# Measurement and Improvement of Manufacturing Capacity (MIMAC) Final Report

**SEMATECH**

**Technology Transfer 95062861A-TR**

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**Abstract:** This document describes the Measurement and Improvement of MAnufacturing Capacity (MIMAC) project, a joint effort between JESSI/MST and SEMATECH. Its primary objective was to identify and measure the effects and interactions of the major factors that cause loss in fab capacity. In particular, the project focused on understanding the impact of these factors on the capacity planning process. Secondary objectives were to identify areas for further investigation by researchers and to demonstrate the feasibility of European and American cooperation in manufacturing modeling. Supporting documents for the MIMAC project are as follows: *Measurement and Improvement of Manufacturing Capacity (MIMAC) Survey and Interview Results*, Technology Transfer #94052374A-XFR, *Measurement and Improvement of Manufacturing Capacity (MIMAC) Bibliography*, Technology Transfer # 94062424A-XFR, and *Measurement and Improvement of Manufacturing Capacity (MIMAC) Designed Experiment Report*, Technology Transfer # 95062860A-TR.

**Keywords:** Manufacturing, Fab Capacity, Planning, Productivity Analysis, Factory Modeling, Cycle Time

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## Table of Contents

## List of Figures



## List of Tables

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## 1 EXECUTIVE SUMMARY

This document describes the Measurement and Improvement of MAnufacturing Capacity (MIMAC) project. MIMAC was a joint effort between Joint European Submicron Silicon (JESSI) and SEMATECH. The primary objective of MIMAC was to identify and measure the effects and interactions of major factors that cause loss in fab capacity. In particular, the project focused on understanding the impact of these factors on the capacity planning process. Secondary objectives were to identify areas for further investigation by researchers and to demonstrate the feasibility of European and American cooperation in manufacturing modeling.

The project was divided into the following four activities:

- Survey and interview process
- Preliminary factor investigation
- Global factor analysis
- Technology transfer

**Survey and Interview Process** – A written survey, followed by interviews at SEMATECH and Manufacturing Science and Technology (MST) member companies, revealed a key finding: the factory performance measures viewed as the most important overall were cycle time and on-time delivery. However, cycle time was typically not included explicitly in the capacity planning process. Because of this discrepancy, the MIMAC Team attempted to include cycle time in planning and measuring capacity throughout the project.

**Preliminary Factor Investigation** (including an extensive bibliography of articles related to MIMAC) – The MIMAC Team demonstrated the local effects of the following 18 factors by developing small models to study each factor in isolation: tool dedication, batching, breakdowns, dispatching/sequencing, end-of-shift effect, factory shutdown, hot lots, inspection/yield, operator cross-training, lot sizes, mix, operator availability, order release/WIP limits, redundant tools, rework, setup, and time bound sequences. In some cases these models were expanded to evaluate particular interaction effects.

**Global Factor Analysis** – The MIMAC Team investigated the global (factory-level) effects of the factors and their interactions. A simulation experiment was designed to study 11 factors, using four factory-level datasets from actual semiconductor fabs.

**Technology Transfer** – The MIMAC Team held six workshops to transfer the results of the project to JESSI and SEMATECH. Overall, the recipients of the project results responded favorably on the workshop evaluation form.

## 2 INTRODUCTION

Increasing competition in semiconductor manufacturing, coupled with shorter market windows and higher costs, have made designing good products insufficient to guarantee success. Manufacturing products well is also important. Unfortunately, unlike semiconductor product design, manufacturing methods does not have an established science base. The situation is particularly critical when it comes to operations. The innovations in fab operation strategies and policies have not kept pace with innovations in the design of manufacturing equipment, materials handling systems, and integrated equipment. Why semiconductor fabs operate below their theoretical capacity is not fully understood, and methods for measuring or predicting fab performance need to be improved. The effect of lot size, job release, maintenance, batching, dispatching, time-constrained processing, product mix, and equipment set are just some of the factors believed to influence manufacturing capacity.

## 2.1 JESSI and SEMATECH

Both JESSI and SEMATECH member companies are interested in determining more efficient ways to manufacture semiconductor devices. This is evident in their current activities. JESSI is interested in being able to plan and schedule wafer fabs effectively and has a project to determine the present state of planning and scheduling software systems being used by JESSI member companies. In their long-range plans, SEMATECH has identified a need for models to support future factory design and operations.

The JESSI organization has, for instance, supported the MST T30 project. MST is funded within the European Union (EU) research and development framework ESPRIT and is referenced as project 7365. MST has a goal of making submicron integrated circuit manufacturing in Europe profitable. The MST project is now in its third phase, MST-III. MIMAC was integrated into MST-III. The main project partner for MIMAC in the EU was Nimble nv, which entered MST as an associated partner of Mietec-Alcatel.

SEMATECH established the Operational Modeling (OM) department within the Modeling and Statistical Methods division. The OM department, in conjunction with the Future Factory division, established the Future Factory Design project J82 in support of Future Factory modeling activities. Part of the J82 project involved investigating models developed to answer specific questions about the nature and performance of the future factory. The MIMAC project helped to provide analysis for some of these applications and to identify important interactions.

Since JESSI and SEMATECH were interested in developing a better understanding of capacity loss factors, and since both considered the area to be pre-competitive, they established the MIMAC project. The direct consequences of MIMAC are expected to be improved usage of resources and more realistic planning. This realism is important for investment decisions for which knowing when new equipment will be needed is important. Simply stated, to improve something, one must understand why it is not performing at its theoretical optimal rate.

## 2.2 Participants

Members of the MIMAC project team are listed below:

| JESSI T30C / ESPRIT 8003 MST III: | |
|---|---|
| Nimble | Luc De Ridder |
| | Ben Rodriguez |
| | Anneleen Bekkens |
| | Stefan Hoelzl |
| Matra MHS | Michel Garrigue |
| Siemens | Hans Ehm |
| Univ. of Würzburg | Alexander Schömig |
| | Manfred Mittler |
| | Notker Gerlich |
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| SEMATECH | John Fowler |
| | Jennifer Robinson |
| | David Nehme |
| IBM | Hans Fromm |
| | Ottmar Gihr |
| Motorola | Eileen Neacy |
| National | Norman Abt |
| Univ. of California - Berkeley | Frank Chance |
| Cornell University | Lee Schruben |

## 2.3 Project Approach and Goals

MIMAC was divided into four activities: survey and interview process, preliminary factor investigation, global factor analysis, and technology transfer. The relationship among these activities is shown in Figure 1.

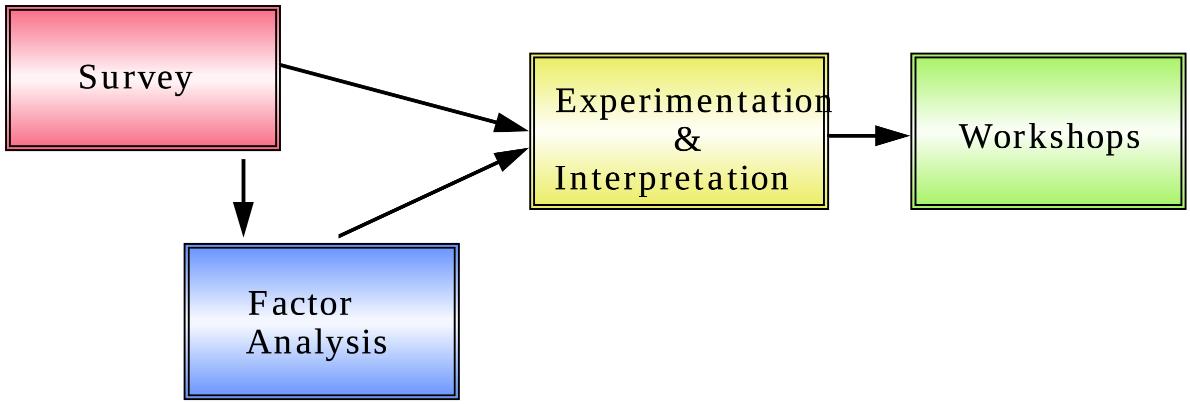


**Figure 1 Relationship Among Project Activities**

The first activity consisted of a written survey on capacity, followed by interviews at several SEMATECH and MST member companies. The goals of the survey and interview process were as follows:

1. To understand how capacity is defined and measured, what limits capacity, and what factors are used to approximate capacity loss within semiconductor fabrication facilities.
2. To determine where improvements are most needed in factory capacity measurement and definition, to provide direction to the MIMAC Team.

The second activity consisted of preliminary investigation of several capacity loss factors. An extensive literature review was conducted. The factors were also studied in isolation, using small spreadsheet, queuing, and simulation models. The goal of the preliminary analysis was to define and understand the factors before studying them at the factory level.

The third phase of the project involved extensive experimentation and interpretation using factory-level data. This effort drew on the results of the survey process and the individual factor analyses. The goals of this phase of the project were as follows:

1. To identify the factors that had a significant effect on factory-level capacity.
2. To develop a methodology for conducting factory-level experiments that people from the JESSI and SEMATECH member companies could follow at their own sites.

The project included six international workshops on fab capacity measurement and improvement (three in Europe and three in the United States). The audience for the workshops included fab management, capacity planners, and operations personnel. The goals of the workshops were as follows:

1. To have participants revisit the capacity planning process.
2. To present advanced capacity planning techniques and show how to use them in factories.
3. To transfer the research findings and insights gained from the project.
4. To provide opportunities for a useful exchange of information in this area.
5. To get opinions on areas for further research.

## 2.4 Summary of Project Deliverables

Various deliverables besides the six workshops have been and will be made available to SEMATECH and MST members. These include a bibliography summarizing the initial literature search and reports on the survey and interview process, individual factor studies, and factory-level experiments. An additional report will address research and recommendations related to the capacity planning process. A semiconductor manufacturing testbed consisting of six factory-level datasets and a manufacturing simulator has also been provided, as has a spreadsheet-based training tool (called the MIMAC prototype or "game") for planning capacity under a cycle-time constraint. These deliverables are described in more detail in Section 3.

## 2.5 Project Timeline

| | |
|---|---|
| February 1, 1994 | Report on U.S. survey and interview results |
| March 1, 1994 | Project bibliography |
| April, 1994 | European surveys conducted |
| April 18, 1994 | Preliminary project report, including:<br>• Overview of project available<br>• Preliminary factor identification |
| November/December, 1994 | 6 project workshops |

# 3 DELIVERABLES

The workshops provided the primary means for transfer of the MIMAC results to JESSI-MST and SEMATECH member companies. The workshops are discussed in Section 4. Several other deliverables are also available, as described below.

## 3.1 Survey and Interview Results

Early in the MIMAC project (October 1993) a written survey was sent to more than 220 fab managers, production managers, capacity planners, production planners, and production supervisors from each SEMATECH member company. The U.S. survey response rate was 60%. In addition, detailed interviews were conducted with four SEMATECH member companies to enhance understanding of the survey results. The results of the SEMATECH survey and interview process are available as Technology Transfer #94052374A-XFR.

The same written survey was also distributed in April 1994 to about 25 fab managers, planning managers and planning and/or scheduling specialists in each MST member company. Sometimes one person filled out a questionnaire representative of his company’s practices. Responses were received from each of the eight MST companies, amounting to virtually a 100% response rate. Several companies were visited for follow-up interviews.

A key finding from the survey and interviews was that the factory performance measures viewed as the overall most important were cycle time and on-time delivery. However, typically cycle time was not included explicitly in the capacity planning process. Because of this discrepancy, the MIMAC Team attempted to include cycle time in the planning and measuring of capacity throughout the project.

## 3.2 Project Bibliography

The MIMAC bibliography represents a compilation of over 250 articles related to measuring and improving capacity in semiconductor manufacturing. Members of the MIMAC Team suggested articles for inclusion based on their particular areas of expertise. Various general reference documents were also consulted and included. Articles were placed under 38 different subject headings, related where practical to the areas being studied under MIMAC. The articles were also classified using an index of authors. The bibliography is available to both SEMATECH and JESSI members as SEMATECH Technology Transfer #94062424A-XFR.

## 3.3 Individual Factor Study Report

After compiling the bibliography, the MIMAC Team demonstrated the local effects of single factors by developing small models to study each factor in isolation. Occasionally these models were expanded to evaluate particular interaction effects. The individual factor study report includes a discussion of each of the following 18 factors: tool dedication, batching, breakdowns, dispatching/sequencing, end-of-shift effect, factory shutdown, hot lots, inspection/yield, operator cross-training, lot sizes, mix, operator availability, order release/WIP limits, redundant tools, rework, setup, and time bound sequences. Each factor is defined (often referencing the MIMAC bibliography), and the individual experiment results are presented. The relevance of the results to the capacity planning process is also discussed. This report is available from John Fowler at SEMATECH or Ben Rodriguez at Nimble.

## 3.4 Global Experiment Report

Following the local effect experiments, the MIMAC Team investigated the global (factory-level) effects of the factors and their interactions. A simulation experiment was designed to study 11 factors, using four factory-level datasets from actual semiconductor fabs (see Section 3.7). The global experiment report includes a detailed description of the methodology used to conduct the experiments, and also a comparison of the results across the four datasets. This report is available to SEMATECH members as Technology Transfer #95062806A-XFR.

## 3.5 Spreadsheet Training Tool

The MIMAC Team developed a simplified capacity planning spreadsheet as a learning tool for the workshop participants. The spreadsheet models product, tool, and process specifications. In addition to the usual static spreadsheet computations, the MIMAC tool includes limited queuing analysis and simulation capabilities. The tool has been customized to play two different ‘games,’ one at the single step level, the other at a multiple-tool, multiple-step level. In both games, the objective is to produce as many wafers as possible subject to the constraint that the average cycle time does not exceed a specified multiple of the raw process time. Players may change the start rate and minimum batch sizes, buy tools (subject to a budget), and purchase improvements in machine downtime. The MIMAC spreadsheet and documentation are available from John Fowler at SEMATECH or from Ben Rodriguez at Nimble.

## 3.6 Capacity Planning Process Report

The capacity planning report summarizes the findings of the MIMAC project as they relate to the capacity planning process. This includes a review of the different stages of capacity planning (strategic, tactical, and operational) and the reasons why capacity planning is so challenging. The report then discusses the modeling tools available at different stages of the process (spreadsheets, queuing analysis, simulation) and makes recommendations for when and how cycle time can be included. Requirements for the 'ideal' capacity planning tool are also discussed.

### 3.7 Semiconductor Manufacturing Testbed

The testbed was developed under another sub-task of SEMATECH project J82. European data was added and validated under the MIMAC project. The testbed currently includes a set of six factory-level datasets and a manufacturing simulator. The datasets contain actual manufacturing data from wafer fabrication facilities, organized into a standard format. The datasets include no real product names, company names, or other nomenclature that could identify the source of the data. Each dataset contains the minimum information necessary to model a factory, including product routings and processing times, rework routings, equipment availability, operator availability, and product starts. The simulator, Delphi, is a C-based discrete-event simulator developed by Frank Chance at Cornell University. Delphi was extended during the course of the MIMAC project.  Delphi models factory-level data described in the datasets, including breakdowns, setups, rework, scrap, and operators. It also includes a queuing network analyzer. The datasets and Delphi are available via anonymous ftp from ftp.sematech.org or by contacting John Fowler at SEMATECH or Ben Rodriguez at Nimble.

## 4 WORKSHOPS

To transfer the results of the project to the JESSI and SEMATECH member companies, the MIMAC Team held six workshops. Workshop dates are shown in Table 1. The remainder of this section describes the workshop participants and their general evaluation of the workshops. It also presents participant feedback concerning definitions of capacity, the requirements for the ideal capacity planning tool, lessons learned, and next steps.

**Table 1 Workshop Dates (1994)**

| | |
|---|---|
| November 14-15 | London, England |
| November 17-18 | Nantes, France |
| November 21-22 | Munich, Germany |
| December 1-2 | Marlboro(Boston), Massachusetts |
| December 5-6 | Santa Clara, California |
| December 8-9 | Austin, Texas |

### 4.1 Participants/General Evaluation

A total of 113 people attended the MIMAC workshops. Of these, 87 filled out evaluation forms. The evaluation form is included as Appendix A. The first 16 questions asked people to rank several positive statements about the workshops on a scale of one to five, in which one indicated strong disagreement, and five indicated strong agreement. For each of the 16 questions, the average ranking was greater than 4. The overall average across all 16 questions was 4.35. The lowest ranking (4.08) was for question 2 (“I understood why this meeting was being held, and what specified outcomes were expected.”). However, question 12 (“The material covered in this workshop was relevant to my job”) was one of the highest ranked (4.53). Scores for the other questions are included as Table 3.1.

The audience filling out the evaluation forms included 44 capacity planners, four fab managers, ten operations managers, five production planners, five supervisors, six industrial engineers, and seven process engineers. Of these, 43 said that they would recommend the workshop to their boss, 54 would recommend it to their peers, and 29 would recommend it to their subordinates. A few also indicated that they would recommend the workshop to either marketing people or fab managers. People tended to be pleased with the workshop locations and sizes. Eighty-five people said that the location was convenient; 84 said that the number of participants was “just right.”

Most respondents expressed enthusiasm for follow-on work to MIMAC. Sixty-five believed that a follow-on project to develop a capacity planning tool would definitely be valuable. Another 18 thought that it might be valuable. Three people thought that such a project would not have value, and four were unsure. Fifty-four people expressed interest in a follow-on project to study capacity planning for the back-end. Seventeen more thought the back-end work might be valuable, while 15 said that they did not know. Only three people said that such work would not be valuable.

The responses to questions about JESSI/SEMATECH cooperation were also positive. Seventy-eight people said that the cooperation worked well for this project. Three others thought that it worked somewhat well, and five said that they did not know. No one answered an outright “no” to this question. Asked whether JESSI and SEMATECH should have other joint projects in the future, 63 said “yes,” 13 said “maybe,” 13 said “don’t know,” and one person said “no.”

**Table 2 MIMAC Workshop Evaluation Report**

| | | Strongly Disagree | | | | Strongly Agree | |
|---|---|---|---|---|---|---|---|
| **Question** | **Evaluation Category** | **1** | **2** | **3** | **4** | **5** | **Avg.** |
| 1 | Notified in time | 1 | 2 | 5 | 18 | 66 | 4.59 |
| 2 | Why meeting was held | 0 | 2 | 20 | 39 | 31 | 4.08 |
| 3 | Understood expectations | 0 | 1 | 16 | 48 | 27 | 4.10 |
| 4 | Open expression of ideas | 0 | 1 | 3 | 32 | 56 | 4.55 |
| 5 | Proceeded as scheduled | 1 | 0 | 5 | 32 | 54 | 4.50 |
| 6 | Time for clarification | 0 | 0 | 7 | 33 | 52 | 4.49 |
| 7 | Improve ability to do job | 0 | 2 | 15 | 43 | 32 | 4.14 |
| 8 | Meeting achieved objectives | 0 | 0 | 3 | 46 | 43 | 4.43 |
| 9 | Worth my time | 0 | 2 | 3 | 37 | 49 | 4.46 |
| 10 | Meeting set-up was sufficient | 0 | 2 | 12 | 27 | 48 | 4.36 |
| 11 | Food and beverage satisfactory | 0 | 0 | 9 | 34 | 47 | 4.42 |
| 12 | Material relevant to my job | 0 | 0 | 6 | 30 | 54 | 4.53 |
| 13 | Length of workshop was okay | 0 | 3 | 10 | 27 | 48 | 4.36 |
| 14 | Tutorials were at the right level | 0 | 3 | 8 | 47 | 34 | 4.22 |
| 15 | Capacity game at the right level | 0 | 2 | 18 | 32 | 34 | 4.14 |
| 16 | Game was effective learning tool | 0 | 3 | 12 | 37 | 38 | 4.22 |
| | | | | | Overall Average | | 4.35 |

## 4.2 Definitions of Capacity

Early in each workshop participants were asked to share their definitions of capacity. A variety of answers resulted. However, some common themes emerged. For example, many people defined capacity in terms of throughput, or the amount that a facility could produce in a given time. Sometimes the definition was narrowed to refer to the maximum amount that the bottleneck or bottlenecks could produce. Assumptions about equipment availability, line yield, setups, and product mix were recommended as part of some definitions, as were assumptions on budget, quality, operators, hot lots, lot sizes, and batch sizes. In a few cases, cycle time was cited as important to the definition of capacity. For example, capacity “while achieving the cycle time the customer asks for” was defined, as was the “output rate that will sustain and not exceed that (given) cycle time.” The standard deviation of cycle time was also mentioned occasionally as a parameter.

The MIMAC Team later shared their working definition of capacity, which was motivated by the importance of cycle time as a performance measure for survey and interview respondents. The team defined capacity as "the maximum output rate (or start rate) sustainable for a particular factory with a given product mix and a constraint on the average cycle time." This capacity can be measured by generating the characteristic curve of cycle time versus output rate (or start rate) for the factory and by finding the output rate that corresponds to the specified cycle time constraint. The characteristic curve is obtained using either simulation or queuing models.

### 4.3 Characteristics of the Ideal Capacity Planning Tool

Workshop participants cited the items listed in Table 3 as characteristics of the 'ideal' capacity planning tool. One element mentioned frequently was the ability to use multiple modeling techniques (spreadsheets, queuing, and simulation) with a single tool. Other essential attributes included data integration; model accuracy and affordability; and various performance criteria such as speed and ease of use.

**Table 3 Characteristics of the Ideal Capacity Planning Tool**

| The ideal capacity planning tool should be |
|---|
| Accurate |
| A combination of different modeling techniques |
| Cost effective (affordable) |
| Easy to interpret |
| Easy to use |
| Fast |
| Flexible |
| Simple |
| Useable weekly / short-term decision making |
| User friendly |
| |
| The ideal capacity planning tool should able to |
| Attach notes to scenarios |
| Generate characteristic curves |
| Generate graphics |
| Handle semiconductor manufacturing technology |
| Identify opportunities |
| Look backwards (retrospective) |
| Model interactions |
| Model operators |
| Sanity check for errors |

**Table 3 (continued)**

| |
|---|
| Support ramp-up |
| Toggle options on and off |
| The ideal capacity planning tool should have |
| A built-in statistics package |
| Automatic design of experiments capability/response surface generation |
| Automatic updates after process changes |
| Cost modeling capability (wafer and die) |
| Dynamic and probabilistic elements |
| Easy, automatic data integration / data gathering / data viewing |
| Ease of use of a spreadsheet |
| Goal-seeking capabilities (including multi-criteria) |
| Graphical user interface |
| Minimal data requirements |
| Optimization capability |
| Portability |
| Simulation capability |
| Spreadsheet capability |
| Queuing analysis capability |
| What-if capability |

## 4.4 Lessons Learned by Participants

Near the end of each workshop, the MIMAC Team reviewed the main points presented throughout the workshop. They then asked participants which of these had been particularly valuable and what additional lessons had been learned. Many responses pertained to cycle time. Examples include the relevance of cycle time and ways to deal with it, the importance of variability of cycle times, clarification of the relationship between capacity and cycle time, and the fact that reducing variability reduces cycle times and increases capacity. Other responses related to confirmation of various intuitions, including the Pareto (ranking) of factors; the representation of variability; and the knowledge of how far modeling tools have advanced in the past few years. Some participants pointed to specific methodologies that they had learned, including how to build characteristic curves, how to treat the relationship between data gathering and model building, and how to do simulation and queuing modeling. Others focused more on specific MIMAC research topics, such as batch machine control policies and the interaction of setup and downtime. Still others emphasized results that might be relevant to the capacity planning process. For example, people mentioned the ideas of integrating cost more into capacity decisions, adding capacity at non-bottleneck tools in a cycle-time constrained environment, and integrating strategic, tactical, and operational planning.

Participants also gained some insights from listening to Professor Robert Leachman, the dinner speaker for the U.S. workshops. Professor Leachman presented the results to date of the Sloan Foundation's Competitive Semiconductor Manufacturing study, in which researchers are evaluating the performance of semiconductor fabs around the world. Of particular interest was Professor Leachman's observation that productivity and capacity losses are as important as yield losses.

Some general comments in this session were that the workshop provided a good summary of the important concepts for fab people and that there is a large gap between what people have and what they would like to have in capacity planning tools. Some participants also felt that they had learned (or at least had confirmed) that people in other fabs are facing similar problems. A few managers also commented that they had learned some lessons from the MIMAC Team on holding successful workshops.

### 4.5 Lessons Learned by the MIMAC Team

The MIMAC Team learned much about planning and measuring capacity throughout the project. Many of these findings and lessons are included in Section 5. Specific lessons learned during the workshops themselves are discussed here. Several of these lessons pertain to areas that should be included or extended in future work. For example, people pointed out that defining capacity in terms of mean cycle times might not be sufficient. Consideration of the distribution of cycle times will also be necessary. Similarly, while studying setups was considered useful, people recommended an extension to include studying variability in the setups. Other suggestions included inviting more process engineers to participate in future work, trying to close the loop between planning and operations, and considering time to acquire capital in capacity planning.

Several lessons concerned differing perspectives of the audience. The MIMAC Team learned that there are many dimensions to discussing a ‘balanced’ factory, including cost, throughput, and floor-space considerations. Different definitions of ‘steady state’ of a factory were also apparent, as were different definitions of terminology describing modeling and simulation. Even contingency factors are defined and used differently in various contexts, including one example where different contingency factors were selected according to the cost of the tools. Two other points about the practice of capacity planning were that 1) sometimes it is necessary to buy a new tool for technological, rather than capacity, reasons; and 2) the age of the equipment determines the ability to do detailed capacity planning. The latter occurs because uncertainty about the characteristic data of new equipment makes it difficult to produce accurate capacity planning figures. Overall, the team learned more about the state of the practice of capacity planning, and the requirements for new or improved capacity planning tools.

The MIMAC Team also gained some insights from listening to Professor Leachman's talk. In particular, the Team had experienced difficulty in comparing performance across different factories, because traditional productivity measures are not always applicable. They felt that Professor Leachman's proposal for new, invariant productivity measures based on the number of mask layers completed might be useful for future work.

Finally, the MIMAC Team learned a great deal about holding workshops. A number of improvements in the presentation materials were suggested. Some were in fact carried out between the European and U.S. workshops. Others will help in future distribution of the information from this project. The suggestions for using the MIMAC game to its full advantage were particularly helpful. On a lighter note, the team learned that holding six workshops on two continents in one month is a challenging endeavor.

### 4.6 Recommendations for Next Steps

After investing a day and a half in the MIMAC workshops, participants had many suggestions for next steps to be taken by the MIMAC Team, academia, and themselves. Recommendations for the MIMAC Team have been grouped into categories and included in Table 4. Participants had fewer recommendations for academia. Several people felt that JESSI and SEMATECH member companies should continue subcontracting universities where expertise is needed and continue to organize these efforts directly. Some JESSI representatives suggested that the MIMAC Team and the individual companies should encourage European universities to get more involved in semiconductor manufacturing and operations research. Other specific recommendations for research are listed below:

1. Improve computing productivity to get detailed models to work in real time.
2. Investigate other ways of achieving dramatically improved performance.
3. Look at optimization to generate response surface curves to determine where you want to operate your factory.
4. Explore integrating techniques from other industries.
5. Continue to do research on equipment dedication.

Workshop participants identified several possible next steps for themselves. Some suggested transferring the MIMAC workshop materials, especially the spreadsheet game, to others in their organizations. Others highlighted opportunities for future learning, such as becoming more familiar with queuing theory and having additional workshops. Interest was expressed in agreeing on requirements for a capacity planning tool. However, there was a tendency to feel that the MIMAC Team should synthesize workshop inputs and come up with proposed next steps. It would then be the responsibility of interested workshop participants to ensure the availability of funds for future work. The MIMAC Team’s follow-up activities since the workshops and proposals for next steps are discussed in Section 6.

## 5 LESSONS LEARNED ABOUT OVERALL PROJECT

The MIMAC Team learned many things during the course of this project. Most of the more technical lessons are described in various project reports. Other, more qualitative insights are listed here. For example, the survey and interview reports document lessons learned about how people in the MST and SEMATECH member companies plan and measure capacity in wafer fabs. A lesson learned since the reports were published is that surveys can be a good way to increase the visibility of a project. Many of the workshop attendees were people who had filled out a survey form and/or participated in an interview a year earlier.

The MIMAC Team also learned about the trials and tribulations of conducting large-scale designed experiments. They learned to set realistic expectations concerning the number of runs that would be needed for an experiment, and that data validation is a never-ending process. They learned to automate runs across multiple workstations, and to transfer data and results electronically between two continents. Ultimately, they proposed a methodology (see Section

3.4) for running similar experiments at member company sites. Hopefully, this methodology will let other people benefit from mistakes made during this project.

Several lessons learned concerned JESSI/SEMATECH cooperation. For example, funding issues are treated very differently by JESSI and SEMATECH. This makes it difficult to synchronize the starting dates of joint projects. However, the experience gained in starting up the MIMAC project should make it easier to start projects in the future. Given the limited number of people working in this area, joint projects are a good way to find sufficient resources.

Other observations pertain to having a successful project with team members in many locations. MIMAC had people working in three locations in Europe and in four different states in the U.S. Keeping time zone differences in mind was critical. For example, sending something at the end of the day from the U.S. meant that the Europeans would have it to work on when they arrived the next morning, rather than having to wait six to nine hours. Incidentally, a lesson learned the hard way was that daylight savings time starts on a different date in the U.S. than it does in Europe. Maintaining close communication was also important. Joint meetings were held approximately every other month. The key to remaining productive in between was holding weekly conference calls.

Although it was sometimes difficult to coordinate among team members at many different sites, the MIMAC Team found that having people with varied backgrounds contributed immeasurably to the success of the project. Some team members came from manufacturing backgrounds. They worked to keep the MIMAC results tied to the ultimate users. Meanwhile, several university researchers added expertise in different areas. Overall, the different backgrounds resulted in a synergy by which ideas were proposed and executed.

## 6 NEXT STEPS AND FOLLOW-UP ACTIVITIES

Since the original six workshops were completed, a number of follow-up activities have taken place. Additional workshops have been held at AT&T, Motorola, Rockwell, and Siemens. Other workshops are planned or anticipated in the U.S. and Europe. Several companies have expressed interest in applying the MIMAC capacity planning methods at their sites. Some of these efforts will be undertaken with help from MIMAC Team members. Others will be done independently. One company is performing sensitivity analyses in terms of cycle-time constrained capacity. The capacity planning prototype (MIMAC spreadsheet), Delphi, and the testbed datasets have been delivered to workshop participants and to others from the member companies.

Based on the concepts demonstrated by the MIMAC prototype, Nimble is improving their existing capacity planning system to realize the Dynamic Capacity Planning System, DeSIReS/DCP. In the U.S., SEMATECH is defining its strategy and gathering requirements for a Factory Planning System. Further cooperation between these activities is being considered.

Most JESSI/MST and SEMATECH member companies have expressed interest in or are actively pursuing back-end capacity improvements. Both sides are organizing research projects for back-end. DCP will be extended by Nimble for back-end capacity planning. A back-end version of Delphi is also being developed. Both the U.S. and the EU sides support further cooperative work to study back-end productivity.

**Table 4 Next Step Recommendations for the MIMAC Team**

| |
|---|
| Future Information Exchange: |
| Continue JESSI/SEMATECH cooperation |
| Explore the possibility of working with the Japanese |
| Include, or share information with, commercial software suppliers |
| Provide opportunities for follow-on networking among member companies |
| |
| Additional Workshops and Technology Transfer: |
| Host specific workshops or tutorials on |
| Capacity related to scheduling |
| How to use MIMAC tools (Delphi, scripts, etc.) |
| Queuing |
| Back-end / probe |
| Repeat sections of the existing workshop for |
| Rockwell |
| AT&T |
| TEMIC |
| Motorola |
| Siemens |
| MHS |
| Mietec |
| Other general offerings in the U.S. and Europe |
| Tailor sections of the workshop to capacity planners vs. managers or supervisors/operators |
| Find additional ways to spread information (e.g. annotated handouts) |
| Benchmarking: |
| Repeat the MIMAC DOE using other factories |
| Do benchmarking at the factory level on |
| Use of modeling tools and techniques |
| Lot release strategies |
| WIP control policies |
| Scheduling |
| Overall production control best practices |
| Benchmark against the Japanese |

**Table 4 (continued)**

| |
|---|
| Additional Factory-level Research: |
| Look at different ways to ‘balance’ a factory |
| Study the variability (distribution) of cycle time |
| Explore the cost of reducing cycle time |
| Try to get the characteristic curve used in accounting practices |
| Investigate ABC costing |
| Look at optimizing the capacity of the bottleneck |
| Do more detailed analysis of the factors, including |
| Setups - changing the magnitudes of the setups (with sensitivity information) |
| Downtime - where you get the biggest benefit from improvements |
| Lot sizes |
| Mix |
| Research the applicability of existing queuing algorithms |
| Investigate real-time control and its link with planning |
| Continue to work on the relationship among capacity, cycle time, and utilization |
| |
| Tool Development or Recommendations: |
| Develop a new tool |
| Investigate and make recommendations concerning existing tools |
| Make a pilot implementation of a capacity planning system |
| |
| Extensions of Capacity Planning to: |
| New equipment technologies (e.g. AMHS) |
| Strategic decisions / enterprise-level planning |
| Back-end |
| Operational decisions, including scheduling and the impact of processing times |
| Improve capital productivity |

## APPENDIX A
## WORKSHOP EVALUATION FORM

# MIMAC Workshop Evaluation Form

Questions 1 to 16 have a sliding scale from 1 to 5.

1 means that you completely disagree and 5 means you completely agree.

*****************************

1. I was notified of this meeting in sufficient time to prepare for it.

| | | | | |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |

2. I understood why this meeting was being held and what specified outcomes were expected.

| | | | | |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |

3. I understood what was expected of me and of the other participants.

| | | | | |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |

4. Participants expressed themselves openly, honestly, and directly.

| | | | | |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |

5. The meeting generally proceeded as scheduled in the agenda.

| | | | | |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |

6. Sufficient time was provided for clarification and feedback.

| | | | | |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |

7. The information/ideas from this meeting should improve my ability to do my job.

| | | | | |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |

8. The meeting achieved its objectives.

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|

9. Overall, I felt that the meeting was worth my time and expense to attend.

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|

10. The room set-up was sufficient for this type of meeting.

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|

11. The food and beverage arrangements were satisfactory.

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|

12. The material covered in this workshop was relevant to my job.

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|

13. The workshop was about the right length.

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|

Comments (Too long? Too short?):_________________________

_____________________________________________________________________

_____________________________________________________________________

_____________________________________________________________________

14. The tutorial style of the workshop was at the right level.

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|

Comments (Too simple? Too difficult to understand?):__________

_____________________________________________________________________

_____________________________________________________________________

_____________________________________________________________________

_____________________________________________________________________

15. The capacity game was at the right level of difficulty.

| | | | | |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |

Comments (Too simple? Too difficult to understand?):________

________________________________________________________________

________________________________________________________________

________________________________________________________________

________________________________________________________________

16. The game was an effective tool for explaining concepts.

| | | | | |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |

17. What was the most difficult section of the workshop?________________

________________________________________________________________

________________________________________________________________

________________________________________________________________

________________________________________________________________

18. I would recomment this workshop to:
    - A) My Boss
    - B) My Peers
    - C) My subordinates
    - D) Other______________________________________

19. Job Description: (circle one)
    - A) Production Planner
    - B) Capacity Planner
    - C) Fab. Mgr.
    - D) Ops. Mgr.
    - E) Supervisor
    - F) Other:__________________________

20. What is the most interesting thing that you learned during the workshop?______________________________________________

______________________________________________________________

______________________________________________________________

21. What have you learned during the workshop that you will be able to use soon at your company?_______________________________________

______________________________________________________________

______________________________________________________________

22. What have you learned during the workshop that you will be able to use at your company in the future?_____________________________________

______________________________________________________________

______________________________________________________________

23. How could we change the workshop to make it more valuable for groups in the future?________________________________________________

______________________________________________________________

______________________________________________________________

24. Do you believe that a follow-on project to develop a wafer fabrication capacity planning tool, based on MIMAC concepts, would be valuable?

YES MAYBE NO DON´T KNOW

25. Do you believe that a follow-on project to study capacity planning in the backend (sort, assemble and test) would be valuable?

YES MAYBE NO DON´T KNOW

26. Please list any other follow-on work which you think is needed in this area.

______________________________________________________________

______________________________________________________________

______________________________________________________________

27. Was this workshop location convenient? YES NO

28. Is there another location that you would prefer for future workshops?_______

________________________________________________________________________

29. How did you feel about the number of participants at this workshop?

TOO MANY JUST RIGHT TOO FEW

30. Do you feel that JESSI/SEMATECH cooperation worked well for this project?

YES SOMEWHAT NO DON'T KNOW

31. Do you think that JESSI and SEMATECH should have other joint projects in the future?

YES MAYBE NO DON'T KNOW

Please list below any other general comments about the workshops or the overall MIMAC project.

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

**We appreciate your comments.**

OPTIONAL:

Name:______________________________________________________

Company:___________________________________________________

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