The results from the simulation runs show that scheduling has definite and significant impacts on operations but larger improvements are seen from discretionary input control than from lot sequencing rules. Fabs that are characterized by controllable inputs can achieve improvements through strict and appropriate input control and fabs with priority-designated lots could achieve improvements in performance by using a better form of input control. There is an interaction observed between the combination of the type of the input and scheduling rules employed. It is concluded that the improvement from input control and lot sequencing depends upon factors like amount of variability in the effective processing

times, the actual-to-theoretical ratio, the number of bottleneck and non-bottleneck stations in the fab, the amount of rework required, the amount of “hot lots” or priority-designated lots processed and whether the fab is a production or R&D fab.

Domaschke, Brown, Robinson and Leibl (1998) investigate areas for improving productivity in production fabs with a goal to reduce cycle time by 60%. A project management approach is used for this methodology. Data is verified by visits to the shop floor and consultations with the floor personnel. The data is then used for constructing a model on Factory Explorer. These efforts and some other intuitive decision making lead to the mean values of the data to fall within 10% of historical values. The model is validated and sensitivity analyses conducted whose findings and recommendations are presented. Results include a 12% decrease in back-end cycle time, reduction in inventory, efficient utilization of bottleneck tools, other reductions in cycle time due to elimination of tool dedication at bottlenecks and modifications to operator staffing. Making lot release less variable and modifying the batch size for material handling also realize significant cycle time reductions. The overall result on the cycle time due to these modifications is a 41% decrease. The actual implementation of these techniques leads to a 32% decrease in cycle time for back-end manufacturing.

Hung and Chen (1998) establish that shortest-processing-time, earliest-due-date, simulation-based and least-slack are good dispatching rules for cycle time reduction but they can result in negative effects in practice. Flow-time based decisions rather than those based on waiting times and complex look-ahead based dispatching techniques are more suited to semiconductor manufacturing facilities. Production management decisions are better made using active flow time prediction. Changes made to the SRPT rule that would also account for remaining flow time would render the rule a much better one to use.

Sada, Yuen, Ichikawa, Yamada and Kabata (2001) describe a simple technique of achieving cycle time reduction in semiconductor fabs. Theoretical queue time is compared with actual queue times to identify opportunities for cycle time reduction. This theoretical queue time is calculated using operations research queuing theory with due weight age given to the influence of very high priority lots or “super hot lots”. The average queue time increases due to the influence of the extremely high priority lots on normal processing. Equipment utilization decreases based on the number and process time of the “super hot lots”. Lot transfer time is assumed to be equal for all equipment types for simplicity. Also mean process times are entered into the spreadsheet, which are calculated depending on hours per wafer or per batch. If actual queue times exceed theoretical queue times, the concerned equipment groups are candidates for productivity improvements. A process improvement in average steps/day across the fab of 24% and queue time reduction of 21% are realized by placing the responsibility on the respective process operator. A maximum number of super hot lots are calculated to keep damage to fab progress under 5%.

Narahari et al. (1997) study the effects of hot lots or high priority jobs in semiconductor manufacturing systems using mean value analysis (MVA). The performance metrics considered are mean steady-state cycle time, variance of steady-state cycle time and mean steady-state throughput rates of hot lots and regular lots. The analysis method models scheduling policies such as LBFS (Last Buffer First Serve) and FBFS (First Buffer First Serve). Detailed simulations of several re-entrant lines validate and verify the analytical method and the accuracy of the performance predictions. It is found that the MVA approximation is effective and accurate in performance prediction of semiconductor manufacturing facilities in the presence of hot lots.

Fronckowiak et al. (1996) use the semiconductor manufacturing line simulator, ManSim/X, to analyze the impact of different percentages of hot lots on the cycle times of two different products to develop rules of thumb to release high priority lots so as not to significantly alter the overall cycle time of the product. A constant work in process is maintained and the assumed lot size is 25 wafers. Cycle time graphs are generated for increasing percentages of both the products relative to base cycle time with no hot lots. Bar graphs are also generated to compare increasing cycle time for hot lots of product 1 at various percentage hot lots of product 2. Also, deviation of regular lot cycle time and hot lot cycle time due to the effects of the increased hot lots and comparison of the effects of hot lots for both products on manufacturing cycle time for regular lots are plotted. Discrete event simulation is thus used to investigate the impact of hot lots in a fab. It is concluded that the percentage of hot lots in a manufacturing line should be maintained between 10% and 20%.

Ehteshami et al. (1992) talk about object oriented simulation experiments on a wafer fabrication model to study the impact of hot lots on the cycle time of other lots in the system. The simulation experiments are setup to maintain a constant WIP even though this release strategy has proven to be inferior to other rules like the bottleneck starvation avoidance policy. In reality, a factory manager is provided with a maximum number of hot lots that can be in the system at any time. The use of the constant WIP release strategy means that a certain classification of lots will not be started into the facility unless the same type came out at the other end. Hot lots are given priority over regular lots with no interruption of current service. Lots of same classes are prioritized by the FIFO rule. The model is run at different WIP levels with a constant lot size of 50 wafers. The number of hot lots changed for each of five scenarios for each level ranging from 0% to 16.7%, which corresponds to findings in industry. With a constant WIP

for each of the two classifications of lots, the system's throughput rate is larger than the ratio of the respective WIP levels. This conclusion is derived using the equation $L = \lambda w$, where L is the average WIP in the system, λ is the average throughput rate and w is the average cycle time. The simulation results show that the overall cycle time and equipment utilization levels remain constant as the proportion of hot lots in the fab varies. The overall variance of cycle time distribution increases dramatically when more hot lots are introduced in the system, given a constant WIP level. As more and more hot lots are introduced in the WIP, the average and standard deviation of cycle time for these lots will become large.

Lee et al. (2000) in their paper, "Super-Hot-Runs Management System" create a system which can make sure that cycle time of push lots can be kept under 0.8 days/layer and keep the average cycle time in manageable proportions. Cycle time is subdivided into running time, holding time and queue time. It is concluded that reducing queue times is the only opportunity to improve push lots' cycle times. Reasonable queue times must be identified to meet customers' required deadlines. The formula of reasonable step queue time is $(\text{Required days} - \text{Theoretical process time}) / \text{Total step no.}$. When a new push lot is introduced in the system, operators are made aware of its presence and the production team is equipped to track the path. A pre-announcement is made to preempt regular lots from processing on machines 5 steps downstream. Certain operating disciplines, rules and procedures are followed by the operators, which are the keys to cycle time reduction. The status of the lot can be checked to see if it will be delayed or is ahead of time. If the slack for a lot is negative, it implies that the lot will be delayed. Remaining processing time in days is given by $\text{Due date} - \text{Current time in system (in days)}$. Demand cycle time is given by $\text{Remaining Layers} * \text{Cycle Time goal (0.8 days per layer)}$. If $\text{Due Date} > \text{Demand cycle time}$, the slack is positive and the super-hot-lot can be completed on time. The

forecast system, the current status and event history also give lot status. This enables the analysis of the root cause of any delay. Data collection in a database system can be used to analyze performances and make new strategies. Hence using the PDCS (Plan, Do, Check, Action) concept, the cycle time goals of 0.8 days/layer for super-hot-lots and one day/layer for pilot lots are achieved. These improvements have a positive impact on queue time percentage of cycle time also.

Chikamura, Nakamae and Fujioka (1999) evaluate the effect of express lots on production dispatch rule testing and cost in VLSI manufacturing final test process. The FIFO and WEIGHT+RPM rules are used and compared in the assignment of express lots. The simulation model has two queues set for each station - one for regular lots and the other for express lots. The three production rules applied to each stage and station are FIFO, JIG and WEIGHT+RPM. The JIG rule enables the lot in queue with the least preparation time to process on a free machine. The WEIGHT+RPM rule considers time for jig and temperature exchanges, the remaining process time of the machine in use and the lot waiting time in queue. If a machine becomes free, an optimum combination of the machine and lot in queue is selected using the following equation:

$$W = (\text{preparing time}) - K * (\text{waiting time in queue})$$

where K is the constant to consider the waiting time in queue and is estimated roughly from the number of past tested lots per month and their test flows. 100 replications of a six-month run time simulation are executed. Assumptions made are the regular lots have a due date of one week after they arrive at the final test facility and every express lot must be processed as soon as possible. The proportion of express lots in the total planned lots is varied from 0% to 100%. When using the FIFO rule, the number of total processed lots decreases with an increase in the

number of express lots. When using the WEIGHT+RPM rule, the decrease in number of total processed lots is very small even for 50% of the WIP accounting for express lots. The average test turnaround time (TAT) of regular lots increases when WIP content of express lots exceeds 10% for FIFO rule but does not increase for up to express lot content of 30% for the WEIGHT+RPM rule. Also, tool efficiency and test cost per wafer also show the same trends for both rules. When using the WEIGHT+RPM rule express lot tolerance (ELT), defined as the maximum content of express lots which permit the deterioration of the system characteristics by 5% is thrice as high as ELT when using the FIFO rule.

DeJong and Wu (2002) present a paper describing a modeling approach to study the behaviors of priority lots and to quantify their impact to manufacturing. An integrated discrete event simulation modeling approach is used to evaluate the impact to performance metrics by factory components. The fab capacity model methodology has two key attributes specific to priority lots. The model can comprehend the different levels of priority assigned to the lots. P1, P2, P3 and NP are the priorities, where P1 has the highest priority, P2 has the second highest priority, P3 has the third highest priority and NPs are non-priority lots. The model also has the ability to model complex rules based on the priority of the lot. Lot priorities also affect AMHS (Automated Material Handling System) rules and classes. The model can track throughput time, WIP turns, units out, tool starvation rates and waiting times. The baseline model with no high priority lots is simulated. The model report shows that the throughput target is met. The model report also tracks the fastness of WIP movement through the line. An immediate impact to the non-priority lot is felt once a high priority lot is introduced. With increased amount of priority lots, the downstream machines are held idle to wait for these lots. Even though overall weekly

outs are not significantly impacted, the NP lot velocity and factory outs are significantly reduced with increasing proportion of high priority lots.

4 SIMULATION OF REPRESENTATIVE SEMICONDUCTOR R&D FABs

This thesis investigates methods to increase productivity and quantify the performance of semiconductor R&D fabs considering cycle time and throughput along with the influence of hot lots or high priority lots using system simulation with a focus on employing production control. Hence the research is operations based and narrows in on testing controllable parameters at different levels. The other techniques to improve productivity, which the research does not touch on are design, process and yield improvements among other technological enhancement possibilities.

Models of representative semiconductor R&D fabs are built and analyzed as part of three different experiments. The sub-sections in this chapter detail the modeling assumptions, description of the setup of the simulation software package to be used for the simulation and the methodology. The modeling assumptions include the considered constraints, operator actions and tool certifications for technicians. The capabilities and working of the simulation software are described in the setup section.

4.1 Simulation Model Assumptions and Details

The Complementary Metal Oxide Semiconductor (CMOS) recipe is chosen as the routing for the representative wafer lots. This recipe comes closest to matching the average tool usage in the SMFL. This ensures that the routing loads the fab like the actual tool usage in the fab. The constraints that stop these lots from processing on the tools are:

- Tool reservations;
- Down events;
- PM events;
- Off shift events; and

- Waiting times.

Tools are reserved for researchers with specific requests. Other researchers can use tools and other fab facilities during reserved hours. Shift calendars dictate the availability of fab personnel.

A researcher spends 8 hours in the fab, Mondays through Fridays, from 8 am to 4 pm. The model also has preemption provisions. The researcher will not put a lot on his worklist unless he has sufficient time on hand to process the lot. For e.g. the LPCVD tool requires a total processing time of 220 min and a lot has the LPCVD operation in the next step of its route. The researcher will not process the lot unless he has the full 220 min available before his shift ends. The simulation software package used, AutoSched AP, does not have the required preemption options, as is described above. To model such an event, control resources are added to the operator and station files. Every station and operator has a corresponding control station and control operator. These do not in any way affect the performance and statistics of interest related to the stations and workers. Each lot has to visit a control station each time it needs to be processed or re-processed on a given station. A control operator mans every control station. With the LPCVD control station in place, the lot has to visit the control station before being processed or placed in queue at the LPCVD station. The first lot in queue at the control station seizes both the control operator and the LPCVD operator and the control station for a processing time of 0 seconds. This means that all three resources have to be available for the lot to seize them. The control operator and control stations are then released and the LPCVD operator processes the lot at the LPCVD station. The transfer time from the control station to the LPCVD station is 0 seconds. These actions are shown in Figure 4.1. Now, the LPCVD operator cannot process a lot at the LPCVD station unless he has sufficient time before the end of his shift to complete all

processing the wafer lot. In this case, that time is 220 minutes. The control operator is thus made unavailable 220 minutes before the LPCVD operator ends his shift. This ensures that no lots go through for processing to the LPCVD station, since the control operator is not available to be seized by the lot at the control station for 220 minutes. This also ensures that the LPCVD operator does not process any lots at the LPCVD station for which there is not a sufficient enough time window for processing before his shift ends.

Figure 4.1: Resource Actions When LPCVD Operator Has Sufficient Time to Process a Lot Before End of Shift

Figure 4.2: Resource Actions When LPCVD Operator Has Insufficient Time to Process a Lot Before End of Shift

Action lists in the model provide sets of instructions or actions for task performance by the schedulable entity. Steps in the route either require a researcher to be present:

- for setup only
- for setup and processing

Custom action lists are made and associated with the steps in the route, according to their need for researchers as above.

Technical operators are dedicated to PM events and down times for tools. These operators are available Mondays through Fridays from 8:30 a.m. to 4 p.m. The model has a total of 5 technical operators with different certifications. The certifications are shown in Table 4.1. Tools undergo PM events or are forced down by lots whose processing time is equal to the time distribution for the PM event or the downtime of the tool. Order files are used to trigger these lots. PM events are deterministic events whereas downtimes are stochastic. Hence the inter-arrival time of the lots that cause the tools to go down is the mean time between failure (MTBF)

and the processing times for these lots as well as those that cause PM events is the mean time to repair (MTTR). When any one of these lots seizes a station, it also seizes a primary or a secondary technician, if specified, with the required certification. Order files are used to trigger PM events and downtimes because AutoSched AP does not have the provision for multiple technician certifications. Hence technicians have to use certifications, normally given to operators.

Table 4.1: Tool Certifications for Technicians

Technical Support	Tool Certification	Processing Efficiency
Tech. Worker 1	ASM LPCVD	1.00
	Branson Asher	0.66
	Drytek RIE	1.00
	Bruce furnace tubes	0.66
Tech. Worker 2	LAM 490 Plasma etch	1.00
	Varian 350D Implanter	1.00
	CVC-601 Sputter	1.00
Tech. Worker 3	RCA Clean	1.00
	Canon & GCA Steppers	1.00
	Bruce furnace tubes	1.00
Tech. Worker 4	RCA clean	0.66
	Branson Asher	1.00
	Varian 350D Implanter	0.66
Tech. Worker 5	RCA clean	0.66
	Drytek RIE	0.66
	LAM 490 Plasma etch	0.66
	Varian 350D Implanter	0.66

The primary technician has a higher processing efficiency than the secondary technician. The secondary technicians operate at 2/3 times the efficiency as the primary technicians on the concerned tools. The secondary technician works on the tool only if the primary technician is busy or unavailable. PM events never interrupt a resource from processing a wafer lot. The scheduled PM comes into effect once the resource finishes processing on the lot. All resources in

the fab including the technical operators have a capacity of 1. This means that they can process only one entity at a time.

Data used for modeling the fabs for Experiments 1, 2 and 3 and the assumptions made are detailed in the workbooks on the CD attached to the back cover of the bound thesis. The contents of the spreadsheets are briefly described in Table G.1 of Appendix G.

4.2 Simulation Software Setup

The representative semiconductor R&D fab is simulated using Brooks Automation's Autosched AP (ASAP), a discrete-event simulation software package. Autosched AP, a finite capacity planning and scheduling tool is used to model the working of factories. The factory's real system terms are translated into model terms

ASAP uses worksheets to allocate stations, routes, orders, parts and storage. The categories of data essential for model creation are resources, products and demands. These data sets can be imported from other databases or from the shop floor control system. (Phillips, 1998). Autosched AP models systems using the following:

- Calendars;
- Random Distributions;
- ASAP Extensions;
- ASAP Action Lists; and
- ASAP Dispatch Rules.

ASAP supports constant, normal, exponential, weibull, uniform, lognormal, triangular and gamma distributions. Standard extensions can be employed to use other distributions. Extensions in ASAP are dynamic linked libraries that enhance the features of the model. Actions lists allow users to choose how they want to model resource behavior and data access. Process

and preempt are the two types of action lists used. Dispatch rules are standard for all resources. The same rule engine is used to dispatch stations, operators and resources. The dispatch rules determine lot queue ranking, lot selection and batching of lots. (Phillips, 1998)

4.3 Verification and Validation

Once the simulation model is built, verification is done to ensure that the AutoSched AP model runs as is intended. The software package includes a message file that can be read at the end of every simulation run. Events are traced in the message file and this allows for the user to conduct verification steps such as walkthroughs and checking for errors. This message file feature is used to authenticate the modeling of end of shift effects, technician certification and tool downtime and PM events.

After the verification process, the model is validated to ensure that it adequately represents a semiconductor R&D fab. Discarding outliers and suspicious entries and walkthroughs with experts validates data on stations, routings, process and setup times, pulled from the Camstar Manufacturing Execution System Application (MESA) database at RIT. Information on down times, preventive maintenance (PM) events and statistics on distributions for these events are obtained by compiling empirical data from the MESA. All the data and the information are validated as exclusive to typical semiconductor R&D fabs. The specific characteristics may differ from fab to fab but essential characteristics like down times, PM events, single shifts and the representative product load that are built into the model are representative of semiconductor R&D fabs.

5 EXPERIMENTS AND RESULTS

As mentioned in the problem statement (Chapter 2), this thesis investigates production control methods to quantify the performance of semiconductor R&D fabs. This chapter details the methodology and the results obtained, of the experiments carried out. The following are the experiments conducted, which have been detailed in the subsequent sections:

- Experiment 1: The Effect of WIP on Average Cycle Time and Throughput
- Experiment 2: The Effect of Resource Levels and WIP on Productivity
- Experiment 3: Comparing Primary/Secondary Dispatching Rules

5.1 Experiment 1: The Effect of WIP on Average Cycle Time and Throughput

This experiment is conducted to comprehend the effects of change in WIP to average cycle time and throughput in semiconductor R&D fabs. Little's law in equation form is, $L = \lambda * W$. Little's law equates the average number of jobs in the system (L) to the product of the average arrival rate of the jobs (λ) and the average time a job spends in the system (W). Little's law is used in queuing theories and is applied to areas such as manufacturing and logistics, among others. In this case of the simulation model of the representative R&D fab, Little's Law equates WIP to the product of average cycle time and throughput. Hence, $WIP = \text{Average Cycle Time} * \text{Throughput}$. WIP, in this experiment is used as the independent variable and the average cycle time and throughput are recorded at different levels of WIP. The goal of this experiment is to investigate the changes of WIP to the average cycle time and throughput in the confines of Little's law.

5.1.1 The Experimental Design

A simulation model of a representative R&D fab is built (For details see section 4: Simulation of Representative Semiconductor R&D Fabs). Typical characteristics of

semiconductor R&D fabs are modeled, which include end of shift effects, different levels of certifications for technicians, a representative product routing, random tool breakdowns and preventive maintenance events. The queuing discipline chosen is FIFO. A representative CMOS routing is used where every wafer lot accounts for a full time equivalent (FTE) researcher. This representative routing is chosen as it approximates tool usage in the fab. As mentioned earlier, WIP is used as the independent variable. The WIP levels tested range from 1 to 30 with increments of 1. For e.g., at a WIP level of 6, there are 6 lots in process in the system and a lot enters the system, only, each time a lot in process traverses all the steps in the representative product routing. This is essentially a pull system. Every lot in the WIP is a research project carried out by a FTE researcher. An assumption is made that with the given number of tools in the fab and the steps in the representative product routing, not more than 30 researchers can be present in the fab at any given time. The replication/deletion method is used to run the simulations. Each run has a warm-up period of to bring the model into the steady state and five replication runs of 6 years each. This replication deletion method ensures that the replications are independent of the initial warm-up period. Multiple replications are conducted to ensure that each replication is independent and identically distributed. It is sufficient to conduct five replications to minimize variation between these replications. Table 5.1 shows that at a WIP of 12, the average cycle time is approximately 1296 hours with a very small half-width value, which is within 1% of this cycle time.

Table 5.1: Average Cycle Time Values by Replication for WIP=12 lots

Average Cycle Time (hours) by replication					Average Cycle Time (hours)	Standard Deviation (hours)	Half-Width at 95% CI
Rep. 1	Rep. 2	Rep. 3	Rep. 4	Rep. 5			
1284	1304	1299	1286	1306	1295.8	10.2	12.7

5.1.2 Results and Productivity Graphs

The graphs in Figure 5.1 and Figure 5.2 plot WIP vs. Average Cycle Time and WIP vs. Throughput respectively. The average cycle time and throughput values are average values from the five replication runs for each level of WIP. The graphs indicate that at a certain WIP level, production reaches a maximum level. Increasing the WIP level from here on increases the cycle time without significant increase in throughput. As the WIP increases from 1 to 12, the throughput goes up from 12 to 81 lots/year with a cycle time increase from 1000 total hours to 1590 total hours. Increasing the WIP beyond this point until 30 results in no increase in throughput, whereas cycle time progressively increases to a high of 3250 total hours.

Figure 5.1: WIP vs. Average Cycle Time

Figure 5.2: WIP vs. Throughput

Figure 5.3: Cycle Time / Throughput Tradeoff

Figure 5.3 is a cycle time/throughput tradeoff graph. This graph plots WIP vs. a Half-WIP multiplier. For a given WIP, the Half WIP Multiplier (HW_x) graph compares throughput (T) and cycle-time (CT) metrics to those at half the WIP level. Extremes in performance are observed as follows:

- $T\text{-HW}_X \sim 2$ AND $CT\text{-HW}_X \sim 1$ (fab resources underutilized)
- $T\text{-HW}_X \sim 1$ AND $CT\text{-HW}_X \sim 2$ (fab resources overloaded)

The intersection of both HW_x curves suggests a nominal fab load considering the following tradeoffs:

- Decreasing the WIP below this level leads to lower cycle times for the researchers but underutilization of fab resources; and
- Increasing the WIP beyond this level can provide some increase in throughput, however researchers experience a large increase in cycle time.

Based on the plots from Figure 5.1 and Figure 5.2, the HW_x curves (Figure 5.3) are found to intersect at a WIP level of close to 12 and a HW of 1.4. This suggests that a compromise of 40% on cycle time and an increase of 40% on throughput may represent a nominal tradeoff. The underutilized region is not self-supporting, i.e. throughput is too low. This means that the revenue will be affected. The overburdened region has high throughput, however researchers can't get their project done due to high cycle times.

5.1.3 Conclusions of Experiment 1

A simulation model of a representative R&D fab is modeled, which incorporates typical characteristics of semiconductor R&D fabs. The experiment is conducted to record the effects of changing WIP levels to average cycle time and throughput, in the confines of Little's law, given the production uncertainties associated with semiconductor R&D fabs. The results indicate that

beyond a certain WIP level, average cycle time progressively increases with no increase in throughput. The simulation model of a given fab enables a fab manager to investigate possibilities to increase the capacity of the fab. This means achieving better average cycle time and throughput values at increased WIP levels as compared to the results obtained from simulating the base model of the fab. One of the ways this can be done is to increase resources in the fab. The resources can be tools, operators or technicians.

5.2 Experiment 2: The Effects of Resource Levels and WIP on Productivity

This experiment is conducted to quantify the effects of added resources to the fab layout to two levels of WIP. The previous experiment involves simulating a base model of a representative semiconductor R&D fab to comprehend the effects to average cycle time and throughput with increasing levels of WIP. This experiment enables a fab manager to evaluate the fab performance in terms of average cycle time and throughput with increased resources. Any increase in capacity due to added resources is the ability to accommodate more researchers in the fab, which in this case is the ability to accommodate more representative wafer lots as part of the WIP. The added resources in this case are tools and technicians.

5.2.1 The Experimental Design

A design of experiments is conducted with 2 levels on factors including WIP, number of tools and technical support. The performance measures are average cycle time and throughput. The simulation model for this experiment is the same as the one Experiment 1 uses, only with changes to the WIP and resource levels as described below. The queuing discipline stays as FIFO. From the results obtained in the previous section, a WIP of 12 is the recommended operating point for the fab with a nominal tradeoff between cycle time and throughput. This is chosen as one level for the WIP. A WIP of 16 is chosen as the higher level to test the capacity of the fab at the different levels of number of tools and technical support. A WIP of 16 as this level

allows the model to be tested with four additional researchers in the fab. From the initial runs of the base model, it is seen that the furnace and the LPCVD tool have the highest utilizations. The first level of the number of tools factor is the same as the base model, with no redundancy on these tools. In a steady state system, the bottleneck tools have the maximum utilization. Increasing the number of bottleneck tools leads to increased capacity. Hence, the higher level has 2 furnaces and 2 LPCVD tools. The technicians in the base model have different levels of certifications. These certifications dictate their performance on the tools that they can fix. The first level of the technical support factor has 5 technicians with primary and secondary certifications (See Table 4.1). The higher level of this factor sees the addition of a fully cross-trained technician with primary certifications on all tools. Table 5.2 shows the factors and their levels.

Table 5.2: Design of Experiments on Factors to Test R&D Fab Productivity

Factor	Level	
WIP	12	16
Number of Tools	Same number of tools as in base model	Added furnace and LPCVD tools
Technical Support	5 technicians with different levels of certifications	Added cross-trained technician

5.2.2 Results

Table 5.3 shows throughput and average cycle time values at all tested levels. At a WIP of 16, with tool redundancy and additional technical support, 126 lots per year are completed at an average cycle time of 1108 total hours. This translates to a 56% increase in throughput (compared to Experiment 1) with a marginal increase in cycle-time. Increase in resources (tools

and/or technical support) must be justified by the projected increase in throughput, as increased throughput means increased revenue.

Table 5.3: Run by Run Results of the Performed Experiment

WIP	Number of Tools	Technical Support	Throughput (lots/year)	Average Cycle Time (hours)
16	Added furnace and CVD tool	Added cross-trained technician	126	1108
12	Same number of tools as in base model	5 technicians with different levels of certifications	81	1296
12	Added furnace and CVD tool	5 technicians with different levels of certifications	112	939
16	Same number of tools as in base model	5 technicians with different levels of certifications	81	1722
12	Same number of tools as in base model	Added cross-trained technician	89	1180
16	Same number of tools as in base model	Added cross-trained technician	90	1541
16	Added furnace and CVD tool	5 technicians with different levels of certifications	123	1133
12	Added furnace and CVD tool	Added cross-trained technician	113	928

5.2.3 Conclusions of Experiment 2

A simulation model of a representative semiconductor R&D fab is run as part of a formally designed experiment to check for increased fab capacity. The different levels of resources and WIP in the designed experiment test capacity in terms of average cycle time and throughput. The results show improvements in average cycle time and throughput for the levels with added resources as compared to the results from Experiment 1. The dispatching rule for the lots is FIFO. Semiconductor R&D fabs employ various dispatching rules. Often times, these fabs

have lots with certain processing priorities in the product mix. The simulation model of the representative semiconductor R&D fab allows for the testing of different dispatching rules. Fab performance in such cases can be quantified by performance measures including percent on time delivery, average cycle time, standard deviation of cycle time and average WIP.

5.3 Experiment 3: Comparing Primary/Secondary Dispatching Rules

This experiment tests different levels of production volume, primary/secondary dispatching rules, due date tightness and product mix. Fab performance is quantified by performance measures including percent on time delivery, average cycle time, standard deviation of cycle time and average WIP. Running a simulation model of a semiconductor R&D fab with different levels of pertinent factors enables fab managers to use the best dispatching rules to minimize time-to-market.

“Hot Lots” or priority-designated lots as they are termed in this research are labeled as a factor causing capacity loss in semiconductor manufacturing. The other capacity loss factors that are pertinent to this research are Tool Dedication, End-of-Shift effects, Operator Cross-Training, Operator Availability, Preventive Maintenance, Reentrant Flow, Dispatch/Sequencing, Order Release, WIP Control and lack of Tool Redundancy (Robinson, Fowler, & Neacy, 2003).

The objective of this research is to find out which of the dispatching rules tested are the most robust. This means that they can be applied to a given semiconductor R&D fab, without a huge cycle time/on time delivery trade off. Also certain dispatching rules may perform better than others according to the prevalent operating conditions of the fab. The analysis of the results give a clear picture as to what rules can be applied for different scenarios.

This experiment is conducted to check if the effect of the application of different dispatching strategies has statistical significance on percent on time delivery, average cycle time, standard deviation of cycle time and average WIP.

5.3.1 Simulation Model

The literature review summarizes papers on the effects of “hot lots” to performance of production fabs. There is a need to study and analyze the effects to performance of R&D fabs due to the presence of priority-designated lots.

To model semiconductor R&D fabs it is important not to overlook what sets it apart from production fabs. The *Simulation of Representative Semiconductor R&D Fabs* chapter (Chapter 4) details the simulation model. An extra Chemical Vapor Deposition (CVD) tool is added to increase fab capacity. Tech. Worker 5 is given secondary certification on the CVD tool. The results from the initial design of experiments on tool redundancy and technical support justify these modifications (See 5.2 *Experiment 2: The Effects of Resource Levels and WIP on Productivity*). Priority-designated lots are introduced into the fab. These lots have three different classifications viz. H, M and L lots. These lots follow the same product routing.

5.3.2 The Experimental Design

A formally designed experiment is run with the factors being production volumes (PV), dispatching rules (DR), due date tightness (DDT) and product mix (PM). Table 5.4 shows the factors and their levels.

Table 5.4: The Design of Experiments

Factors/Levels	1	2	3	4	5	6	7
Production Volume (PV)	154 lots per year	128 lots per year	-	-	-	-	-
Dispatching Rules (DR)	P/FIFO	FIFO	CR/FIFO	HXT/FIFO	P/CR	P/HXT	LBA/FIFO
Due Date Tightness (DDT)	10,15,20	15,20,25	-	-	-	-	-
Product Mix (PM)	25-25-50	15-15-70	5-5-90	-	-	-	-

Production volumes are in lots started in the fab per year, dispatching rules consist of primary and secondary rules, in the format primary/secondary, due date tightness is in the format H,M,L and the numbers for H, M and L represent the flow factors, multiples of raw processing time, for high, medium and low priority lots respectively and the Product Mix which is the ratio of high, medium and low priority lots is given in the format H-M-L.

5.3.2.1 Production Volume

Production volume (PV) is used as a factor in the experimental design to control the lot starts into the fab. Semiconductor R&D fabs are characterized by varying levels of production volumes. It is important to vary the levels of the volumes to test for significance of this factor.

Having lots enter the fab at constant average interarrival rate levels of 57 hours and 68.4 hours controls the production volume. At a constant average interarrival rate of 57 hours, the bottleneck tool has a utilization of between 95% and 99%. The total lot starts amount to 154 lots/year. A constant interarrival rate of 68.4 hours sees a reduction in lot starts by 20% and this will indirectly ease the bottleneck utilization. Here, the number of lot stars amount to 128 lots/year.

Table 5.5: Inter-arrival Rates for Lots

Production Volume	Product Mix								
	Level 1			Level 2			Level 2		
	50% L	25% M	25% H	70% L	15% M	15% H	90% L	5% M	5% H
Level 1 (57 hour interarrival average)	114 hours	228 hours	228 hours	81.426 hours	380 hours	380 hours	63.333 hours	1140 hours	1140 hours
Level 2 (68.4 hour interarrival average)	136.8 hours	273.6 hours	273.6 hours	97.714 hours	456 hours	456 hours	76 hours	1368 hours	1368 hours

Table 5.5 lists the interarrival rates depending upon the desired product mix on the fab floor. The lot start rates for the different classification of priority-designated lots always average

to the desired level of the production volume. For e.g. for a product mix of 50% L lots, 25% M lots and 25% H lots, the lots start rates are 114 per hour, 228 per hour and 228 per hour respectively. This means that in a time window of 228 hours, 4 lots enter the fab with a constant average interarrival rate of 57 hours.

5.3.2.2 Dispatching Rules

Dispatching rules (DR) are used to rank wafer lots in resource worklists according to chosen lot attributes. These attributes may be time, due date or priority based or any combination of these. The dispatching rules used in this research are FIFO, Priority-based, Critical Ratio, Highest X-Theoretical Ratio first and Least Balance Ahead. The FIFO, Critical Ratio and Highest X-Theoretical Ratio rules are also used in conjunction with the Priority-based rule as secondary dispatching rules. Secondary dispatching rules break a possible tie between lots ranked by the primary dispatching rule.

Here is a brief description of the dispatching rules used in this research:

- **The Priority Dispatching Rule (P):** This rule ranks lots in resource worklists according to the processing priority associated with the lot. Higher priority lots are ranked ahead of lots with lower priorities. When the priority based rule is applied, the H lots get the highest priority in resource worklists and are ranked ahead of M and L lots, with the M lots having the second-highest priority and L lots having the least priority.
- **First-In-First-Out (FIFO):** This rule ranks lots according to their order of arrival on resource worklists. It treats lots on a first come first serve basis.
- **Critical Ratio (CR):**

$$\text{Critical Ratio} = \frac{\text{time until due}}{\text{remaining processing time}}$$

This rule ranks lots according to the lowest Critical Ratio first. A lot is late if its critical ratio is less than zero. The ratio is between one and zero when the lot's remaining processing time is greater than the time until its due date. The ratio is greater than one when the lot has more time for processing before it is due.

- **Highest X-Theoretical Ratio First (HXT):**

$$\text{X-Theoretical Ratio} = \frac{\text{total time in system}}{\text{theoretical processing time}}$$

This rule ranks lots according to the highest X-Theoretical Ratio first. The theoretical processing time is calculated by adding up the mean processing times for the steps in the route. The X-Theoretical value reflects the queue times. A ratio of one indicates that the queue time is zero. Lots with high X-theoretical ratios have been delayed longer than the ones with lower ratios.

- **Least Balance Ahead (LBA):** This rule ranks lots that have the least number of lots of the same part type in the next step in the route.

5.3.2.3 Due Date Tightness

Flow factors, which are multiples of the raw or theoretical processing times, are used to lay down due date tightness (DDT) levels. Flow factor multiplied by the raw processing time gives the target cycle time or lead time (Rose, 2002). The simulation software used, then calculates the due date for every lot by the estimated lead-time entered for the product. This due date critically affects the behavior of the CR rule, which is a due date based rule. The raw processing time for a wafer lot in the representative CMOS route is 83 hours. Two levels of target cycle times or due dates for each priority classification are tested. The first level employs due date tightness at 20, 15 and 10 times that of the raw processing time for low, medium and

high priority lots respectively. The second level tests these lots for on time delivery at 25, 20 and 15 times the raw processing time. These levels have been set taking into consideration the priorities of the lots and the urgency associated with these priorities.

5.3.2.4 Product Mix

In semiconductor R&D fabs, the definition of priority-designated lots may tend to differ. Ehteshami et al. (1992), in their paper tested the effects of these lots in ranges varying from 0% to 16.7%. While, this is true for semiconductor production fabs, this proportion may be exceeded in R&D fabs. In R&D fabs, high priorities may be assigned to lots based on the urgency and nature of the research and the lots' path in the product development cycle. This research assumes that the proportion of priority lots in the route may go up to 50% of total lots in the system. These lots, by way of applying dispatching rules, are given priority in queue at stations over those lots that have a lower level of urgency associated with them. Priority-designated lots follow the same routes as regular lots but are set apart due to the upgrade in priority. This research assumes that the priority-designated lots, apart from following the same representative product route, have the same number of wafers and belong to the same product type. The overall average cycle time essentially remains the same but due to the presence of variability in operations of R&D fabs, an overwhelming presence of priority-designated lots may cause this overall cycle time to increase.

Priority-designated lots are introduced in a fab to prove innovations. Various levels of priorities are run in the fab with pre-determined targets for completion that are multiples of theoretical cycle time. Targets are assigned so that these lots can be tested and revised so that new products can be introduced to the market at the earliest possible (Hillis, & Robinson, 2002).

Three levels of lot start percentages are used in order to vary the product mix (PM) on the fab floor. The L lots are tested at levels of 50%, 70% and 90% of the total lots with the remaining proportion being equally distributed between M and H lots.

5.3.3 Performance Measures

The performance measures analyzed in this study are the average cycle time, standard deviation of cycle time, percentage on time delivery and average WIP. These parameters reflect fab behavior and have been used widely for that purpose. The literature review section discusses papers that have used these parameters before.

The semiconductor R&D fab modeled as part of this research operates in one shift per weekday. The length of this shift varies from 8 to 10 hours per day. This means that all the above performance measures include the shelf times or the non-operational times of the fab. This is one reason that the flow factor is high as compared to those used for conventional production fabs. For e.g. if the fab shuts at 4 pm on a Monday and opens on 8 am on Tuesday, the lot cycle time will include the time spent by the lot in the state between the 4 pm on Monday and 8 am on Tuesday. It is important not to exclude this time from the performance measures since a characteristic of semiconductor R&D fabs is non-contiguous shifts.

The lot cycle time is hence defined as the total time taken by the lot to traverse from the lot start to the end of the product route. The Average Cycle Time averages the cycle times of the lots that make it out of the fab. The percentage on time delivery depends on the lots abiding by the set due dates (See 5.4.2.3 Due Date Tightness). The average WIP is the number of lots in process or on the worklist of resources at any given time in the fab during the simulation run length.

5.3.4 Statistical Analyses Procedures

The goal of this research is to determine which dispatching rules, due date tightness and combinations of the two are most suited to different levels of production volumes and production mixes. To come up with these results, detailed statistical analyses are required. The analyses are done using the statistical software program MINITAB after compiling the simulation results. See Appendix A for the data averaged from the replications of the simulation experiments.

Based on previous research, it is expected that the factors tested in this research are significant. An ANOVA (Analysis of Variance) test is conducted on all the four factors to determine whether the main effects and the interaction effects are significant. The p-value given in the ANOVA table established the statistical significance of the factors and their interactions. The level of confidence for the factor significance is set at 95%. Hence, a p-value of 0.05 or smaller makes the factor or an interaction significant. All the factors and their interactions are expected to be significant. This leads to a three factor investigation of dispatching rules, due date tightness and product mix for each of the two levels of product mix. These factors and their interactions are again expected to be significant. This leads to a two factor analyses which tests dispatching rules and due date tightness at every combination of production volume and product mix level. These analyses are especially important since the results will show the best combination of dispatching rules and due date tightness for a given R&D fab. The results are particularly useful when the due dates are not a controllable factor in fabs. The fab manager can instantly decide a production control strategy if the determination of due dates is beyond his control. Depending on whether the two factor interactions or the main effects are significant, Tukey pairwise comparison tests are done to determine which factor levels are statistically significant from each other. The Tukey family error rate is set at 5%. This test evaluates confidence intervals generated for the mean values for each performance measure at each level.

If the confidence interval limits span zero for the difference between a pair in the group, it can be concluded that the members of the pair are not statistically different from each other; else the members are statistically different from each other. After the two factor analyses and Tukey Tests are done, it becomes possible to list the combination of dispatching rules and due date tightness that perform the best for each level of product mix at each level of production volume.

The last set of analyses will test the performance of dispatching rules by using production volume, product mix and due date tightness as controlling factors. Again, ANOVA tables are analyzed for the significance of the main effect and Tukey Tests are conducted. A summary table gives the top group of dispatching rules for each fab type.

5.3.4.1 Analysis of All Factors and Their Interactions

All the experiments from the formally designed set of experiments are run. An ANOVA is conducted on all four factors under consideration. This analysis will determine the factors that significantly affect the performance measures. The performance measures chosen for analyses here are overall performance measures. The chosen level of confidence for the ANOVA is 95%. Most of the factors and their interactions are seen to be significant at this confidence level. Table 5.6 shows that all the factors and interactions for the percentage on time delivery performance measure are found to be significant. The ANOVA tables for percentage on time delivery are shown here to reflect the most important performance measure of the ones chosen in this research. ANOVA tables for the other performance measures can be seen in Appendix B. In the ANOVA table, single effects of the production volume (PV), dispatching rule (DR), due date tightness (DDT), and product mix (PM) and their interactions are shown. Table 5.7 summarizes the factors and/or interactions from the analyses of all the performance measures. S and N are abbreviations for significant and non-significant respectively.

Table 5.6: Analysis of All Factors and Interactions for % On Time Delivery

Source	DF	Seq SS	Adj SS	Adj MS	F	P
PV	1	54166.7	54166.7	54166.7	55634.0	0.000
DR	6	22321.7	22321.7	3720.3	3821.1	0.000
DDT	1	8321.8	8321.8	8321.8	8547.3	0.000
PM	2	17005.1	17005.1	8502.6	8732.9	0.000
PV*DR	6	31966.2	31966.2	5327.7	5472.0	0.000
PV*DDT	1	1678.9	1678.9	1678.9	1724.4	0.000
PV*PM	2	10407.9	10407.9	5204.0	5344.9	0.000
DR*DDT	6	1217.0	1217.0	202.8	208.3	0.000
DR*PM	12	15021.8	15021.8	1251.8	1285.7	0.000
DDT*PM	2	2736.0	2736.0	1368.0	1405.1	0.000
PV*DR*DDT	6	2452.3	2452.3	408.7	419.8	0.000
PV*DR*PM	12	16546.0	16546.0	1378.8	1416.2	0.000
PV*DDT*PM	2	1696.7	1696.7	848.4	871.3	0.000
DR*DDT*PM	12	5526.0	5526.0	460.5	473.0	0.000
PV*DR*DDT*PM	12	4855.2	4855.2	404.6	415.6	0.000
Error	168	163.6	163.6	1.0		
Total	251	196082.9				

Table 5.7: Summary of Factors and Interactions for All Performance Measures for the Four Factor ANOVA (S-Significant, N-Not Significant, at $\alpha=0.05$)

Effects and Interactions	% On Time Delivery	Average Cycle Time	Std. Dev. Of Cycle Time	Average WIP
PV	S	S	S	S
DR	S	S	S	S
DDT	S	N	N	N
PM	S	S	S	S
PV*DR	S	S	S	S
PV*DDT	S	N	N	N
PV*PM	S	S	S	S
DR*DDT	S	N	N	N
DR*PM	S	S	S	S
DDT*PM	S	N	N	N
PV*DR*DDT	S	N	N	N
PV*DR*PM	S	S	S	S
PV*DDT*PM	S	N	N	N
DR*DDT*PM	S	S	S	S
PV*DR*DDT*PM	S	S	S	S

5.3.4.2 Analysis of Dispatching Rules, Product Mix and Due Date Tightness With Given Levels of Production Volume

Once the four factor analyses have been complete, it is important to determine if the Dispatching Rules, Due Date Tightness and Product Mix and their interactions are significant for each level of production volume viz. 154 lots/year and 128 lots/year. For this purpose, an

ANOVA is conducted again. For the percent on time delivery response, Tables 5.8 and 5.10 shows that all the factors and their interactions are significant at a confidence level of 95%. The other ANOVA tables can be seen in Appendix C and Appendix D. Tables 5.9 and 5.11 summarize the factors and/or interactions for all performance measures.

Table 5.8: Three Factor ANOVA Table for % On Time Delivery in the Fab with PV=154 lots/year

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	53187.5	53187.5	8864.6	4870.0	0.000
DDT	1	8738.2	8738.2	8738.2	4800.6	0.000
PM	2	27005.9	27005.9	13503.0	7418.3	0.000
DR*DDT	6	2624.4	2624.4	437.4	240.3	0.000
DR*PM	12	31215.2	31215.2	2601.3	1429.1	0.000
DDT*PM	2	4044.9	4044.9	2022.4	1111.1	0.000
DR*DDT*PM	12	10049.0	10049.0	837.4	460.1	0.000
Error	84	152.9	152.9	1.8		
Total	125	137018.0				

Table 5.9: Summary of Factors and Interactions for All Performance Measures for the Three Factor ANOVA with PV=154 lots/year (S-Significant, N-Not Significant, at $\alpha=0.05$)

Effects and Interactions	% On Time Delivery	Average Cycle Time	Std. Dev. Of Cycle Time	Average WIP
PV	S	S	S	S
DR	S	S	S	S
DDT	S	N	N	N
PM	S	S	S	S
PV*DR	S	S	S	S
PV*DDT	S	S	S	S
PV*PM	S	S	S	S
DR*DDT	S	N	N	N
DR*PM	S	S	S	S
DDT*PM	S	N	S	N
PV*DR*DDT	S	S	S	S
PV*DR*PM	S	S	S	S
PV*DDT*PM	S	S	S	S
DR*DDT*PM	S	S	S	S
PV*DR*DDT*PM	S	S	S	S

Table 5.10: Three Factor ANOVA Table for % On Time Delivery in the Fab with PV=128 lots/year

Source	DF	Seq SS	Adj SS	Adj MS	F	P
PM	2	407.1	407.1	203.6	1602.9	0.000
DR	6	1100.4	1100.4	183.4	1444.2	0.000
DDT	1	1262.5	1262.5	1262.5	9941.8	0.000
PM*DR	12	352.6	352.6	29.4	231.4	0.000
PM*DDT	2	387.9	387.9	193.9	1527.1	0.000
DR*DDT	6	1044.9	1044.9	174.2	1371.3	0.000
PM*DR*DDT	12	332.1	332.1	27.7	217.9	0.000
Error	84	10.7	10.7	0.1		
Total	125	4898.2				

Table 5.11: Summary of Factors and Interactions for All Performance Measures for the Three Factor ANOVA with PV=128 lots/year (S-Significant, N-Not Significant, at $\alpha=0.05$)

Effects and Interactions	% On Time Delivery	Average Cycle Time	Std. Dev. Of Cycle Time	Average WIP
PV	S	S	S	S
DR	S	S	S	S
DDT	S	S	S	S
PM	S	S	S	S
PV*DR	S	S	S	S
PV*DDT	S	S	S	S
PV*PM	S	S	S	S
DR*DDT	S	S	S	S
DR*PM	S	S	S	S
DDT*PM	S	N	N	N
PV*DR*DDT	S	S	S	S
PV*DR*PM	S	S	S	S
PV*DDT*PM	S	S	S	S
DR*DDT*PM	S	N	N	N
PV*DR*DDT*PM	S	S	S	S

5.3.4.3 Analysis of Dispatching Rules and Due Date Tightness With Given Levels of Production Volume and Product Mix

The three factor ANOVA results are used as the basis for conducting a two factor ANOVA with the factors being Dispatching Rules and Due Date Tightness for each Product Mix level at each production volume level. Table 5.12 shows that the for the percent on time delivery response, all factors and their interactions are significant at a confidence level of 95%. All tables can be viewed in Appendix E.

Table 5.12: ANOVA Table for % On Time Delivery at PV=154 lots/year and PM = 25-25-50

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	23693.3	23693.3	3948.9	2648.6	0.000
DDT	1	2565.0	2565.0	2565.0	1720.4	0.000
DR*DDT	6	790.0	790.0	131.7	88.3	0.000
Error	28	41.7	41.7	1.5		
Total	41	27090.0				

From the tables it can be concluded that the dispatching rules, due date tightness and their interactions are significant for the percent on time delivery response, for each production volume and product mix. Now, the combinations of the factors, those significantly perform the best need to be determined. Although the main effects individually may be significant, Tukey tests are not conducted on them unless the interaction itself is not significant. If the interaction is shown as not significant, a Tukey Test is only conducted on the dispatching rules, since the due date tightness has only two levels, which is below the minimum of three required to carry out a Tukey test.

The vertical lines in the significance column group the strategies that are not statistically different from each other. In Table 5.13, the FIFO and 15,20,25 combination is not statistically different from the LBA/FIFO and 15,20,25 combination but is statistically different from the HXT/FIFO and 15,20,25 combination. The Tukey tables for all the performance measures at all levels of production volume and product mix can be seen in Appendix F.

Table 5.13: Tukey Pairwise Comparison Test for % On Time Delivery for PV=154 lots/year and PM=25-25-50

Dispatching Rule	Due Date Tightness (H,M,L)	% on time delivery	Sig.
FIFO	15,20,25	86.343	
LBA/FIFO	15,20,25	85.205	
HXT/FIFO	15,20,25	71.125	
FIFO	10,15,20	66.052	
LBA/FIFO	10,15,20	64.61	
P/CR	15,20,25	50.311	
P/HXT	15,20,25	50.109	
P/FIFO	15,20,25	49.856	
HXT/FIFO	10,15,20	41.303	
P/FIFO	10,15,20	39.406	
P/HXT	10,15,20	37.252	
P/CR	10,15,20	34.917	
CR/FIFO	10,15,20	0	
CR/FIFO	15,20,25	0	

Table 5.13 shows the Tukey comparison for the combination of Dispatching Rules and Due Date Tightness for percent on time delivery. FIFO and LBA/FIFO at flow factors of 15,20 and 25 for the H, M and N lots perform well. After all the Tukey tests are conducted, the top groups of strategies for each performance measure are listed. This will also serve the purpose of establishing if a strategy is robust across production mixes at that level of production volume.

Table 5.14 lists the top groups combination of dispatching rules and due date tightness strategies at a production volume of 154 lots/year at the three levels of product mix. The FIFO and LBA/FIFO rules at both the levels of due date tightness seem to perform well and are in the top groups for all levels of product mix for all responses except for percent on time delivery for the lower proportions of medium and high priority-designated lots and for one level of product mix for standard deviation of cycle time. It is interesting to observe that for percent on time delivery, the CR/FIFO rule comes into play when the fab has relatively fewer medium and high priority-designated lots and does not make it in the top groups for any level of product mix for average cycle time. The CR rule is a due date based rule and is expected to perform well for the

percent on time delivery and average cycle time performance measures. The due date based rules used in this research and their performances are discussed in a later section.

Table 5.15 lists the top groups combination of dispatching rules and due date tightness strategies at a production volume of 154 lots/year at the three levels of product mix. The due date based rules of CR/FIFO and P/CR at the second and more relaxed level of due date tightness find themselves in the top groups of all three levels of product mixes for the percent on time delivery response.

Table 5.14: Top Groups of Strategies for PV=154 lots/year

PM	% On Time Delivery	Average Cycle Time	Std. Dev. Of Cycle Time	Average WIP	Robust Strategies Across Performance Measures
25-25-50	FIFO 15,20,25 LBA/FIFO 15,20,25	FIFO 10,15,20 FIFO 15,20,25 LBA/FIFO 10,15,20 LBA/FIFO 15,20,25 HXT/FIFO 10,15,20 HXT/FIFO 15,20,25 P/HXT 10,15,20 P/HXT 15,20,25	HXT/FIFO 10,15,20 HXT/FIFO 15,20,25 FIFO 10,15,20 FIFO 15,20,25 LBA/FIFO 10,15,20 LBA/FIFO 15,20,25 CR/FIFO 10,15,20 CR/FIFO 15,20,25 P/HXT 10,15,20 P/HXT 15,20,25	FIFO 10,15,20 FIFO 15,20,25 LBA/FIFO 10,15,20 LBA/FIFO 15,20,25 HXT/FIFO 10,15,20 HXT/FIFO 15,20,25 P/HXT 10,15,20 P/HXT 15,20,25 CR/FIFO 10,15,20 CR/FIFO 15,20,25	FIFO 15,20,25 LBA/FIFO 15,20,25
15-15-70	CR/FIFO 15,20,25 P/FIFO 15,20,25 P/HXT 15,20,25	FIFO 10,15,20 FIFO 15,20,25 LBA/FIFO 10,15,20 LBA/FIFO 15,20,25 HXT/FIFO 10,15,20 HXT/FIFO 15,20,25 P/FIFO 10,15,20 P/FIFO 15,20,25	HXT/FIFO 10,15,20 HXT/FIFO 15,20,25 FIFO 10,15,20 FIFO 15,20,25 LBA/FIFO 10,15,20 LBA/FIFO 15,20,25	FIFO 10,15,20 FIFO 15,20,25 LBA/FIFO 10,15,20 LBA/FIFO 15,20,25 HXT/FIFO 10,15,20 HXT/FIFO 15,20,25 P/FIFO 10,15,20 P/FIFO 15,20,25	P/FIFO 15,20,25
5-5-90	CR/FIFO 15,20,25 P/FIFO 15,20,25 P/HXT 15,20,25	FIFO 10,15,20 FIFO 15,20,25 P/HXT 10,15,20 P/HXT 15,20,25 P/FIFO 10,15,20 P/FIFO 15,20,25 HXT/FIFO 10,15,20 HXT/FIFO 15,20,25 LBA/FIFO 10,15,20 LBA/FIFO 15,20,25	HXT/FIFO 10,15,20 HXT/FIFO 15,20,25	FIFO 10,15,20 FIFO 15,20,25 P/HXT 10,15,20 P/HXT 15,20,25 P/FIFO 10,15,20 P/FIFO 15,20,25 HXT/FIFO 10,15,20 HXT/FIFO 15,20,25 LBA/FIFO 10,15,20 LBA/FIFO 15,20,25	P/FIFO 15,20,25 P/HXT 15,20,25

Table 5.15: Top Groups of Strategies for PV=128 lots/year

PM	% On Time Delivery	Average Cycle Time	Std. Dev. Of Cycle Time	Average WIP	Robust Strategies Across Performance Measures
25-25-50	CR/FIFO 15,20,25 HXT/FIFO 15,20,25 P/CR 15,20,25 P/FIFO 15,20,25 P/HXT 15,20,25 FIFO 15,20,25 LBA/FIFO 15,20,25	P/FIFO 10,15,20 P/FIFO 15,20,25 P/HXT 10,15,20 P/HXT 15,20,25 FIFO 10,15,20 FIFO 15,20,25 P/CR 15,20,25 P/CR 10,15,20	HXT/FIFO 10,15,20	P/FIFO 10,15,20 P/FIFO 15,20,25 P/HXT 10,15,20 P/HXT 15,20,25 FIFO 10,15,20 FIFO 15,20,25 P/CR 15,20,25 P/CR 10,15,20	P/FIFO 15,20,25 P/HXT 15,20,25 FIFO 15,20,25
15-15-70	CR/FIFO 15,20,25 HXT/FIFO 15,20,25 P/CR 15,20,25 P/FIFO 15,20,25 P/HXT 15,20,25 LBA/FIFO 15,20,25 FIFO 15,20,25 P/FIFO 10,15,20 P/HXT 10,15,20 P/CR 10,15,20	P/HXT FIFO HXT/FIFO LBA/FIFO P/FIFO (@ both levels of DDT)	HXT/FIFO 10,15,20 HXT/FIFO 15,20,25	P/HXT FIFO HXT/FIFO LBA/FIFO P/FIFO (@ both levels of DDT)	P/FIFO 10,15,20 P/FIFO 15,20,25 P/HXT 10,15,20 P/HXT 15,20,25 LBA/FIFO 15,20,25 FIFO 15,20,25 HXT/FIFO 15,20,25
5-5-90	CR/FIFO 15,20,25 HXT/FIFO 15,20,25 LBA/FIFO 15,20,25 P/CR 15,20,25 P/FIFO 15,20,25 P/HXT 15,20,25 FIFO 15,20,25 CR/FIFO 10,15,20 P/CR 10,15,20 P/HXT 10,15,20 P/FIFO 10,15,20	P/HXT 15,20,25 HXT/FIFO 10,15,20 HXT/FIFO 15,20,25 P/HXT 10,15,20 FIFO 10,15,20 FIFO 15,20,25 LBA/FIFO 10,15,20 LBA/FIFO 15,20,25	HXT/FIFO 10,15,20 HXT/FIFO 15,20,25 P/HXT 15,20,25	P/HXT 15,20,25 HXT/FIFO 10,15,20 HXT/FIFO 15,20,25 P/HXT 10,15,20 FIFO 10,15,20 FIFO 15,20,25 LBA/FIFO 10,15,20 LBA/FIFO 15,20,25	HXT/FIFO 15,20,25 LBA/FIFO 15,20,25 P/HXT 10,15,20 P/HXT 15,20,25 FIFO 15,20,25

5.3.4.4 Using Due Date Tightness as a Controllable Factor

By using due date tightness as a controllable factor, dispatching rules can be examined individually, as to what rules work best given a certain operating condition in the fab. In this case, the production volume, product mix and due date tightness are all used to generate 12 fab types. This is done to give fab managers a good indication as to what dispatching rules work best

for given operating conditions. Table 5.16 lists the levels of production volume, due date tightness and product mix under which each fab operates.

Table 5.16: Fab Type by Operating Condition

Fab Type	Production Volume (lots per year)	Due Date Tightness (multiples of raw processing time - H,M,L)	Product Mix (lot start percentages - H-M-L)
I	154	10,15,20	25-25-50
II	154	15,20,25	15-15-70
III	154	10,15,20	5-5-90
IV	154	15,20,25	25-25-50
V	154	10,15,20	15-15-70
VI	154	15,20,25	5-5-90
VII	128	10,15,20	25-25-50
VIII	128	15,20,25	15-15-70
IX	128	10,15,20	5-5-90
X	128	15,20,25	25-25-50
XI	128	10,15,20	15-15-70
XII	128	15,20,25	5-5-90

ANOVA and Tukey tests are conducted for all 12 fab types for all four performance measures. ANOVA tables and Tukey tests conducted for each fab type can be seen in Appendix F.

Table 5.17 lists the top groups of dispatching rules for every fab type for every performance measure. The last column contains those rules that perform consistently well for a given fab type across all performance measures. The rules that have been named robust in most cases perform well for percent on time delivery, average cycle time and average WIP. The standard deviation of cycle time measure gives an indication as to how consistent the average

cycle time of the lots in fab is. Hence rules find themselves as being robust even if they don't make it to the top group for the standard deviation of cycle time performance measure.

Table 5.17: Analysis of Dispatching Rules for the 12 Fab Types

Fab Type	% On Time Delivery	Average Cycle Time	Std. Dev. Of Cycle Time	Average WIP	Robust dispatching rules
I	FIFO LBA/FIFO	FIFO LBA/FIFO HXT/FIFO P/HXT CR/FIFO	HXT/FIFO FIFO LBA/FIFO CR/FIFO P/HXT	FIFO LBA/FIFO HXT/FIFO P/HXT CR/FIFO	FIFO LBA/FIFO
II	CR/FIFO P/FIFO P/HXT	FIFO LBA/FIFO HXT/FIFO P/FIFO	HXT/FIFO FIFO LBA/FIFO	FIFO LBA/FIFO HXT/FIFO P/FIFO	P/FIFO
III	P/FIFO P/HXT	FIFO P/HXT P/FIFO HXT/FIFO LBA/FIFO	HXT/FIFO	FIFO P/HXT P/FIFO HXT/FIFO LBA/FIFO	P/FIFO P/HXT
IV	FIFO LBA/FIFO	FIFO LBA/FIFO HXT/FIFO	HXT/FIFO FIFO LBA/FIFO CR/FIFO	FIFO LBA/FIFO HXT/FIFO	FIFO LBA/FIFO
V	LBA/FIFO	FIFO LBA/FIFO HXT/FIFO P/FIFO	HXT/FIFO FIFO LBA/FIFO	FIFO LBA/FIFO HXT/FIFO	LBA/FIFO
VI	CR/FIFO P/FIFO P/HXT	FIFO P/HXT P/FIFO	HXT/FIFO	FIFO P/HXT P/FIFO HXT/FIFO	P/FIFO P/HXT
VII	P/FIFO P/HXT CR/FIFO P/CR	P/FIFO P/HXT FIFO P/CR	HXT/FIFO	P/FIFO P/HXT FIFO P/CR	P/FIFO P/HXT P/CR
VIII	CR/FIFO HXT/FIFO P/CR P/FIFO P/HXT	P/HXT FIFO HXT/FIFO LBA/FIFO P/FIFO	HXT/FIFO	P/HXT FIFO HXT/FIFO LBA/FIFO P/FIFO	HXT/FIFO P/FIFO P/HXT
IX	CR/FIFO P/CR P/HXT P/FIFO	HXT/FIFO P/HXT FIFO LBA/FIFO	HXT/FIFO	HXT/FIFO P/HXT FIFO LBA/FIFO	P/HXT
X	CR/FIFO HXT/FIFO P/CR P/FIFO P/HXT FIFO	P/FIFO P/HXT FIFO P/CR	HXT/FIFO	P/FIFO P/HXT FIFO P/CR	P/CR P/FIFO P/HXT
XI	P/FIFO P/HXT P/CR CR/FIFO	P/HXT FIFO HXT/FIFO LBA/FIFO P/FIFO	HXT/FIFO	P/HXT FIFO HXT/FIFO LBA/FIFO P/FIFO	P/FIFO P/HXT
XII	CR/FIFO HXT/FIFO LBA/FIFO P/CR P/FIFO P/HXT	P/HXT HXT/FIFO FIFO LBA/FIFO	HXT/FIFO P/HXT	P/HXT HXT/FIFO FIFO LBA/FIFO	HXT/FIFO LBA/FIFO P/HXT

For the levels of product mix with lower proportions of low priority designated lots, it is seen that the FIFO and LBA/FIFO rules perform the best. The P/FIFO and P/HXT rules perform better for the lower level of production volume and for product mixes with higher proportion of low priority-designated lots. It is interesting to note that the due date based rules, CR/FIFO finds it self in the top group of almost all fab types for the percent on time delivery but is not a robust rule across other performance measures. Similarly, the HXT/FIFO rule performs consistently well for the standard deviation of cycle time performance measure for most fab types but is a robust rule only for two fab types.

5.3.4.5 Performance of the Due Date Based Rules

Past research has shown that due date-based rules like Critical Ratio (CR) and Earliest Due Date (EDD) perform well for due date constrained scenarios (Rose, 2002). Taking into account the good performance of the due date based rules; the CR/FIFO and P/CR rules have been used as levels in the dispatching rule factor while conducting simulations.

From the results in Table 5.17, it is clear that the CR/FIFO rule does not perform well across all the performance measures. The CR/FIFO performs well for the percent on time delivery response but fails to perform consistently well over the other measures. The P/CR rule is a robust rule for only one of the twelve fab types. Figures 5.4 and 5.5 show column graphs comparing percent on time delivery and average cycle time respectively of the due date based rules (CR/FIFO and P/CR) with those of the other robust rules (P/FIFO, P/HXT, LBA/FIFO and FIFO). It is seen that the CR/FIFO rule has extremes when it comes to percent on time delivery with value of either 0% or grater than 96%. The P/CR rule does not do very well when compared to the other rules. The CR/FIFO rule performs better than the P/CR rule for average cycle time but does poorly when compared to the other robust rules.

Figure 5.4: Comparison of % On Time Delivery Between the Due Date Based Rules and Four Robust Rules, for the 12 Fab Types

Figure 5.5: Comparison of Average Cycle Time Between the Due Date Based Rules and Four Robust Rules, for the 12 Fab Types

A few reasons for this unexpected behavior of the due date based rules maybe:

- Lots with high slack remain at the bottom of resource worklists to give way to lots with lesser slack;
- Newer lots with high slack always give way to older lots with lesser slack;
- High numbers of reentrant steps, characteristic to semiconductor process routes hinder lot progress on account of slack and/or priority; and
- Due date based rules exclusively cater to giving precedence to lots with least slack and hence for higher volumes of production or higher proportions of one level of priority, lots will often have negative slack because of waiting on resource lists for processing. On the other hand, when due date based rules give good percent on time delivery values for certain fab scenarios, tend to balance out the average cycle time among the many products in the fab. These average cycle time values are not as high as some other rules. This is where the due date rules lose out on being robust because there is no good tradeoff between on time delivery and cycle time.

5.3.5 Conclusions of Experiment 3

A formally designed experiment tests the representative semiconductor research and development simulation model. The factors include production volume, primary/secondary dispatching rules, due date tightness and product mix. Fab behavior is quantified in performance measures including percent on time delivery, average cycle time, standard deviation of cycle time and average WIP. Statistical analyses are first conducted on all factors to check for significance of the factors for all performance measures. Subsequently production volume, product mix and due date tightness are used as blocking factors on the next three sets of statistical analyses. It is concluded that the dispatching rules, FIFO, LBA/FIFO, P/FIFO and

P/HXT are the most robust dispatching rules across performance measures. The due date based dispatching rules; CR/FIFO and P/CR do not perform with the expected consistency.

The results of the statistical analyses conducted in this section enable fab managers to employ dispatching rules according to the production volume and product mix present in the given R&D fab. Also, if the fab managers have control of the due date of the products in the fab, they can employ the dispatching rules that perform the best, given the production volume and product mix. The use of these rules minimizes the time-to-market of these products.

5.4 Summary of Experiments

The experiments conducted and the results shown in this chapter deal with understanding the behavior of semiconductor R&D fabs and quantifying performance statistically.

First, a simulation model of a representative R&D fab is built to understand the relationship between WIP, average cycle time and throughput. It is seen from the graphs that the average cycle time of lots progressively increases with increase in WIP and throughput increases with increase in WIP initially but remains constant at a maximum production level. A performance tradeoff metric is used to determine the WIP level at which there is a nominal tradeoff between average cycle time and throughput.

Second, a design of experiments is conducted where the WIP, number of tools and number of technical support personnel are tested at different levels by using a formally designed experiment. This tests the capacity of the modeled fab. Having redundancy of bottleneck tools, an extra technician and increasing the WIP on the fab floor see gains for throughput and cycle time.

Lastly, priority-designated lots are introduced in the fab and production strategies are compared. High, medium and low are the three levels of priority-designated lots introduced in the fab. A formally designed experiment tests levels of production volume, product mix,

dispatching rules and due date tightness at different levels. The performance measures for production strategy evaluation are percent on time delivery, average cycle time, standard deviation of cycle time and average WIP. Production strategies are evaluated first by assigning production volume and product mix as controllable factors. It is observed that the due date based rule, CR/FIFO, performs well for product mixes where there are larger numbers of low priority-designated lots at a relaxed level of due date tightness. Although this rule does not find itself in the top groups for the average cycle time performance measure, it helps reduce the time to market for the fab products. Due date tightness then is assigned as a controllable factor and dispatching rules are evaluated according to 12 fab types with different levels of production volume, product mix and due date tightness. Again it is observed that the CR/FIFO rule performs well for fabs with lower proportions of medium and high priority-designated lots for the percent on time delivery performance measure. FIFO, LBA/FIFO, P/FIFO and P/HXT are observed to be the most robust dispatching rules across performance measures. Table 5.18 summarizes the best performance of these dispatching rules.

Table 5.18: Summary of Best Performing Rules

Scenarios	Robust Rules across performance measures
High Production Volume level and high proportion of high and medium priority-designated lots	FIFO LBA/FIFO
High Production Volume Level, relaxed due date and lower proportion of high and medium priority-designated lots	P/FIFO
High Production Volume level, tight due date and 70% low priority designated lots	LBA/FIFO
Both Production Volume levels, both due date levels and lowest proportion of high and medium priority-designated lots	P/FIFO P/HXT
Low Production Volume level, both due date levels and higher proportions of high and medium priority-designated lots	
Low Production Volume level, both due date levels and lowest proportion of high and medium priority-designated lots	P/HXT

6 SEMICONDUCTOR RESEARCH AND DEVELOPMENT FAB CASE STUDY

The Semiconductor and Microsystems Fabrication Laboratory (SMFL) at the Rochester Institute of Technology (RIT) is a semiconductor R&D fab, which offers processing resources and technical expertise in the design and development of microsystems to industrial and academic customers (<http://smfl.microe.rit.edu>). Researchers use the fab facilities during day shifts with the lab closing at 6 pm. The researchers may be college students or outsiders paying to use fab time. Applying the production strategies to the SMFL tests the results from the statistical analyses conducted in the previous chapter.

6.1 Simulation Model

The simulation model used for this case study uses the same assumptions and setup as described in *Simulation of Representative Semiconductor R&D Fabs* chapter (Chapter 4). A Sub-Micron CMOS recipe is chosen as the routing for the representative wafer lots. Tools are reserved for class labs according to the SMFL tool reservation timetable for the Fall quarter of 2003, see Figure 6.1. The researchers can use tools and other fab facilities during class lab hours except those that have been reserved during these hours. Five technicians work in the fab to repair tools that are down or to work on tools undergoing preventive maintenance events. The technicians and their tool certifications are as listed in Table 6.1. The primary technician has a higher processing efficiency than the secondary technician. The secondary technicians operate at $2/3$ times the efficiency as the primary technicians on the concerned tools. The secondary technician works on the tool only if the primary technician is busy or unavailable.

Fall 2003 Quarter Lab Schedule

Time	Sun	Monday	Tuesday	Wednesday	Thursday	Friday	Sat
7 to 8 am							
8 to 9 am							
9 to 10 am		632 Lab	201 Lab	201 Lab		701 Lab	
10 to 11 am							
11 to 12 pm					632 Lab		
12 to 1 pm							
1 to 2 pm							
2 to 3 pm							
3 to 4 pm		650 Lab	201 Lab	721 Lab	650 Lab	201 Lab	676 Lab
4 to 5 pm							
5 to 6 pm							

Figure 6.1: SMFL Tool Reservation Time Table

Table 6.1: SMFL Tool Certifications for Technicians

Technical Support	Tool Certification	Processing Efficiency
Bruce	ASM LPCVD	1.00
	Branson Asher	0.66
	Drytek RIE	1.00
	Bruce furnace tubes	0.66
Rich	LAM 490 Plasma etch	1.00
	Varian 350D Implanter	1.00
	CVC-601 Sputter	1.00
Dave	RCA Clean	1.00
	Canon & GCA Steppers	1.00
	Bruce furnace tubes	1.00
Scott	RCA clean	0.66
	Branson Asher	1.00
	Varian 350D Implanter	0.66
John	RCA clean	0.66
	Drytek RIE	0.66
	LAM 490 Plasma etch	0.66
	Varian 350D Implanter	0.66

6.2 The Experimental Design

The simulation model is tested at different levels of a formally designed experiment. The simulation model is run for a full-factorial design. Production volume (PV), dispatching rules (DR), due date tightness (DDT) and product mix (PM) are the factors and the performance measures are percent on time delivery and average cycle time. The levels of the designed experiment are shown in Table 6.2. PV is in lots per year, DDT is in terms of flow factors which are multiples of the raw processing time in the format H,M,L, for the high, medium and low priority-designated lots respectively and PM is the percentage of high, medium and low priority-designated lots present in the fab, in the format H-M-L.

Table 6.2: Design of experiments for the SMFL

Factors/Levels	1	2	3	4
Production Volume (PV)	90 lots per year	70 lots per year	-	-
Dispatching Rules (DR)	P/FIFO	CR/FIFO	P/HXT	LBA/FIFO
Due Date Tightness (DDT)	10,15,20	15,20,25	-	-
Product Mix (PM)	25-25-50	15-15-70	-	-

The dispatching rules used are CR/FIFO, LBA/FIFO, P/FIFO and P/HXT. LBA/FIFO, P/FIFO and P/HXT are the rules found to be the most robust across performance measures (See *Table 5.18: Summary of Best Performing Rules* in Chapter 5). CR/FIFO is used to check if its application continues to provide good values for the percent on time delivery performance measure. Primary/Secondary dispatching rules are tested under different scenarios, according to the different levels of PM, DDT and PV. The simulation model is run for eight such scenarios. Table 6.3 lists the operating conditions for these eight fab types.

Table 6.3: Fab Types for the SMFL

Fab Type	PV	DDT	PM
I	90	10,15,20	25-25-50
II	90	15,20,25	25-25-50
III	90	10,15,20	15-15-70
IV	90	15,20,25	15-15-70
V	70	10,15,20	25-25-50
VI	70	15,20,25	25-25-50
VII	70	10,15,20	15-15-70
VIII	70	15,20,25	15-15-70

6.3 Results

Table 6.4 lists the percent on time delivery and average cycle time values for the eight fab types by dispatching rule. The table also lists the dispatching rule that performs best as per the operating conditions of the fab type.

Table 6.4: Results from the Simulation Run of the SMFL

Fab Type	CR/FIFO		P/FIFO		P/HXT		LBA/FIFO		Best Rule
	% On Time Delivery	Average Cycle Time	% On Time Delivery	Average Cycle Time	% On Time Delivery	Average Cycle Time	% On Time Delivery	Average Cycle Time	
I	5.34	2021.9	43.45	2034.6	39.203	2020.4	75.23	1198.3	LBA/FIFO
II	7.29	1987.3	48.32	2034.6	59.64	2020.4	89.36	1198.3	LBA/FIFO
III	7.76	1994.6	80.36	1649.2	41.39	1756.08	92.71	1020.45	LBA/FIFO
IV	100	1809.5	99.75	1649.2	99.43	1756.08	94.23	1020.45	P/FIFO
V	98.84	980.45	99.06	956.4	98.94	967.98	79.08	976.6	P/FIFO
VI	100	993.67	100	956.4	100	967.98	98.43	976.6	P/FIFO
VII	97.99	991.24	100	950.5	99.93	948.98	88.84	948.8	P/HXT
VIII	100	997.65	100	950.5	100	948.98	96.78	948.8	P/HXT

It can be seen that the CR/FIFO rule gives good percent on time delivery values for most of the fab types, as seen earlier, but does not perform well for average cycle time. P/FIFO and P/HXT are robust across both performance measures for lower volumes of production. LBA/FIFO give good average cycle time values but fail to compete with the other rules for the percent on time delivery performance measure for lower production levels.

6.4 Conclusions of Case Study

A simulation model of the SMFL is used as a case study to test the results obtained from experiments described in Chapter 5. The due date based rule, CR/FIFO, fails to perform as the best rule for any fab type. The LBA/FIFO rule performs well for low production volumes and the P/FIFO and P/HXT rules perform well for high volumes of production. These results are similar to the results obtained for the experiments conducted in Chapter 5 for representative semiconductor R&D fabs. The results from this case study serve to successfully test the best performing dispatching rules, by operating scenarios and verify their performance.

7 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

7.1 Conclusions

Semiconductor Research and Development fabs feed the technology to semiconductor production fabs for commercial large-scale manufacturing. It is essential that this technology be transferred to the production fabs on time so as to be on par if not beat the competition. In other words, the time to market the technology has to be as short as possible. Previous research has touched on the prevalent conditions of semiconductor R&D fabs and improvement from a project management approach but not focused on the important issue of analyzing production control methodologies and strategies for semiconductor R&D fabs. This research involves understanding the behavior of semiconductor R&D fabs and evaluating fab specific production control methods to increase productivity by shortening the time to market of the products.

Initial experiments conducted show that with increase in the number of lots in the fab, the average cycle time dramatically rises with the throughput remaining constant. Also, tool redundancy and numbers and certifications of technical personnel have a direct bearing on the average cycle time and throughput. It is also concluded that a representative product load works well to provide an appropriate production load for analysis and evaluation purposes and also accounts for the variety of research activities in the fab. This led to conducting a last set of experiments to test production control methods for the best percent on time delivery, average cycle time, standard deviation of cycle time and average work-in-process, with the presence of three levels of priority designated lots. Simulation models of research fabs with varying levels of production volumes, product mixes, dispatching rules and due date tightness are run. All these factors are shown to be significant for the performance measures in question.

From the statistical analyses conducted from the simulation results, it is seen that the due date based rule CR/FIFO works well for the percent on time delivery response in most fab scenarios but fails to be a robust rule across all performance measures. The robust rules across performance measures are found to be the FIFO, LBA/FIFO, P/FIFO and P/HXT rules. The CR/FIFO rule can still be used as an effective dispatching rule to get the best percent on time deliveries but at the cost of cycle time of the lots in the fab. It works best in scenarios where the proportion of low priority-designated lots outweighs the proportion of medium and high priority-designated lots. The P/FIFO and P/HXT rules work best for all performance measures except when there is a heavy volume of production. In such cases the FIFO and LBA/FIFO prove to be robust rules.

7.2 Recommendations for Future Research

The findings and conclusions from this research provide opportunities for further research in the same area. The areas for future research in improving productivity in semiconductor R&D fabs can focus on alternative prioritization of lots, examining the effects of super-hot lots, further investigating the behavior of due date based rules and due date determination and selectively applying chosen dispatching rules

This research uses three levels of priority-designated lots. The dispatching rules that are not priority based like the CR, FIFO, HXT and LBA rules unless coupled with the priority rule as primary or secondary rules, do not acknowledge the priority of these lots. Further research can focus on giving some dispatching weight to according to the priority of the lots when using non-priority based rules. This could be used to break ties in queues or give priority to lots having relatively lower slack.

This research tests the effects of priority-designated lots and their varying proportions to fab productivity. These priority-designated lots take precedence in resource worklists according

to the level of priority associated with them but their presence does not warrant blocking tools downstream for processing purposes. Doing this ensures minimal waiting time for these lots and helps the average cycle time. This practice though, can prove disastrous for other lots in the fab and hold them up in worklists depending on the proportion of these lots in the fab. These lots are termed super hot lots and their effects to semiconductor R&D fab productivity need to be evaluated and quantified.

The due dates for lots in this research are determined by assigning a lead-time to the lots that enter the fab (Rose, 2002). This lead-time is assigned by multiplying a flow factor to the raw processing time of the lot. The flow factor in this case depends on the priority associated with the lot, in which case the lots with the highest priority have earlier due dates than the other lots. Another approach to determining due dates can be researched if the raw data collected does not provide a value.

The primary and secondary dispatching rules applied in this research are applied to worklists of all resources. A selective application of these rules to bottleneck tools or otherwise can be investigated. Also applying more than one dispatching strategy and dynamically changing strategies in semiconductor R&D fabs can be investigated.

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APPENDICES

The appendices contain raw data, process routings and statistical analyses conducted as part of this research. Every appendix is explained and contains labeled tables and figures.

Appendix A. Data Averaged from Replications of Simulation Runs For Experiment 3

This appendix has the data averaged from all the replications of all the runs of the designed experiment for Experiment 3. It is separated into two tables containing data from production levels of 154 and 128 lots/year respectively.

Table A.1: Data for Production Volume = 154 lots/year

Product Mix (lot start percentages, H-M-L)	Dispatching Rules (Primary/Secondary)	Due Date Tightness(flow factor - multiple of raw processing time, H,M,L)	Average % On Time Delivery	Average Cycle Time (hours)	Std. Dev. Of Cycle Time (hours)	Average WIP (lots)
25-25-50	CR/FIFO	10,15,20	0.00	2136.12	322.77	37.48
	FIFO	10,15,20	66.05	1261.26	100.55	22.13
	HXT/FIFO	10,15,20	41.30	1567.65	90.03	27.50
	LBA/FIFO	10,15,20	64.61	1286.48	110.52	22.57
	P/CR	10,15,20	34.92	4334.07	3393.54	77.07
	P/FIFO	10,15,20	39.41	3104.28	2132.61	54.36
	P/HXT	10,15,20	37.25	1866.98	903.92	32.75
	CR/FIFO	15,20,25	0.00	2556.43	357.29	44.85
	FIFO	15,20,25	86.34	1261.26	100.55	22.13
	HXT/FIFO	15,20,25	71.12	1567.65	90.03	27.50
	LBA/FIFO	15,20,25	85.20	1286.48	110.52	22.57
	P/CR	15,20,25	50.31	3477.67	2475.12	61.28
15-15-70	P/FIFO	15,20,25	49.86	3104.28	2132.61	54.36
	P/HXT	15,20,25	50.11	1866.98	903.92	32.75
	CR/FIFO	10,15,20	0.00	2231.15	293.95	39.14
	FIFO	10,15,20	79.62	1247.73	95.52	21.89
	HXT/FIFO	10,15,20	72.01	1320.98	63.62	23.18
	LBA/FIFO	10,15,20	91.38	1276.10	115.64	22.39
	P/CR	10,15,20	21.54	2747.41	1163.44	48.24
	P/FIFO	10,15,20	79.52	1369.50	319.67	24.03
	P/HXT	10,15,20	38.30	1520.81	353.39	26.68
	CR/FIFO	15,20,25	100.00	1572.35	302.66	27.58
	FIFO	15,20,25	91.73	1247.73	95.52	21.89
	HXT/FIFO	15,20,25	86.59	1320.98	63.62	23.18
5-5-90	LBA/FIFO	15,20,25	91.38	1276.10	115.64	22.39
	P/CR	15,20,25	29.91	3089.55	1379.88	54.16
	P/FIFO	15,20,25	99.96	1369.50	319.67	24.03
	P/HXT	15,20,25	99.93	1520.81	353.39	26.68
	CR/FIFO	10,15,20	96.52	1441.01	177.09	25.28
	FIFO	10,15,20	92.09	1255.87	103.51	22.03
	HXT/FIFO	10,15,20	90.65	1285.47	67.02	22.55
	LBA/FIFO	10,15,20	91.88	1306.48	121.81	22.92
	P/CR	10,15,20	8.01	2464.66	526.51	43.24
	P/FIFO	10,15,20	98.52	1283.30	169.24	22.51
	P/HXT	10,15,20	97.86	1281.73	143.01	22.49
	CR/FIFO	15,20,25	100.00	1560.85	207.74	27.38
	FIFO	15,20,25	96.52	1255.87	103.51	22.03
	HXT/FIFO	15,20,25	95.61	1285.47	67.02	22.55
	LBA/FIFO	15,20,25	96.63	1306.48	121.81	22.92
	P/CR	15,20,25	10.00	2774.09	622.60	48.66
	P/FIFO	15,20,25	100.00	1283.30	169.24	22.51
	P/HXT	15,20,25	100.00	1281.73	143.01	22.49

Table A.2: Data for Production Volume = 128 lots/year

Product Mix (lot start percentages, H-M-L)	Dispatching Rules (Primary/Secondary)	Due Date Tightness(flow factor - multiple of raw processing time, H,M,L)	Average % On Time Delivery	Average Cycle Time (hours)	Std. Dev. Of Cycle Time (hours)	Average WIP (lots)
25-25-50	CR/FIFO	10,15,20	97.52	1050.05	195.93	15.35
	FIFO	10,15,20	79.25	995.36	97.99	14.56
	HXT/FIFO	10,15,20	76.18	1024.62	71.91	14.98
	LBA/FIFO	10,15,20	77.95	1049.12	116.03	15.34
	P/CR	10,15,20	97.43	1009.98	177.32	14.77
	P/FIFO	10,15,20	98.34	979.09	160.25	14.32
	P/HXT	10,15,20	97.57	989.56	156.28	14.47
	CR/FIFO	15,20,25	100.00	1078.82	189.57	15.77
	FIFO	15,20,25	99.78	995.36	97.99	14.56
	HXT/FIFO	15,20,25	100.00	1024.62	71.91	14.98
	LBA/FIFO	15,20,25	99.39	1049.12	116.03	15.34
	P/CR	15,20,25	100.00	1002.60	190.03	14.66
	P/FIFO	15,20,25	100.00	979.09	160.25	14.32
	P/HXT	15,20,25	100.00	989.56	156.28	14.47
15-15-70	CR/FIFO	10,15,20	97.74	1044.69	159.72	15.27
	FIFO	10,15,20	87.03	972.18	92.31	14.21
	HXT/FIFO	10,15,20	87.21	972.80	69.59	14.22
	LBA/FIFO	10,15,20	87.12	974.46	90.52	14.24
	P/CR	10,15,20	98.91	1000.23	149.80	14.62
	P/FIFO	10,15,20	99.26	975.18	136.38	14.26
	P/HXT	10,15,20	99.00	965.37	114.84	14.11
	CR/FIFO	15,20,25	100.00	1058.18	166.58	15.47
	FIFO	15,20,25	99.65	972.18	92.31	14.21
	HXT/FIFO	15,20,25	100.00	972.80	69.59	14.22
	LBA/FIFO	15,20,25	99.83	974.46	90.52	14.24
	P/CR	15,20,25	100.00	1027.72	174.99	15.03
	P/FIFO	15,20,25	100.00	975.18	136.38	14.26
	P/HXT	15,20,25	100.00	965.37	114.84	14.11
5-5-90	CR/FIFO	10,15,20	99.70	1036.60	132.25	15.15
	FIFO	10,15,20	95.95	970.34	88.37	14.19
	HXT/FIFO	10,15,20	95.43	960.27	66.97	14.04
	LBA/FIFO	10,15,20	95.78	972.74	92.39	14.22
	P/CR	10,15,20	99.52	1010.82	127.16	14.77
	P/FIFO	10,15,20	99.30	1019.31	144.96	14.89
	P/HXT	10,15,20	99.43	962.02	83.57	14.06
	CR/FIFO	15,20,25	100.00	1053.66	146.33	15.40
	FIFO	15,20,25	99.91	970.34	88.37	14.19
	HXT/FIFO	15,20,25	100.00	960.27	66.97	14.04
	LBA/FIFO	15,20,25	100.00	972.74	92.39	14.22
	P/CR	15,20,25	100.00	1031.53	142.39	15.08
	P/FIFO	15,20,25	100.00	1019.31	144.96	14.89
	P/HXT	15,20,25	100.00	952.44	79.62	13.93

Appendix B. Four Factor ANOVA Results

This appendix lists the ANOVA tables for all four performance measures when all four factors are included. The p-value indicates the significance of the factors and the interactions.

Table B.1: Four Factor ANOVA Table for % On Time Delivery

Source	DF	Seq SS	Adj SS	Adj MS	F	P
PV	1	54166.7	54166.7	54166.7	55634.0	0.000
DR	6	22321.7	22321.7	3720.3	3821.1	0.000
DDT	1	8321.8	8321.8	8321.8	8547.3	0.000
PM	2	17005.1	17005.1	8502.6	8732.9	0.000
PV*DR	6	31966.2	31966.2	5327.7	5472.0	0.000
PV*DDT	1	1678.9	1678.9	1678.9	1724.4	0.000
PV*PM	2	10407.9	10407.9	5204.0	5344.9	0.000
DR*DDT	6	1217.0	1217.0	202.8	208.3	0.000
DR*PM	12	15021.8	15021.8	1251.8	1285.7	0.000
DDT*PM	2	2736.0	2736.0	1368.0	1405.1	0.000
PV*DR*DDT	6	2452.3	2452.3	408.7	419.8	0.000
PV*DR*PM	12	16546.0	16546.0	1378.8	1416.2	0.000
PV*DDT*PM	2	1696.7	1696.7	848.4	871.3	0.000
DR*DDT*PM	12	5526.0	5526.0	460.5	473.0	0.000
PV*DR*DDT*PM	12	4855.2	4855.2	404.6	415.6	0.000
Error	168	163.6	163.6	1.0		
Total	251	196082.9				

Table B.2: Four Factor ANOVA Table for Average Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
PV	1	38644331.0	38644331.0	38644331.0	3137.4	0.000
DR	6	24549724.0	24549724.0	4091621.0	332.2	0.000
DDT	1	1938.0	1938.0	1938.0	0.2	0.692
PM	2	5916571.0	5916571.0	2958286.0	240.2	0.000
PV*DR	6	22803778.0	22803778.0	3800630.0	308.6	0.000
PV*DDT	1	6123.0	6123.0	6123.0	0.5	0.482
PV*PM	2	5087377.0	5087377.0	2543689.0	206.5	0.000
DR*DDT	6	5691.0	5691.0	949.0	0.1	0.998
DR*PM	12	4868792.0	4868792.0	405733.0	32.9	0.000
DDT*PM	2	47051.0	47051.0	23525.0	1.9	0.151
PV*DR*DDT	6	16905.0	16905.0	2818.0	0.2	0.967
PV*DR*PM	12	5755096.0	5755096.0	479591.0	38.9	0.000
PV*DDT*PM	2	47241.0	47241.0	23620.0	1.9	0.150
DR*DDT*PM	12	1166802.0	1166802.0	97233.0	7.9	0.000
PV*DR*DDT*PM	12	1069073.0	1069073.0	89089.0	7.2	0.000
Error	168	2069337.0	2069337.0	12317.0		
Total	251	112055830.0				

Table B.3: Four Factor ANOVA Table for Std. Dev. Of Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
PV	1	9017439.0	9017439.0	9017439.0	749.0	0.000
DR	6	18475205.0	18475205.0	3079201.0	255.8	0.000
DDT	1	7830.0	7830.0	7830.0	0.7	0.421
PM	2	7063950.0	7063950.0	3531975.0	293.4	0.000
PV*DR	6	15435132.0	15435132.0	2572522.0	213.7	0.000
PV*DDT	1	12678.0	12678.0	12678.0	1.1	0.306
PV*PM	2	5970461.0	5970461.0	2985230.0	248.0	0.000
DR*DDT	6	70511.0	70511.0	11752.0	1.0	0.443
DR*PM	12	10580564.0	10580564.0	881714.0	73.2	0.000
DDT*PM	2	84247.0	84247.0	42124.0	3.5	0.032
PV*DR*DDT	6	96784.0	96784.0	16131.0	1.3	0.242
PV*DR*PM	12	10313784.0	10313784.0	859482.0	71.4	0.000
PV*DDT*PM	2	77336.0	77336.0	38668.0	3.2	0.043
DR*DDT*PM	12	508017.0	508017.0	42335.0	3.5	0.000
PV*DR*DDT*PM	12	497263.0	497263.0	41439.0	3.4	0.000
Error	168	2022629.0	2022629.0	12039.0		
Total	251	80233829.0				

Table B.4: Four Factor ANOVA Table for Average WIP

Source	DF	Seq SS	Adj SS	Adj MS	F	P
PV	1	17543.0	17543.0	17543.0	4512.3	0.000
DR	6	7600.3	7600.3	1266.7	325.8	0.000
DDT	1	1.0	1.0	1.0	0.3	0.619
PM	2	1824.8	1824.8	912.4	234.7	0.000
PV*DR	6	7151.8	7151.8	1192.0	306.6	0.000
PV*DDT	1	2.2	2.2	2.2	0.6	0.452
PV*PM	2	1608.1	1608.1	804.1	206.8	0.000
DR*DDT	6	3.1	3.1	0.5	0.1	0.992
DR*PM	12	1535.4	1535.4	128.0	32.9	0.000
DDT*PM	2	15.5	15.5	7.8	2.0	0.139
PV*DR*DDT	6	6.4	6.4	1.1	0.3	0.949
PV*DR*PM	12	1764.2	1764.2	147.0	37.8	0.000
PV*DDT*PM	2	15.5	15.5	7.8	2.0	0.139
DR*DDT*PM	12	371.1	371.1	30.9	8.0	0.000
PV*DR*DDT*PM	12	345.6	345.6	28.8	7.4	0.000
Error	168	653.2	653.2	3.9		
Total	251	40441.2				

Appendix C. Three Factor ANOVA Tables for Production Volume of 154 lots/year

This appendix lists the ANOVA tables from the statistical analyses of runs with production level of 154 lots/year.

Table C.1: Three Factor ANOVA Table for % On Time Delivery

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	53187.5	53187.5	8864.6	4870.0	0.000
DDT	1	8738.2	8738.2	8738.2	4800.6	0.000
PM	2	27005.9	27005.9	13503.0	7418.3	0.000
DR*DDT	6	2624.4	2624.4	437.4	240.3	0.000
DR*PM	12	31215.2	31215.2	2601.3	1429.1	0.000
DDT*PM	2	4044.9	4044.9	2022.4	1111.1	0.000
DR*DDT*PM	12	10049.0	10049.0	837.4	460.1	0.000
Error	84	152.9	152.9	1.8		
Total	125	137018.0				

Table C.2: Three Factor ANOVA Table for Average Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	47270190.0	47270190.0	7878365.0	320.8	0.000
DDT	1	7475.0	7475.0	7475.0	0.3	0.583
PM	2	10986728.0	10986728.0	5493364.0	223.7	0.000
DR*DDT	6	20545.0	20545.0	3424.0	0.1	0.991
DR*PM	12	10589608.0	10589608.0	882467.0	35.9	0.000
DDT*PM	2	94249.0	94249.0	47124.0	1.9	0.153
DR*DDT*PM	12	2234608.0	2234608.0	186217.0	7.6	0.000
Error	84	2063177.0	2063177.0	24562.0		
Total	125	73266580.0				

Table C.3: Three Factor ANOVA Table for Std. Dev. Of Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	33764926.0	33764926.0	5627488.0	233.9	0.000
DDT	1	20217.0	20217.0	20217.0	0.8	0.362
PM	2	13010958.0	13010958.0	6505479.0	270.4	0.000
DR*DDT	6	166059.0	166059.0	27676.0	1.2	0.341
DR*PM	12	20880645.0	20880645.0	1740054.0	72.3	0.000
DDT*PM	2	161507.0	161507.0	80753.0	3.4	0.040
DR*DDT*PM	12	1004887.0	1004887.0	83741.0	3.5	0.000
Error	84	2020807.0	2020807.0	24057.0		
Total	125	71030006.0				

Table C.4: Three Factor ANOVA Table for Average WIP

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	14734.4	14734.4	2455.7	316.5	0.000
DDT	1	3.1	3.1	3.1	0.4	0.533
PM	2	3429.1	3429.1	1714.6	221.0	0.000
DR*DDT	6	9.0	9.0	1.5	0.2	0.978
DR*PM	12	3292.3	3292.3	274.4	35.4	0.000
DDT*PM	2	31.1	31.1	15.5	2.0	0.141
DR*DDT*PM	12	716.4	716.4	59.7	7.7	0.000
Error	84	651.8	651.8	7.8		
Total	125	22867.2				

Appendix D. Three Factor ANOVA Tables for Production Volume of 128 lots/year

This appendix lists the ANOVA tables from the statistical analyses of runs with production level of 128 lots/year.

Table D.1: Three Factor ANOVA Table for % On Time Delivery

Source	DF	Seq SS	Adj SS	Adj MS	F	P
PM	2	407.1	407.1	203.6	1602.9	0.000
DR	6	1100.4	1100.4	183.4	1444.2	0.000
DDT	1	1262.5	1262.5	1262.5	9941.8	0.000
PM*DR	12	352.6	352.6	29.4	231.4	0.000
PM*DDT	2	387.9	387.9	193.9	1527.1	0.000
DR*DDT	6	1044.9	1044.9	174.2	1371.3	0.000
PM*DR*DDT	12	332.1	332.1	27.7	217.9	0.000
Error	84	10.7	10.7	0.1		
Total	125	4898.2				

Table D.2: Three Factor ANOVA Table for Average Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
PM	2	17221.0	17221.0	8610.5	117.4	0.000
DR	6	83312.1	83312.1	13885.3	189.4	0.000
DDT	1	585.8	585.8	585.8	8.0	0.006
PM*DR	12	34281.0	34281.0	2856.7	39.0	0.000
PM*DDT	2	42.4	42.4	21.2	0.3	0.749
DR*DDT	6	2052.7	2052.7	342.1	4.7	0.000
PM*DR*DDT	12	1266.7	1266.7	105.6	1.4	0.164
Error	84	6158.7	6158.7	73.3		
Total	125	144920.3				

Table D.3: Three Factor ANOVA Table for Std. Dev. Of Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
PM	2	23453.4	23453.4	11726.7	540.6	0.000
DR	6	145409.7	145409.7	24234.9	1117.2	0.000
DDT	1	290.6	290.6	290.6	13.4	0.000
PM*DR	12	13702.9	13702.9	1141.9	52.6	0.000
PM*DDT	2	76.2	76.2	38.1	1.8	0.179
DR*DDT	6	1235.6	1235.6	205.9	9.5	0.000
PM*DR*DDT	12	392.1	392.1	32.7	1.5	0.138
Error	84	1822.2	1822.2	21.7		
Total	125	186382.7				

Table D.4: Three Factor ANOVA Table for Average WIP

Source	DF	Seq SS	Adj SS	Adj MS	F	P
PM	2	3.8	3.8	1.9	120.0	0.000
DR	6	17.8	17.8	3.0	189.0	0.000
DDT	1	0.1	0.1	0.1	8.2	0.005
PM*DR	12	7.3	7.3	0.6	38.6	0.000
PM*DDT	2	0.0	0.0	0.0	0.3	0.739
DR*DDT	6	0.4	0.4	0.1	4.7	0.000
PM*DR*DDT	12	0.3	0.3	0.0	1.4	0.175
Error	84	1.3	1.3	0.0		
Total	125	30.9				

Appendix E. Two Factor ANOVA and Tukey Tables

The appendices in this section have ANOVA and Tukey test tables for the two factor analyses conducted. Depending on whether the two factor interactions or the main effects are significant, Tukey pairwise comparison tests are done to determine which factor levels are statistically significant from each other. The Tukey family error rate is set at 5%. The vertical lines in the significance column group the strategies that are not statistically different from each other.

Two Factor Analysis for Production Volume = 154 lots/year and Product Mix = 25-25-50

Table E.1.A: Two Factor ANOVA Table for % On Time Delivery

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	23693.3	23693.3	3948.9	2648.6	0.000
DDT	1	2565.0	2565.0	2565.0	1720.4	0.000
DR*DDT	6	790.0	790.0	131.7	88.3	0.000
Error	28	41.7	41.7	1.5		
Total	41	27090.0				

Table E.1.B: Two Factor Tukey Table for % On Time Delivery

Dispatching Rule	Due Date Tightness (H,M,L)	% on time delivery	Sig.
FIFO	15,20,25	86.343	
LBA/FIFO	15,20,25	85.205	
HXT/FIFO	15,20,25	71.125	
FIFO	10,15,20	66.052	
LBA/FIFO	10,15,20	64.61	
P/CR	15,20,25	50.311	
P/HXT	15,20,25	50.109	
P/FIFO	15,20,25	49.856	
HXT/FIFO	10,15,20	41.303	
P/FIFO	10,15,20	39.406	
P/HXT	10,15,20	37.252	
P/CR	10,15,20	34.917	
CR/FIFO	10,15,20	0	
CR/FIFO	15,20,25	0	

Table E.2.A: Two Factor ANOVA Table for Average Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	35850642.0	35850642.0	5975107.0	85.4	0.000
DDT	1	40752.0	40752.0	40752.0	0.6	0.452
DR*DDT	6	1324378.0	1324378.0	220730.0	3.2	0.017
Error	28	1959124.0	1959124.0	69969.0		
Total	41	39174897.0				

Table E.2.B: Two Factor Tukey Table for Average Cycle Time

Dispatching Rule	Due Date Tightness (H,M,L)	Avg. Cycle Time (hours)	Sig.
FIFO	10,15,20	1261.3	
FIFO	15,20,25	1261.3	
LBA/FIFO	10,15,20	1286.5	
LBA/FIFO	15,20,25	1286.5	
HXT/FIFO	10,15,20	1567.7	
HXT/FIFO	15,20,25	1567.7	
P/HXT	10,15,20	1867	
P/HXT	15,20,25	1867	
CR/FIFO	10,15,20	2136.1	
CR/FIFO	15,20,25	2556.4	
P/FIFO	10,15,20	3104.3	
P/FIFO	15,20,25	3104.3	
P/CR	15,20,25	3477.7	
P/CR	10,15,20	4334.1	

Table E.3.A: Two Factor ANOVA Table for Std. Dev. Of Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	47255809.0	47255809.0	7875968.0	111.2	0.000
DDT	1	167418.0	167418.0	167418.0	2.4	0.135
DR*DDT	6	1099612.0	1099612.0	183269.0	2.6	0.040
Error	28	1983488.0	1983488.0	70839.0		
Total	41	50506327.0				

Table E.3.B: Two Factor Tukey Table for Std. Dev. Of Cycle Time

Dispatching Rule	Due Date Tightness (H,M,L)	Std. Dev. (hours)	Sig.
HXT/FIFO	10,15,20	90	
HXT/FIFO	15,20,25	90	
FIFO	10,15,20	100.6	
FIFO	15,20,25	100.6	
LBA/FIFO	10,15,20	110.5	
LBA/FIFO	15,20,25	110.5	
CR/FIFO	10,15,20	322.8	
CR/FIFO	15,20,25	357.3	
P/HXT	10,15,20	903.9	
P/HXT	15,20,25	903.9	
P/FIFO	10,15,20	2132.6	
P/FIFO	15,20,25	2132.6	
P/CR	15,20,25	2475.1	
P/CR	10,15,20	3393.5	

Table E.4.A: Two Factor ANOVA Table for Average WIP

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	11253.6	11253.6	1875.6	84.8	0.000
DDT	1	15.2	15.2	15.2	0.7	0.414
DR*DDT	6	440.4	440.4	73.4	3.3	0.014
Error	28	619.4	619.4	22.1		
Total	41	12328.5				

Table E.4.B: Two Factor Tukey Table for Average WIP

Dispatching Rule	Due Date Tightness (H,M,L)	Avg. WIP	Sig.
FIFO	10,15,20	22.127	
FIFO	15,20,25	22.127	
LBA/FIFO	10,15,20	22.57	
LBA/FIFO	15,20,25	22.57	
HXT/FIFO	10,15,20	27.5	
HXT/FIFO	15,20,25	27.5	
P/HXT	10,15,20	32.75	
P/HXT	15,20,25	32.75	
CR/FIFO	10,15,20	37.477	
CR/FIFO	15,20,25	44.85	
P/FIFO	10,15,20	54.357	
P/FIFO	15,20,25	54.357	
P/CR	15,20,25	61.283	
P/CR	10,15,20	77.073	

Two Factor Analysis for Production Volume = 154 lots/year and Product Mix = 15-15-70

Table E.5.A: Two Factor ANOVA Table for % On Time Delivery

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	21238.7	21238.7	3539.8	928.5	0.000
DDT	1	10102.4	10102.4	10102.4	2649.9	0.000
DR*DDT	6	11864.6	11864.6	1977.4	518.7	0.000
Error	28	106.7	106.7	3.8		
Total	41	43312.4				

Table E.5.A: Two Factor Tukey Table for % On Time Delivery

Dispatching Rule	Due Date Tightness (H,M,L)	% on time delivery	Sig.
CR/FIFO	15,20,25	100	
P/FIFO	15,20,25	99.96	
P/HXT	15,20,25	99.93	
FIFO	15,20,25	91.73	
LBA/FIFO	10,15,20	91.38	
LBA/FIFO	15,20,25	91.38	
HXT/FIFO	15,20,25	86.59	
FIFO	10,15,20	79.62	
P/FIFO	10,15,20	79.52	
HXT/FIFO	10,15,20	72.01	
P/HXT	10,15,20	38.3	
P/CR	15,20,25	29.91	
P/CR	10,15,20	21.54	
CR/FIFO	10,15,20	0	

Table E.6.A: Two Factor ANOVA Table for Average Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	13065988.0	13065988.0	2177665.0	661.5	0.000
DDT	1	21487.0	21487.0	21487.0	6.5	0.016
DR*DDT	6	805123.0	805123.0	134187.0	40.8	0.000
Error	28	92173.0	92173.0	3292.0		
Total	41	13984771.0				

Table E.6.B: Two Factor Tukey Table for Average Cycle Time

Dispatching Rule	Due Date Tightness (H,M,L)	Avg. Cycle Time (hours)	Sig.
FIFO	10,15,20	1247.7	
FIFO	15,20,25	1247.7	
LBA/FIFO	10,15,20	1276.1	
LBA/FIFO	15,20,25	1276.1	
HXT/FIFO	10,15,20	1321	
HXT/FIFO	15,20,25	1321	
P/FIFO	10,15,20	1369.5	
P/FIFO	15,20,25	1369.5	
P/HXT	10,15,20	1520.8	
P/HXT	15,20,25	1520.8	
CR/FIFO	15,20,25	1572.4	
CR/FIFO	10,15,20	2231.1	
P/CR	10,15,20	2747.4	
P/CR	15,20,25	3089.6	

Table E.7.A: Two Factor ANOVA Table for Std. Dev. Of Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	6324603.0	6324603.0	1054101.0	837.5	0.000
DDT	1	10862.0	10862.0	10862.0	8.6	0.007
DR*DDT	6	59521.0	59521.0	9920.0	7.9	0.000
Error	28	35242.0	35242.0	1259.0		
Total	41	6430229.0				

Table E.7.B: Two Factor Tukey Table for Std. Dev. Of Cycle Time

Dispatching Rule	Due Date Tightness (H,M,L)	Std. Dev. (hours)	Sig.
HXT/FIFO	10,15,20	63.6	
HXT/FIFO	15,20,25	63.6	
FIFO	10,15,20	95.5	
FIFO	15,20,25	95.5	
LBA/FIFO	10,15,20	115.6	
LBA/FIFO	15,20,25	115.6	
CR/FIFO	10,15,20	294	
CR/FIFO	15,20,25	302.7	
P/FIFO	10,15,20	319.7	
P/FIFO	15,20,25	319.7	
P/HXT	10,15,20	353.4	
P/HXT	15,20,25	353.4	
P/CR	10,15,20	1163.4	
P/CR	15,20,25	1379.9	

Table E.8.A: Two Factor ANOVA Table for Average WIP

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	4020.8	4020.8	670.1	650.7	0.000
DDT	1	6.8	6.8	6.8	6.6	0.016
DR*DDT	6	246.5	246.5	41.1	39.9	0.000
Error	28	28.8	28.8	1.0		
Total	41	4302.9				

Table E.8.B: Two Factor Tukey Table for Average WIP

Dispatching Rule	Due Date Tightness (H,M,L)	Avg. WIP	Sig.
FIFO	10,15,20	21.89	
FIFO	15,20,25	21.89	
LBA/FIFO	10,15,20	22.387	
LBA/FIFO	15,20,25	22.387	
HXT/FIFO	10,15,20	23.177	
HXT/FIFO	15,20,25	23.177	
P/FIFO	10,15,20	24.027	
P/FIFO	15,20,25	24.027	
P/HXT	10,15,20	26.68	
P/HXT	15,20,25	26.68	
CR/FIFO	15,20,25	27.577	
CR/FIFO	10,15,20	39.14	
P/CR	10,15,20	48.237	
P/CR	15,20,25	54.163	

Two Factor Analysis for Production Volume = 154 lots/year and Product Mix = 5-5-90

Table E.9.A: Two Factor ANOVA Table for % On Time Delivery

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	39470.7	39470.7	6578.5	41752.7	0.000
DDT	1	115.6	115.6	115.6	733.8	0.000
DR*DDT	6	18.8	18.8	3.1	19.9	0.000
Error	28	4.4	4.4	0.2		
Total	41	39609.5				

Table E.9.B: Two Factor Tukey Table for % On Time Delivery

Dispatching Rule	Due Date Tightness (H,M,L)	% on time delivery	Sig.
CR/FIFO	15,20,25	100	
P/FIFO	15,20,25	100	
P/HXT	15,20,25	100	
P/FIFO	10,15,20	98.517	
P/HXT	10,15,20	97.865	
LBA/FIFO	15,20,25	96.629	
CR/FIFO	10,15,20	96.52	
FIFO	15,20,25	96.516	
HXT/FIFO	15,20,25	95.615	
FIFO	10,15,20	92.09	
LBA/FIFO	10,15,20	91.881	
HXT/FIFO	10,15,20	90.65	
P/CR	15,20,25	9.997	
P/CR	10,15,20	8.007	

Table E.10.A: Two Factor ANOVA Table for Average Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	8943124.0	8943124.0	1490521.0	3508.8	0.000
DDT	1	39485.0	39485.0	39485.0	93.0	0.000
DR*DDT	6	125670.0	125670.0	20945.0	49.3	0.000
Error	28	11894.0	11894.0	425.0		
Total	41	9120172.0				

Table E.10.B: Two Factor Tukey Table for Average Cycle Time

Dispatching Rule	Due Date Tightness (H,M,L)	Avg. Cycle Time (hours)	Sig.
FIFO	10,15,20	1255.9	
FIFO	15,20,25	1255.9	
P/HXT	10,15,20	1281.7	
P/HXT	15,20,25	1281.7	
P/FIFO	10,15,20	1283.3	
P/FIFO	15,20,25	1283.3	
HXT/FIFO	10,15,20	1285.5	
HXT/FIFO	15,20,25	1285.5	
LBA/FIFO	10,15,20	1306.5	
LBA/FIFO	15,20,25	1306.5	
CR/FIFO	10,15,20	1441	
CR/FIFO	15,20,25	1560.8	
P/CR	10,15,20	2464.7	
P/CR	15,20,25	2774.1	

Table E.11.A: Two Factor ANOVA Table for Std. Dev. Of Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	1065197.0	1065197.0	177533.0	2395.9	0.000
DDT	1	3442.0	3442.0	3442.0	46.5	0.000
DR*DDT	6	11817.0	11817.0	1969.0	26.6	0.000
Error	28	2075.0	2075.0	74.0		
Total	41	1082530.0				

Table E.11.B: Two Factor Tukey Table for Std. Dev. Of Cycle Time

Dispatching Rule	Due Date Tightness (H,M,L)	Std. Dev. (hours)	Sig.
HXT/FIFO	10,15,20	67.02	
HXT/FIFO	15,20,25	67.02	
FIFO	10,15,20	103.51	
FIFO	15,20,25	103.51	
LBA/FIFO	10,15,20	121.81	
LBA/FIFO	15,20,25	121.81	
P/HXT	10,15,20	143.01	
P/HXT	15,20,25	143.01	
P/FIFO	10,15,20	169.24	
P/FIFO	15,20,25	169.24	
CR/FIFO	10,15,20	177.09	
CR/FIFO	15,20,25	207.74	
P/CR	10,15,20	526.51	
P/CR	15,20,25	622.6	

Table E.12.A: Two Factor ANOVA Table for Average WIP

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	2752.3	2752.3	458.7	3564.8	0.000
DDT	1	12.1	12.1	12.1	94.3	0.000
DR*DDT	6	38.6	38.6	6.4	50.0	0.000
Error	28	3.6	3.6	0.1		
Total	41	2806.7				

Table E.12.B: Two Factor Tukey Table for Average WIP

Dispatching Rule	Due Date Tightness (H,M,L)	Avg. WIP	Sig.
FIFO	10,15,20	22.033	
FIFO	15,20,25	22.033	
P/HXT	10,15,20	22.487	
P/HXT	15,20,25	22.487	
P/FIFO	10,15,20	22.51	
P/FIFO	15,20,25	22.51	
HXT/FIFO	10,15,20	22.55	
HXT/FIFO	15,20,25	22.55	
LBA/FIFO	10,15,20	22.92	
LBA/FIFO	15,20,25	22.92	
CR/FIFO	10,15,20	25.283	
CR/FIFO	15,20,25	27.383	
P/CR	10,15,20	43.24	
P/CR	15,20,25	48.663	

Two Factor Analysis for Production Volume = 128 lots/year and Product Mix = 25-25-50

Table E.13.A: Two Factor ANOVA Table for % On Time Delivery

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	1056.3	1056.3	176.1	997.6	0.000
DDT	1	1203.3	1203.3	1203.3	6818.3	0.000
DR*DDT	6	1002.2	1002.2	167.0	946.5	0.000
Error	28	4.9	4.9	0.2		
Total	41	3266.8				

Table E.13.A: Two Factor Tukey Table for % On Time Delivery

Dispatching Rule	Due Date Tightness (H,M,L)	% on time delivery	Sig.
CR/FIFO	15,20,25	100	<div></div>
HXT/FIFO	15,20,25	100	
P/CR	15,20,25	100	
P/FIFO	15,20,25	100	
P/HXT	15,20,25	100	
FIFO	15,20,25	99.782	
LBA/FIFO	15,20,25	99.391	
P/FIFO	10,15,20	98.344	
P/HXT	10,15,20	97.567	
CR/FIFO	10,15,20	97.52	
P/CR	10,15,20	97.432	
FIFO	10,15,20	79.251	
LBA/FIFO	10,15,20	77.947	
HXT/FIFO	10,15,20	76.175	

Table E.14.A: Two Factor ANOVA Table for Average Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	36581.6	36581.6	6096.9	81.4	0.000
DDT	1	98.0	98.0	98.0	1.3	0.262
DR*DDT	6	1225.2	1225.2	204.2	2.7	0.033
Error	28	2098.0	2098.0	74.9		
Total	41	40002.8				

Table E.14.B: Two Factor Tukey Table for Average Cycle Time

Dispatching Rule	Due Date Tightness (H,M,L)	Avg. Cycle Time (hours)	Sig.
P/FIFO	10,15,20	979.09	<div></div>
P/FIFO	15,20,25	979.09	
P/HXT	10,15,20	989.56	
P/HXT	15,20,25	989.56	
FIFO	10,15,20	995.36	
FIFO	15,20,25	995.36	
P/CR	15,20,25	1002.6	
P/CR	10,15,20	1009.98	
HXT/FIFO	10,15,20	1024.62	
HXT/FIFO	15,20,25	1024.62	
LBA/FIFO	10,15,20	1049.12	
LBA/FIFO	15,20,25	1049.12	
CR/FIFO	10,15,20	1050.05	
CR/FIFO	15,20,25	1078.82	

Table E.15.A: Two Factor ANOVA Table for Std. Dev. Of Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	74047.4	74047.4	12341.2	596.5	0.000
DDT	1	8.7	8.7	8.7	0.4	0.523
DR*DDT	6	294.3	294.3	49.1	2.4	0.056
Error	28	579.3	579.3	20.7		
Total	41	74929.8				

Table E.15.B: Two Factor Tukey Table for Std. Dev. Of Cycle Time

Dispatching Rule	Std. Dev. (hours)	Sig.
HXT/FIFO	71.91	
FIFO	97.99	
LBA/FIFO	116.03	
P/HXT	156.28	
P/FIFO	160.25	
P/CR	183.68	
CR/FIFO	192.75	

Table E.16.A: Two Factor ANOVA Table for Average WIP

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	7.8	7.8	1.3	81.3	0.000
DDT	1	0.0	0.0	0.0	1.3	0.260
DR*DDT	6	0.3	0.3	0.0	2.7	0.036
Error	28	0.4	0.4	0.0		
Total	41	8.5				

Table E.16.B: Two Factor Tukey Table for Average WIP

Dispatching Rule	Due Date Tightness (H,M,L)	Avg. WIP	Sig.
P/FIFO	10,15,20	14.317	
P/FIFO	15,20,25	14.317	
P/HXT	10,15,20	14.47	
P/HXT	15,20,25	14.47	
FIFO	10,15,20	14.557	
FIFO	15,20,25	14.557	
P/CR	15,20,25	14.663	
P/CR	10,15,20	14.767	
HXT/FIFO	10,15,20	14.98	
HXT/FIFO	15,20,25	14.98	
LBA/FIFO	10,15,20	15.34	
LBA/FIFO	15,20,25	15.34	
CR/FIFO	10,15,20	15.353	
CR/FIFO	15,20,25	15.77	

Two Factor Analysis for Production Volume = 128 lots/year and Product Mix = 15-15-70

Table E.17.A: Two Factor ANOVA Table for % On Time Delivery

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	359.4	359.4	59.9	368.9	0.000
DDT	1	400.2	400.2	400.2	2464.9	0.000
DR*DDT	6	338.4	338.4	56.4	347.4	0.000
Error	28	4.5	4.5	0.2		
Total	41	1102.5				

Table E.17.B: Two Factor Tukey Table for % On Time Delivery

Dispatching Rule	Due Date Tightness (H,M,L)	% on time delivery	Sig.
CR/FIFO	15,20,25	100	
HXT/FIFO	15,20,25	100	
P/CR	15,20,25	100	
P/FIFO	15,20,25	100	
P/HXT	15,20,25	100	
LBA/FIFO	15,20,25	99.826	
FIFO	15,20,25	99.652	
P/FIFO	10,15,20	99.261	
P/HXT	10,15,20	98.999	
P/CR	10,15,20	98.911	
CR/FIFO	10,15,20	97.74	
HXT/FIFO	10,15,20	87.207	
LBA/FIFO	10,15,20	87.119	
FIFO	10,15,20	87.027	

Table E.18.A: Two Factor ANOVA Table for Average Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	36163.4	36163.4	6027.2	81.1	0.000
DDT	1	360.0	360.0	360.0	4.8	0.036
DR*DDT	6	1047.0	1047.0	174.5	2.4	0.058
Error	28	2080.9	2080.9	74.3		
Total	41	39651.3				

Table E.18.B: Two Factor Tukey Table for Average Cycle Time

Dispatching Rule	Avg. Cycle Time (hours)	Sig.
P/HXT	965.37	
FIFO	972.18	
HXT/FIFO	972.8	
LBA/FIFO	974.46	
P/FIFO	975.18	
P/CR	1013.97	
CR/FIFO	1051.44	

Table E.19.A: Two Factor ANOVA Table for Std. Dev. Of Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	48684.6	48684.6	8114.1	507.9	0.000
DDT	1	220.2	220.2	220.2	13.8	0.001
DR*DDT	6	802.3	802.3	133.7	8.4	0.000
Error	28	447.3	447.3	16.0		
Total	41	50154.4				

Table E.19.B: Two Factor Tukey Table for Std. Dev. Of Cycle Time

Dispatching Rule	Due Date Tightness (H,M,L)	Std. Dev. (hours)	Sig.
HXT/FIFO	10,15,20	69.59	
HXT/FIFO	15,20,25	69.59	
LBA/FIFO	10,15,20	90.52	
LBA/FIFO	15,20,25	90.52	
FIFO	10,15,20	92.31	
FIFO	15,20,25	92.31	
P/HXT	10,15,20	114.84	
P/HXT	15,20,25	114.84	
P/FIFO	10,15,20	136.38	
P/FIFO	15,20,25	136.38	
P/CR	10,15,20	149.8	
CR/FIFO	10,15,20	159.72	
CR/FIFO	15,20,25	166.58	
P/CR	15,20,25	174.99	

Table E.20.A: Two Factor ANOVA Table for Average WIP

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	7.7	7.7	1.3	80.4	0.000
DDT	1	0.1	0.1	0.1	4.9	0.035
DR*DDT	6	0.2	0.2	0.0	2.4	0.055
Error	28	0.4	0.4	0.0		
Total	41	8.5				

Table E.20.B: Two Factor Tukey Table for Average WIP

Dispatching Rule	Avg. WIP	Sig.
P/HXT	14.113	
FIFO	14.21	
HXT/FIFO	14.223	
LBA/FIFO	14.243	
P/FIFO	14.257	
P/CR	14.823	
CR/FIFO	15.37	

Two Factor Analysis for Production Volume = 128 lots/year and Product Mix = 5-5-90

Table E.21.A: Two Factor ANOVA Table for % On Time Delivery

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	37.4	37.4	6.2	147.8	0.000
DDT	1	46.9	46.9	46.9	1113.4	0.000
DR*DDT	6	36.4	36.4	6.1	143.9	0.000
Error	28	1.2	1.2	0.0		
Total	41	121.9				

Table E.21.B: Two Factor Tukey Table for % On Time Delivery

Dispatching Rule	Due Date Tightness (H,M,L)	% on time delivery	Sig.
CR/FIFO	15,20,25	100	
HXT/FIFO	15,20,25	100	
LBA/FIFO	15,20,25	100	
P/CR	15,20,25	100	
P/FIFO	15,20,25	100	
P/HXT	15,20,25	100	
FIFO	15,20,25	99.913	
CR/FIFO	10,15,20	99.696	
P/CR	10,15,20	99.522	
P/HXT	10,15,20	99.433	
P/FIFO	10,15,20	99.304	
FIFO	10,15,20	95.954	
LBA/FIFO	10,15,20	95.777	
HXT/FIFO	10,15,20	95.426	

Table E.22.A: Two Factor ANOVA Table for Average Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	44848.1	44848.1	7474.7	105.7	0.000
DDT	1	170.2	170.2	170.2	2.4	0.132
DR*DDT	6	1047.2	1047.2	174.5	2.5	0.048
Error	28	1979.8	1979.8	70.7		
Total	41	48045.2				

Table E.22.B: Two Factor Tukey Table for Average Cycle Time

Dispatching Rule	Due Date Tightness (H,M,L)	Avg. Cycle Time (hours)	Sig.
P/HXT	15,20,25	952.44	
HXT/FIFO	10,15,20	960.27	
HXT/FIFO	15,20,25	960.27	
P/HXT	10,15,20	962.02	
FIFO	10,15,20	970.34	
FIFO	15,20,25	970.34	
LBA/FIFO	10,15,20	972.74	
LBA/FIFO	15,20,25	972.74	
P/CR	10,15,20	1010.82	
P/FIFO	10,15,20	1019.31	
P/FIFO	15,20,25	1019.31	
P/CR	15,20,25	1031.53	
CR/FIFO	10,15,20	1036.6	
CR/FIFO	15,20,25	1053.66	

Table E.23.A: Two Factor ANOVA Table for Std. Dev. Of Cycle Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	36380.5	36380.5	6063.4	213.4	0.000
DDT	1	137.9	137.9	137.9	4.9	0.036
DR*DDT	6	531.1	531.1	88.5	3.1	0.018
Error	28	795.6	795.6	28.4		
Total	41	37845.1				

Table E.23.B: Two Factor Tukey Table for Std. Dev. Of Cycle Time

Dispatching Rule	Due Date Tightness (H,M,L)	Std. Dev. (hours)	Sig.
HXT/FIFO	10,15,20	66.97	
HXT/FIFO	15,20,25	66.97	
P/HXT	15,20,25	79.62	
P/HXT	10,15,20	83.57	
FIFO	10,15,20	88.37	
FIFO	15,20,25	88.37	
LBA/FIFO	10,15,20	92.39	
LBA/FIFO	15,20,25	92.39	
P/CR	10,15,20	127.16	
CR/FIFO	10,15,20	132.25	
P/CR	15,20,25	142.39	
P/FIFO	10,15,20	144.96	
P/FIFO	15,20,25	144.96	
CR/FIFO	15,20,25	146.33	

Table E.24.A: Two Factor ANOVA Table for Average WIP

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DR	6	9.5	9.5	1.6	105.5	0.000
DDT	1	0.0	0.0	0.0	2.5	0.127
DR*DDT	6	0.2	0.2	0.0	2.5	0.048
Error	28	0.4	0.4	0.0		
Total	41	10.2				

Table E.24.B: Two Factor Tukey Table for Average WIP

Dispatching Rule	Due Date Tightness (H,M,L)	Avg. WIP	Sig.
P/HXT	15,20,25	13.927	
HXT/FIFO	10,15,20	14.04	
HXT/FIFO	15,20,25	14.04	
P/HXT	10,15,20	14.063	
FIFO	10,15,20	14.187	
FIFO	15,20,25	14.187	
LBA/FIFO	10,15,20	14.22	
LBA/FIFO	15,20,25	14.22	
P/CR	10,15,20	14.773	
P/FIFO	10,15,20	14.893	
P/FIFO	15,20,25	14.893	
P/CR	15,20,25	15.077	
CR/FIFO	10,15,20	15.153	
CR/FIFO	15,20,25	15.403	

Appendix F. Analysis of Dispatching Rules With Given Levels of Production Volume, Product Mix and Due Date Tightness

The appendices in this section have ANOVA and Tukey test tables for the analysis of dispatching rules with given levels of production volume, product mix and due date tightness. Twelve fab types are analyzed and depending on whether the dispatching rule is significant, Tukey pairwise comparison tests are done to determine which rules are statistically significant from each other. The Tukey family error rate is set at 5. The vertical lines in the significance column group the strategies that are not statistically different from each other. The levels in the fab types are listed in Table F.

Table F: Fab Types

Fab Type	Production Volume (lots/year)	Due Date Tightness (H,M,L)	Product Mix (H-M-L)
I	154	20,15,10	25-25-50
II	154	25,20,15	15-15-70
III	154	20,15,10	5-5-90
IV	154	25,20,15	25-25-50
V	154	20,15,10	15-15-70
VI	154	25,20,15	5-5-90
VII	128	20,15,10	25-25-50
VIII	128	25,20,15	15-15-70
IX	128	20,15,10	5-5-90
X	128	25,20,15	25-25-50
XI	128	20,15,10	15-15-70
XII	128	25,20,15	5-5-90

Analysis of Fab Type I

Table F.1.1: ANOVA and Tukey Tables for % On Time Delivery

Source	DF	SS	MS	F	P
DR	6	8754.1	1459.0	700.5	0.000
Error	14	29.2	2.1		
Total	20	8783.2			

Dispatching Rule	% on time delivery	Sig.
FIFO	66.052	
LBA/FIFO	64.61	
HXT/FIFO	41.303	
P/FIFO	39.406	
P/HXT	37.252	
P/CR	34.917	
CR/FIFO	0	

Table F.1.2: ANOVA and Tukey Tables for Average Cycle Time

Source	DF	SS	MS	F	P
DR	6	22797200.0	3799540.0	34.9	0.000
Error	14	1525580.0	108969.8		
Total	20	24322800.0			

Dispatching Rule	Avg. Cycle Time (hours)	Sig.
FIFO	1261.3	
LBA/FIFO	1286.5	
HXT/FIFO	1567.7	
P/HXT	1867	
CR/FIFO	2136.1	
P/FIFO	3104.3	
P/CR	4334.1	

Table F.1.3: ANOVA and Tukey Tables for Std. Dev. Of Cycle Time

Source	DF	SS	MS	F	P
DR	6	29722600.04953770.0	4953770.0	45.6	0.000
Error	14	1520440.0	108603.0		
Total	20	31243100.0			

Dispatching Rule	Std. Dev. (hours)	Sig.
HXT/FIFO	90	
FIFO	100.6	
LBA/FIFO	110.5	
CR/FIFO	322.8	
P/HXT	903.9	
P/FIFO	2132.6	
P/CR	3393.5	

Table F.1.4: ANOVA and Tukey Tables for Average WIP

Source	DF	SS	MS	F	P
DR	6	7240.8	1206.8	35.1	0.000
Error	14	482.0	34.4		
Total	20	7722.7			

Dispatching Rule	Avg. WIP	Sig.
FIFO	22.127	
LBA/FIFO	22.57	
HXT/FIFO	27.5	
P/HXT	32.75	
CR/FIFO	37.477	
P/FIFO	54.357	
P/CR	77.073	

Analysis of Fab Type II

Table F.2.1: ANOVA and Tukey Tables for % On Time Delivery

Source	DF	SS	MS	F	P
DR	6	11375.5	1895.9	2712.5	0.000
Error	14	9.8	0.7		
Total	20	11385.2			

Dispatching Rule	% on time delivery	Sig.
CR/FIFO	100	
P/FIFO	99.964	
P/HXT	99.927	
FIFO	91.73	
LBA/FIFO	91.379	
HXT/FIFO	86.585	
P/CR	29.914	

Table F.2.2: ANOVA and Tukey Tables for Average Cycle Time

Source	DF	SS	MS	F	P
DR	6	7740730.0	1290120.0	498.9	0.000
Error	14	36201.4	2585.8		
Total	20	7776930.0			

Dispatching Rule	Avg. Cycle Time (hours)	Sig.
FIFO	1247.7	
LBA/FIFO	1276.1	
HXT/FIFO	1321	
P/FIFO	1369.5	
P/HXT	1520.8	
CR/FIFO	1572.4	
P/CR	3089.6	

Table F.2.3: ANOVA and Tukey Tables for Std. Dev. Of Cycle Time

Source	DF	SS	MS	F	P
DR	6	3782620.063	630437.0	481.8	0.000
Error	14	18319.7	1308.6		
Total	20	3800940.0			

Dispatching Rule	Std. Dev. (hours)	Sig.
HXT/FIFO	63.6	
FIFO	95.5	
LBA/FIFO	115.6	
CR/FIFO	302.7	
P/FIFO	319.7	
P/HXT	353.4	
P/CR	1379.9	

Table F.2.4: ANOVA and Tukey Tables for Average WIP

Source	DF	SS	MS	F	P
DR	6	2376.5	396.1	467.6	0.000
Error	14	11.9	0.8		
Total	20	2388.3			

Dispatching Rule	Avg. WIP	Sig.
FIFO	21.89	
LBA/FIFO	22.387	
HXT/FIFO	23.177	
P/FIFO	24.027	
P/HXT	26.68	
CR/FIFO	27.577	
P/CR	54.163	

Analysis of Fab Type III

Table F.3.1: ANOVA and Tukey Tables for % On Time Delivery

Source	DF	SS	MS	F	P	Dispatching Rule	% on time delivery	Sig.
DR	6	19452.5	3242.1	13345.1	0.000	P/FIFO	98.517	
Error	14	3.4	0.2			P/HXT	97.865	
Total	20	19455.9				CR/FIFO	96.52	
						FIFO	92.09	
						LBA/FIFO	91.881	
						HXT/FIFO	90.65	
						P/CR	8.007	

Table F.3.2: ANOVA and Tukey Tables for Average Cycle Time

Source	DF	SS	MS	F	P	Dispatching Rule	Avg. Cycle Time (hours)	Sig.
DR	6	3501080.0583513.0	1016.8	0.000		FIFO	1255.9	
Error	14	8033.9	573.8			P/HXT	1281.7	
Total	20	3509110.0				P/FIFO	1283.3	
						HXT/FIFO	1285.5	
						LBA/FIFO	1306.5	
						CR/FIFO	1441	
						P/CR	2464.7	

Table F.3.3: ANOVA and Tukey Tables for Std. Dev. Of Cycle Time

Source	DF	SS	MS	F	P	Dispatching Rule	Std. Dev. (hours)	Sig.
DR	6	429687.671614.6	752.2	0.000		HXT/FIFO	67.02	
Error	14	1332.8	95.2			FIFO	103.51	
Total	20	431020.4				LBA/FIFO	121.81	
						P/HXT	143.01	
						P/FIFO	169.24	
						CR/FIFO	177.09	
						P/CR	526.51	

Table F.3.4: ANOVA and Tukey Tables for Average WIP

Source	DF	SS	MS	F	P	Dispatching Rule	Avg. WIP	Sig.
DR	6	1077.7	179.6	1026.0	0.000	FIFO	22.033	
Error	14	2.5	0.2			P/HXT	22.487	
Total	20	1080.2				P/FIFO	22.51	
						HXT/FIFO	22.55	
						LBA/FIFO	22.92	
						CR/FIFO	25.283	
						P/CR	43.24	

Analysis of Fab Type IV

Table F.4.1: ANOVA and Tukey Tables for % On Time Delivery

Source	DF	SS	MS	F	P
DR	6	15729.2	2621.5	2916.0	0.000
Error	14	12.6	0.9		
Total	20	15741.7			

Dispatching Rule	% on time delivery	Sig.
FIFO	86.343	
LBA/FIFO	85.205	
HXT/FIFO	71.125	
P/CR	50.311	
P/HXT	50.109	
P/FIFO	49.856	
CR/FIFO	0	

Table F.4.2: ANOVA and Tukey Tables for Average Cycle Time

Source	DF	SS	MS	F	P
DR	6	14377800.0	2396300.0	77.4	0.000
Error	14	433546.7	30967.6		
Total	20	14811300.0			

Dispatching Rule	Avg. Cycle Time (hours)	Sig.
FIFO	1261.3	
LBA/FIFO	1286.5	
HXT/FIFO	1567.7	
P/HXT	1867	
CR/FIFO	2556.4	
P/FIFO	3104.3	
P/CR	3477.7	

Table F.4.3: ANOVA and Tukey Tables for Std. Dev. Of Cycle Time

Source	DF	SS	MS	F	P
DR	6	18632800.0	3105470.0	93.9	0.000
Error	14	463046.5	33074.7		
Total	20	19095800.0			

Dispatching Rule	Std. Dev. (hours)	Sig.
HXT/FIFO	90	
FIFO	100.6	
LBA/FIFO	110.5	
CR/FIFO	357.3	
P/HXT	903.9	
P/FIFO	2132.6	
P/CR	2475.1	

Table F.4.4: ANOVA and Tukey Tables for Average WIP

Source	DF	SS	MS	F	P
DR	6	4453.2	742.2	75.6	0.000
Error	14	137.4	9.8		
Total	20	4590.6			

Dispatching Rule	Avg. WIP	Sig.
FIFO	22.127	
LBA/FIFO	22.57	
HXT/FIFO	27.5	
P/HXT	32.75	
CR/FIFO	44.85	
P/FIFO	54.357	
P/CR	61.283	

Analysis of Fab Type V

Table F.5.1: ANOVA and Tukey Tables for % On Time Delivery

Source	DF	SS	MS	F	P
DR	6	21727.8	3621.3	522.9	0.000
Error	14	97.0	6.9		
Total	20	21824.8			

Dispatching Rule	% on time delivery	Sig.
LBA/FIFO	91.379	
FIFO	79.615	
P/FIFO	79.524	
HXT/FIFO	72.011	
P/HXT	38.303	
P/CR	21.539	
CR/FIFO	0	

Table F.5.2: ANOVA and Tukey Tables for Average Cycle Time

Source	DF	SS	MS	F	P
DR	6	66130380.0	1021730.0	255.6	0.000
Error	14	55971.5	3998.0		
Total	20	66186360.0			

Dispatching Rule	Avg. Cycle Time (hours)	Sig.
FIFO	1247.7	
LBA/FIFO	1276.1	
HXT/FIFO	1321	
P/FIFO	1369.5	
P/HXT	1520.8	
CR/FIFO	2231.1	
P/CR	2747.4	

Table F.5.3: ANOVA and Tukey Tables for Std. Dev. Of Cycle Time

Source	DF	SS	MS	F	P
DR	6	2601500.04	33583.8	358.7	0.000
Error	14	16922.7	1208.8		
Total	20	2618430.0			

Dispatching Rule	Std. Dev. (hours)	Sig.
HXT/FIFO	63.6	
FIFO	95.5	
LBA/FIFO	115.6	
CR/FIFO	294	
P/FIFO	319.7	
P/HXT	353.4	
P/CR	1163.4	

Table F.5.4: ANOVA and Tukey Tables for Average WIP

Source	DF	SS	MS	F	P
DR	6	1890.8	315.1	259.9	0.000
Error	14	17.0	1.2		
Total	20	1907.8			

Dispatching Rule	Avg. WIP	Sig.
FIFO	21.89	
LBA/FIFO	22.387	
HXT/FIFO	23.177	
P/FIFO	24.027	
P/HXT	26.68	
CR/FIFO	39.14	
P/CR	48.237	

Analysis of Fab Type VI

Table F.6.1: ANOVA and Tukey Tables for % On Time Delivery

Source	DF	SS	MS	F	P
DR	6	20037.0	3339.546271.3	0.000	
Error	14	1.0	0.1		
Total	20	20038.1			

Dispatching Rule	% on time delivery	Sig.
CR/FIFO	100	
P/FIFO	100	
P/HXT	100	
LBA/FIFO	96.629	
FIFO	96.516	
HXT/FIFO	95.615	
P/CR	9.997	

Table F.6.2: ANOVA and Tukey Tables for Average Cycle Time

Source	DF	SS	MS	F	P
DR	6	5567710.0927952.5	3365.2	0.000	
Error	14	3860.5	275.8		
Total	20	5571580.0			

Dispatching Rule	Avg. Cycle Time (hours)	Sig.
FIFO	1255.9	
P/HXT	1281.7	
P/FIFO	1283.3	
HXT/FIFO	1285.5	
LBA/FIFO	1306.5	
CR/FIFO	1560.8	
P/CR	2774.1	

Table F.6.3: ANOVA and Tukey Tables for Std. Dev. Of Cycle Time

Source	DF	SS	MS	F	P
DR	6	647326.2107887.7	2035.7	0.000	
Error	14	742.0	53.0		
Total	20	648068.2			

Dispatching Rule	Std. Dev. (hours)	Sig.
HXT/FIFO	67.02	
FIFO	103.51	
LBA/FIFO	121.81	
P/HXT	143.01	
P/FIFO	169.24	
CR/FIFO	207.74	
P/CR	622.6	

Table F.6.4: ANOVA and Tukey Tables for Average WIP

Source	DF	SS	MS	F	P
DR	6	1713.2	285.5	3469.8	0.000
Error	14	1.2	0.1		
Total	20	1714.3			

Dispatching Rule	Avg. WIP	Sig.
FIFO	22.033	
P/HXT	22.487	
P/FIFO	22.51	
HXT/FIFO	22.55	
LBA/FIFO	22.92	
CR/FIFO	27.383	
P/CR	48.663	

Analysis of Fab Type VII

Table F.7.1: ANOVA and Tukey Tables for % On Time Delivery

Source	DF	SS	MS	F	P
DR	6	2057.6	342.9	1011.4	0.000
Error	14	4.7	0.3		
Total	20	2062.3			

Dispatching Rule	% on time delivery	Sig.
P/FIFO	98.344	
P/HXT	97.567	
CR/FIFO	97.52	
P/CR	97.432	
FIFO	79.251	
LBA/FIFO	77.947	
HXT/FIFO	76.175	

Table F.7.2: ANOVA and Tukey Tables for Average Cycle Time

Source	DF	SS	MS	F	P
DR	6	14475.8	2412.6	38.9	0.000
Error	14	867.8	62.0		
Total	20	15343.6			

Dispatching Rule	Avg. Cycle Time (hours)	Sig.
P/FIFO	979.09	
P/HXT	989.56	
FIFO	995.36	
P/CR	1009.98	
HXT/FIFO	1024.62	
LBA/FIFO	1049.12	
CR/FIFO	1050.05	

Table F.7.3: ANOVA and Tukey Tables for Std. Dev. Of Cycle Time

Source	DF	SS	MS	F	P
DR	6	36507.4	6084.6	319.5	0.000
Error	14	266.6	19.0		
Total	20	36774.0			

Dispatching Rule	Std. Dev. (hours)	Sig.
HXT/FIFO	71.91	
FIFO	97.99	
LBA/FIFO	116.03	
P/HXT	156.28	
P/FIFO	160.25	
P/CR	177.32	
CR/FIFO	195.93	

Table F.7.4: ANOVA and Tukey Tables for Average WIP

Source	DF	SS	MS	F	P
DR	6	3.1	0.5	39.3	0.000
Error	14	0.2	0.0		
Total	20	3.3			

Dispatching Rule	Avg. WIP	Sig.
P/FIFO	14.317	
P/HXT	14.47	
FIFO	14.557	
P/CR	14.767	
HXT/FIFO	14.98	
LBA/FIFO	15.34	
CR/FIFO	15.353	

Analysis of Fab Type VIII

Table F.8.1: ANOVA and Tukey Tables for % On Time Delivery

Source	DF	SS	MS	F	P
DR	6	0.3	0.1	4.1	0.014
Error	14	0.2	0.0		
Total	20	0.5			

Dispatching Rule	% on time delivery	Sig.
CR/FIFO	100	
HXT/FIFO	100	
P/CR	100	
P/FIFO	100	
P/HXT	100	
LBA/FIFO	99.826	
FIFO	99.652	

Table F.8.2: ANOVA and Tukey Tables for Average Cycle Time

Source	DF	SS	MS	F	P
DR	6	23150.3	3858.4	57.5	0.000
Error	14	939.6	67.1		
Total	20	24089.9			

Dispatching Rule	Avg. Cycle Time (hours)	Sig.
P/HXT	965.37	
FIFO	972.18	
HXT/FIFO	972.8	
LBA/FIFO	974.46	
P/FIFO	975.18	
P/CR	1027.72	
CR/FIFO	1058.18	

Table F.8.3: ANOVA and Tukey Tables for Std. Dev. Of Cycle Time

Source	DF	SS	MS	F	P
DR	6	28984.2	4830.7	255.8	0.000
Error	14	264.4	18.9		
Total	20	29248.6			

Dispatching Rule	Std. Dev. (hours)	Sig.
HXT/FIFO	69.59	
LBA/FIFO	90.52	
FIFO	92.31	
P/HXT	114.84	
P/FIFO	136.38	
CR/FIFO	166.58	
P/CR	174.99	

Table F.8.4: ANOVA and Tukey Tables for Average WIP

Source	DF	SS	MS	F	P
DR	6	5.0	0.8	56.9	0.000
Error	14	0.2	0.0		
Total	20	5.2			

Dispatching Rule	Avg. WIP	Sig.
P/HXT	14.113	
FIFO	14.21	
HXT/FIFO	14.223	
LBA/FIFO	14.243	
P/FIFO	14.257	
P/CR	15.027	
CR/FIFO	15.47	

Analysis of Fab Type IX

Table F.9.1: ANOVA and Tukey Tables for % On Time Delivery

Source	DF	SS	MS	F	P
DR	6	73.8	12.3	147.2	0.000
Error	14	1.2	0.1		
Total	20	74.9			

Dispatching Rule	% on time delivery	Sig.
CR/FIFO	99.696	
P/CR	99.522	
P/HXT	99.433	
P/FIFO	99.304	
FIFO	95.954	
LBA/FIFO	95.777	
HXT/FIFO	95.426	

Table F.9.2: ANOVA and Tukey Tables for Average Cycle Time

Source	DF	SS	MS	F	P
DR	6	17443.9	2907.3	53.1	0.000
Error	14	766.9	54.8		
Total	20	18210.8			

Dispatching Rule	Avg. Cycle Time (hours)	Sig.
HXT/FIFO	960.27	
P/HXT	962.02	
FIFO	970.34	
LBA/FIFO	972.74	
P/CR	1010.82	
P/FIFO	1019.31	
CR/FIFO	1036.6	

Table F.9.3: ANOVA and Tukey Tables for Std. Dev. Of Cycle Time

Source	DF	SS	MS	F	P
DR	6	15514.2	2585.7	95.5	0.000
Error	14	379.2	27.1		
Total	20	15893.4			

Dispatching Rule	Std. Dev. (hours)	Sig.
HXT/FIFO	66.97	
P/HXT	83.57	
FIFO	88.37	
LBA/FIFO	92.39	
P/CR	127.16	
CR/FIFO	132.25	
P/FIFO	144.96	

Table F.9.4: ANOVA and Tukey Tables for Average WIP

Source	DF	SS	MS	F	P
DR	6	3.7	0.6	50.9	0.000
Error	14	0.2	0.0		
Total	20	3.9			

Dispatching Rule	Avg. WIP	Sig.
HXT/FIFO	14.04	
P/HXT	14.063	
FIFO	14.187	
LBA/FIFO	14.22	
P/CR	14.773	
P/FIFO	14.893	
CR/FIFO	15.153	

Analysis of Fab Type X

Table F.10.1: ANOVA and Tukey Tables for % On Time Delivery

Source	DF	SS	MS	F	P
DR	6	1.0	0.2	11.5	0.000
Error	14	0.2	0.0		
Total	20	1.2			

Dispatching Rule	% on time delivery	Sig.
CR/FIFO	100	
HXT/FIFO	100	
P/CR	100	
P/FIFO	100	
P/HXT	100	
FIFO	99.782	
LBA/FIFO	99.391	

Table F.10.2: ANOVA and Tukey Tables for Average Cycle Time

Source	DF	SS	MS	F	P
DR	6	23331.0	3888.5	44.3	0.000
Error	14	1230.2	87.9		
Total	20	24561.1			

Dispatching Rule	Avg. Cycle Time (hours)	Sig.
P/FIFO	979.09	
P/HXT	989.56	
FIFO	995.36	
P/CR	1002.6	
HXT/FIFO	1024.62	
LBA/FIFO	1049.12	
CR/FIFO	1078.82	

Table F.10.3: ANOVA and Tukey Tables for Std. Dev. Of Cycle Time

Source	DF	SS	MS	F	P
DR	6	37834.3	6305.7	282.3	0.000
Error	14	312.7	22.3		
Total	20	38147.1			

Dispatching Rule	Std. Dev. (hours)	Sig.
HXT/FIFO	71.91	
FIFO	97.99	
LBA/FIFO	116.03	
P/HXT	156.28	
P/FIFO	160.25	
CR/FIFO	189.57	
P/CR	190.03	

Table F.10.4: ANOVA and Tukey Tables for Average WIP

Source	DF	SS	MS	F	P
DR	6	5.0	0.8	43.9	0.000
Error	14	0.3	0.0		
Total	20	5.2			

Dispatching Rule	Avg. WIP	Sig.
P/FIFO	14.317	
P/HXT	14.47	
FIFO	14.557	
P/CR	14.663	
HXT/FIFO	14.98	
LBA/FIFO	15.34	
CR/FIFO	15.77	

Analysis of Fab Type XI

Table F.11.1: ANOVA and Tukey Tables for % On Time Delivery

Source	DF	SS	MS	F	P
DR	6	697.4	116.2	373.8	0.000
Error	14	4.4	0.3		
Total	20	701.8			

Dispatching Rule	% on time delivery	Sig.
P/FIFO	99.261	
P/HXT	98.999	
P/CR	98.911	
CR/FIFO	97.74	
HXT/FIFO	87.207	
LBA/FIFO	87.119	
FIFO	87.027	

Table F.11.2: ANOVA and Tukey Tables for Average Cycle Time

Source	DF	SS	MS	F	P
DR	6	14060.1	2343.4	28.7	0.000
Error	14	1141.3	81.5		
Total	20	15201.4			

Dispatching Rule	Avg. Cycle Time (hours)	Sig.
P/HXT	965.37	
FIFO	972.18	
HXT/FIFO	972.8	
LBA/FIFO	974.46	
P/FIFO	975.18	
P/CR	1000.23	
CR/FIFO	1044.69	

Table F.11.3: ANOVA and Tukey Tables for Std. Dev. Of Cycle Time

Source	DF	SS	MS	F	P
DR	6	20502.8	3417.1	261.6	0.000
Error	14	182.9	13.1		
Total	20	20685.7			

Dispatching Rule	Std. Dev. (hours)	Sig.
HXT/FIFO	69.59	
LBA/FIFO	90.52	
FIFO	92.31	
P/HXT	114.84	
P/FIFO	136.38	
P/CR	149.8	
CR/FIFO	159.72	

Table F.11.4: ANOVA and Tukey Tables for Average WIP

Source	DF	SS	MS	F	P
DR	6	3.0	0.5	28.6	0.000
Error	14	0.2	0.0		
Total	20	3.2			

Dispatching Rule	Avg. WIP	Sig.
P/HXT	14.113	
FIFO	14.21	
HXT/FIFO	14.223	
LBA/FIFO	14.243	
P/FIFO	14.257	
P/CR	14.62	
CR/FIFO	15.27	

Analysis of Fab Type XII

Table F.12.1: ANOVA and Tukey Tables for % On Time Delivery

Source	DF	SS	MS	F	P
DR	6	0.0	0.0	4.0	0.015
Error	14	0.0	0.0		
Total	20	0.0			

Dispatching Rule	% on time delivery	Sig.
CR/FIFO	100	
HXT/FIFO	100	
LBA/FIFO	100	
P/CR	100	
P/FIFO	100	
P/HXT	100	
FIFO	99.913	

Table F.12.2: ANOVA and Tukey Tables for Average Cycle Time

Source	DF	SS	MS	F	P
DR	6	28451.3	4741.9	54.7	0.000
Error	14	1212.9	86.6		
Total	20	29664.3			

Dispatching Rule	Avg. Cycle Time (hours)	Sig.
P/HXT	952.44	
HXT/FIFO	960.27	
FIFO	970.34	
LBA/FIFO	972.74	
P/FIFO	1019.31	
P/CR	1031.53	
CR/FIFO	1053.66	

Table F.12.3: ANOVA and Tukey Tables for Std. Dev. Of Cycle Time

Source	DF	SS	MS	F	P
DR	6	21397.4	3566.2	119.9	0.000
Error	14	416.4	29.7		
Total	20	21813.9			

Dispatching Rule	Std. Dev. (hours)	Sig.
HXT/FIFO	66.97	
P/HXT	79.62	
FIFO	88.37	
LBA/FIFO	92.39	
P/CR	142.39	
P/FIFO	144.96	
CR/FIFO	146.33	

Table F.12.4: ANOVA and Tukey Tables for Average WIP

Source	DF	SS	MS	F	P
DR	6	6.0	1.0	56.1	0.000
Error	14	0.3	0.0		
Total	20	6.3			

Dispatching Rule	Avg. WIP	Sig.
P/HXT	13.927	
HXT/FIFO	14.04	
FIFO	14.187	
LBA/FIFO	14.22	
P/FIFO	14.893	
P/CR	15.077	
CR/FIFO	15.403	

Appendix G. Simulation Models of Semiconductor Research and Development Fabs and Results for Experiments 1, 2 and 3 on CD

This appendix contains a brief description of the simulation models used in Experiments 1, 2 and 3 and results from these experiments. The data used for the modeling and the results can be found in excel workbooks on a CD attached to the back cover of the bound thesis. The Excel workbooks are named “Experiment 1 and Experiment 2.xls”, “Experiment 3.xls” and “Results.xls”. The first workbook is used to simulate models for Experiments 1 and 2 and the second to simulate models for Experiment 3. The third workbook contains results from the simulations of all three experiments.

Table G.1 briefly describes the contents of the spreadsheets of the workbooks containing data for the simulation models. Detailed instructions on changing WIP levels, dispatching rules, production volumes, technical support, tools quantities, product mix and lead time can be found in the spreadsheets of the workbooks.

Table G.1: Contents of Spreadsheets of Workbooks Titled “Experiment 1 and Experiment 2.xls” and “Experiment 3.xls”

Spreadsheet Name	Contents
part.txt	lists the parts and lots used in the model
order.txt	lists the interarrival rate for lots introduced in the fab
stn.txt	contains data on tool quantities, capacities, load times and associated storages
kanban.txt	contains genres to control WIP in the system
oper.txt	lists the operators available to process lots at tools/stations and technical operators to repair down tools
attach.txt	assigns schedules to resources (tools and operators)
kanbandevilloop.txt	contains actionlists for lots to trigger down and PM events
devilPMloop.txt	contains actionlists for lots to trigger PM events at the respective tools
devildownloop.txt	contains actionlists for lots to trigger down events based on statistical distributions
subcmos.txt	contains actionlists for representative lots when they visit tools that require specific actions in their routes
pmroutes.txt	lists routes for lots that trigger PM events
downroutes.txt	lists routes for lots that trigger down events
route2.txt/reproute.txt	details the steps in the representative route, specifying the tool, the operator, the setup and the actionlist required
storage.txt	specifies storages for tools
setup.txt	specifies setup times for tools
shiftcal.txt	specifies schedules for the operators in the fab
techcal.txt	specifies schedules for the technical support group
shiftSTNcal.txt	specifies schedules for tools including tool reservations and off times
shiftrepdummymcal.txt	specifies schedules for the control operators who leave before the designated operators to ensure that tools do not process lots until there is a big enough time window for their completion until the end of shift of the designated operator

Table G.2 contains a description of the contents of the spreadsheet in the workbook having results and graphs from the three experiments.

Table G.2: Contents of Spreadsheets of Workbooks Titled “Results.xls”

Spreadsheet Name	Contents
Experiment 1 Results	contains results from the experimental design conducted for Experiment 1
Experiment 1 Graph	contains graphs for average cycle time, throughput and tradeoff for Experiment 1
Experiment 2 Results	contains results from the experimental design conducted for Experiment 2
Experiment 3 Raw Data	contains raw data from the experimental design conducted for Experiment 3