Proceedings of the 2007 Winter Simulation Conference
S. G. Henderson, B. Biller, M.-H. Hsieh, J. Shortle, J. D. Tew, and R. R. Barton, eds.

AN ANALYSIS OF TOOL CAPABILITIES IN THE PHOTOLITHOGRAPHY AREA OF AN ASIC FAB

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ABSTRACT

Photolithography is generally regarded as the most constraining element in semiconductor manufacturing. This is primarily attributable to the high capital investment and extensive re-entrant flows throughout this section. Cycle time management in this area is crucial to balance the trade off between tool utilization and cycle time. In a low volume, high product mix fab the inclusion of tool capabilities, and their status, can significantly affect tool utilization and overall cycle times. In this paper a simulation model is developed to aid cycle time decision making policies in the photolithography section of a low volume, high product mix fab. The objective of the study is to determine the optimum course of action, for varying levels of expected increased demand, while maintaining acceptable cycle times and minimizing total capital spent in photolithography. The actions reviewed include the increased use of capabilities where available, followed by the purchase of new photolithography equipment.

1 INTRODUCTION

Wafer fabrication is one of the most complex and capital-intensive sections of a semiconductor manufacturing environment. Generally, a wafer fab is referred to as the facility where wafer fabrication takes place. In most cases wafer fabs contain more than 100 machines, dozens of process flows, each with 300-500 specific processing steps (Gupta et al. 2006). Wafer fabs can be categorized into two main types:

1. A logic or commodity wafer fab, which has high volume manufacturing and low product variety in order to gain economies of scale.
2. An application specific integrated circuit (ASIC) fab, which has low volume but high product variety manufacturing in order to have economies of scale.

The wafer fab examined in this study can be categorized as an ASIC fab, which is customer-oriented, flexible with a high product mix. The focus of this study is on the most constraining element of this fab, which is the photolithography area. Briefly, the photolithography process is comprised of four steps, which are coat, exposure, develop and post-photolithography analytical operations.

In "coat", the wafer is covered with photo-resist material followed by "exposure", where circuit patterns are mapped onto the wafer by exposing it to UV light through a reticle. A reticle is a piece of glass containing unique circuit patterns. In "develop", a special solvent is applied to remove the exposed photo-resist and finally in "post-lithography analytical operations", wafers are inspected manually, which is dependent on both the product and layer. The photolithography area is usually viewed as a bottleneck process because it is the most repeated process in fabrication. Furthermore, it has the most dynamic process flows and expensive equipment compared to all other areas in the fab. Thus, any enhancement in this area will affect the overall performance of the wafer fab (Akcali, Nemoto and Uzsoy 2001); Arisha and Young 2004)

In semiconductor manufacturing, cycle time management is getting more crucial due to not only complicated wafer fabrication but also high level capital investment, rapid technology changes and short product life cycles. For these reasons, shorter cycle times are required to maximize total profit, minimize costs, increase due-date performance and improve customer service level. Photolithography tool sets usually have the highest cycle times in the fab due to the re-entrant flows and expensive equipment, which requires a trade off between tool set utilization and cycle time. That is, higher utilization of tool sets reduce capital costs but also create longer queue and cycle times (Williams and Favero 2002). In addition to highly variable product mixes and complexities of tool sets, other operational and technical restrictions exist in photolithography. These are the number of setups, number of available reticles, stepper disqualification rate, inspection time, machine

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failures and process specifications (line width, spacing, and contact dimensions) (Akcali, Nemoto and Uzsoy 2001).

This paper investigates the photolithography section in an ASIC fab. This fab is expecting to face increased demand in the future. This increased demand will place additional pressures on the entire fab, but particularly on the photolithography section as it is the most constraining production element. This paper evaluates possible alternative decisions at varying demand levels on average wait times and tool utilization in photolithography. These alternative decisions are based on retaining the current system configuration, increasing capabilities or the purchase of new steppers. In all cases the objective of the study is to determine the optimal course of action taking into account cost considerations.

The paper is organized as follows. We begin with a survey of relevant photolithography literature, including a review of existing simulation studies in the area of cycle time management. The following section presents a description of the simulation model and its characteristics. The next section outlines the model experimentation and results. Finally, the conclusions to the study are provided.

2 LITERATURE REVIEW

Many studies have been carried out on cycle time management in the literature. This study focuses on cycle time reduction in the photolithography area of an ASIC fab. A number of other relevant studies using discrete event simulation (DES) have been carried out in this area and are described in brief hereafter.

Spence and Welter (1987) developed a detailed simulation model of a photolithography work cell in order to analyze the trade-offs under different scenarios related with additional resources (operators and equipment), process improvements (reducing setup times and rework) and operational rules (lot sizing and repairman wait time). Prasad (1991) created a reusable generic simulation model to understand the photolithography area. In this model, they perform sensitivity analyses for variations in the number of steppers and operators. For each of these experiments they evaluate average throughput time and utilization of machine and operators. Peikert, Thoma and Brown (1998) developed a photolithography model in an attempt to rapidly capture responses for production questions and to analyze cycle time issues. In this model they reviewed the impact of changing dispatch rules and rework reductions on cycle time and throughput.

Akcali, Nemoto and Uzsoy (2001) examine the effects of machine dedication and test run policies in the photolithography area. This is carried out in combination with uncontrollable variables such as stepper disqualification (probability of test wafer failure) rates, inspection times and machine breakdowns. They found that inspection time has the most significant effect on both the average and variance in the cycle time for photolithography and also for the overall cycle time in the fab. Monch, Prause and Schmalfass (2001) present a simulation study for the load-balancing problem in the photolithography area of a wafer fab. They investigate the influence of assignments of certain products to certain stepper subgroups with a local improvement method (i.e., a local search algorithm) on system behavior. The performance measures reviewed are cycle time per mask layer, average tardiness, and average waiting time in front of steppers under different scenarios.

With regard to scheduling problems in photolithography, Akcali and Uzsoy (2000) present a network flow formulation of the capacity allocation problem to maximize the total throughput of photolithography under operational and auxiliary resource constraints. The problem is solved by using a greedy heuristic for critical operations and steppers. The effects of stepper capability is represented by an operation-stepper matrix. The authors conclude that the choice of time horizon has a significant effect on cycle time metrics and on the number of setups, however, little effect is observed when varying reticle and setup constraints. Diaz et al. (2005) present a network flow presentation similar to that of Akcali and Uzsoy (2000). Their model evaluates the impact of reticle requirements based on the photolithography model as originally described by Park et al. (1999). Arisha and Young (2004) deal with the photolithography scheduling problem from a different perspective. They use a hybrid photolithography model with an integrated artificial intelligence scheduler to reduce WIP, setup and throughput time.

3 SIMULATION MODEL

A simulation model has been developed for a particular section in the photolithography area, of the above described ASIC fab. This model has been built using eM-Plant, Tecnomatix (2007). A schematic of this model is shown in Figure 1.

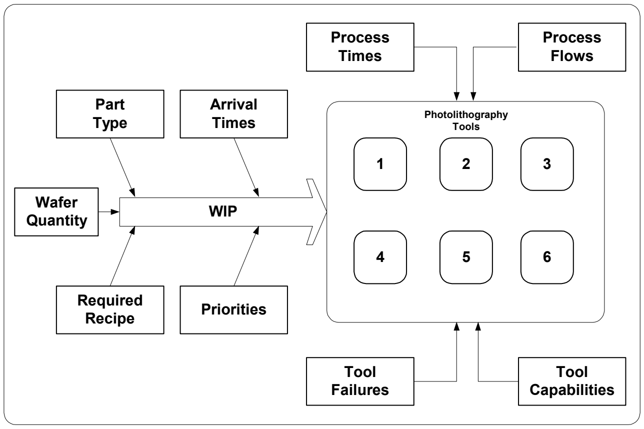

Figure 1: Photolithography model

Each lot entering the photolithography section contains information on its:

- Part type,
- Wafer quantity,
- Required recipe,
- Priority, and
- Arrival time.

All WIP is created using empirical distributions based on historical part input mixes and process flows. This information is then used to order lots in the queue, placing emphasis on priorities followed by arrival time and to send lots to the correct tools. In this particular model there are six tools. Each tool in the model has a unique set of capabilities (to correspond with required recipes), that determines which tool(s) lots can be processed on. An extract of these capabilities is presented in Table 1. The numbers in the table have the following meanings.

- A "0" in the table denotes the fact that this capability ***is not*** on this tool and it is not intended to be turned on. This may be due to certain tool limitations.
- A "1" in the table denotes the fact that this capability ***is on*** this tool.
- A "2" in the table denotes the fact that this capability ***is not*** currently on this tool but it is possible to turn it on in the future.

Table 1: Tool capabilities

	Tool					
Recipe/Capability	**1**	**2**	**3**	**4**	**5**	**6**
xxA00	1	1	2	0	0	2
xxA01	1	1	2	1	0	1
xxA02	1	2	2	1	0	1
xxA03	0	0	2	1	1	0
xxA04	2	1	1	1	2	0
xxA05	2	2	1	0	0	0
xxA06	1	2	1	0	2	1
xxA07	1	2	0	2	0	1
xxA08	0	0	0	2	0	2
xxA09	1	2	0	1	1	0
xxA10	2	1	2	1	0	0
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In the model the process times for each tool is held constant for all recipes processed on it. The process times are measured in wafers per hour (WPH) and are presented in Table 2.

Table 2: Tool process times

	Tool					
	1	**2**	**3**	**4**	**5**	**6**
Wafers Per Hour	45	45	60	45	50	60

The up/downtime of each tool is also based on historically based empirical distributions. This comprises of two empirical distributions, one for the failure interval and another one for the failure duration. The tools have been designed to have an uptime of approximately 80% using distributions similar to those shown in Figure 2 and Figure 3. An example of the fail time Gantt chart for the six tools is given in Figure 4.

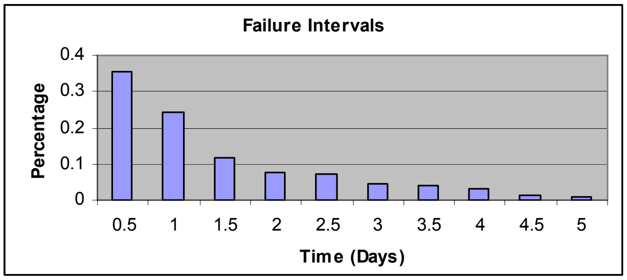

Figure 2: Tool set failures - interval

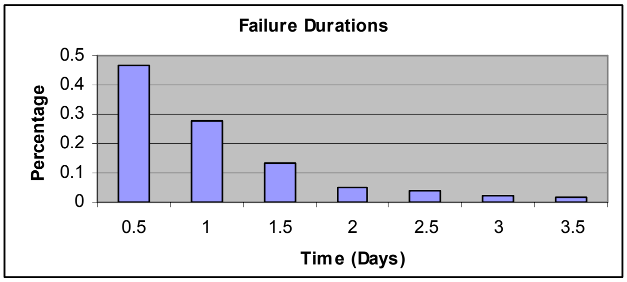

Figure 3: Tool set failures - duration

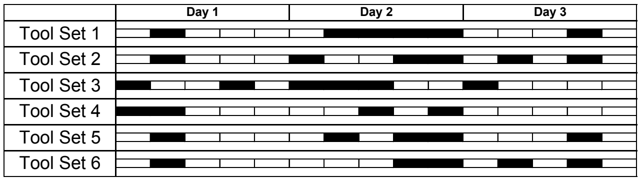

Figure 4: Fail time Gantt

4 EXPERIMENTATION

For the purpose of company anonymity some of the system details have been altered in the following experiments. These include the number of tools in the dedicated section of photolithography and their operational characteristics (WPH and capabilities), the overall number of wafer alignments processed per week and the process/parts mix. After the model was developed and validated, it was used to test a number of different scenarios. One such scenario is described, analyzed and presented in the following sections.

The company involved in this study is anticipating an overall increase in demand for its products (both existing and new) in the future. They currently process approximately 4,000 wafer alignments per week through a dedicated section of its photolithography area. Increased demand will place additional utilization pressure (Figure 5) on the tools in this area and increase the tool wait times (Figure 6). This experiment reviews the impact of this increased demand and analyzes two potential methods to reduce it. The two methods are:

1. Turn on all possible capabilities on all photolithography tools.
2. Purchase a new photolithography stepper.

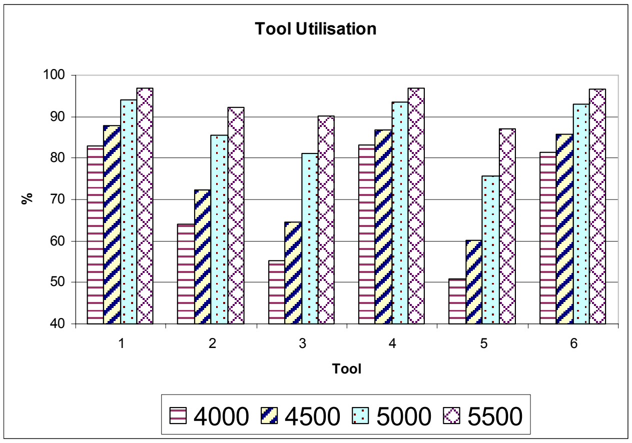

Figure 5: Tool Utilization under increasing demand (wafer alignments per day)

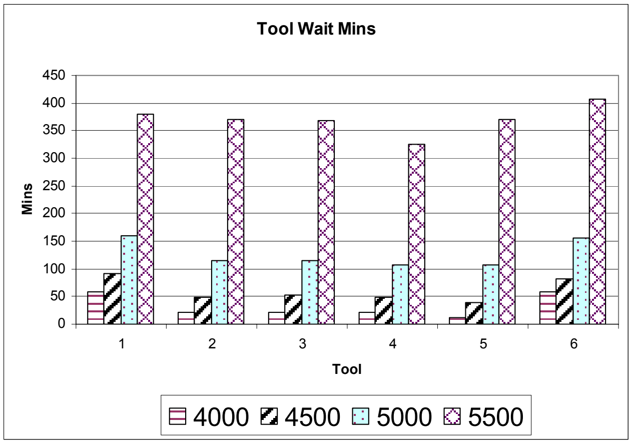

Figure 6: Tool Wait Time under increasing demand (wafer alignments per day)

The objective of this study is to determine the most appropriate course of action for different levels of expected demand. Leading-edge tools in this area are extremely expensive and there is significant cost in turning on all possible capabilities on all photolithography tools. In some cases the addition of a capability may only require a validation program to be completed, in other cases the tools will require physical reconfigurations to enable additional capabilities to be processed on them. With this in mind the preferred courses of action are listed (from most to least preferred) as follows:

1. Continue with original capabilities (Orig Caps).
2. Turn on all possible capabilities in addition to the original capabilities (Orig + Poss Caps).
3. Purchase a new stepper and continue with original capabilities on all existing tools. Two new steppers are being reviewed.
    (a) New stepper with the same capabilities as Tool 4 (Orig + New Step(4)).
    (b) New stepper with the same capabilities as Tool 6 (Orig + New Step(6)).

The capabilities in the model have been described previously in section 3. For this particular experiment the current (original) capabilities in the model are as shown in Table 3. Taking Tool 1, for example. If there are 100 capabilities required, then 61 of these are *currently available* (status = "1"), 18 have the *possibility of being turned* on (status = "2") and 21 *can not be turned on* (status = "0") on Tool 1.

Table 3: Original tool capabilities

	Tool					
	1	**2**	**3**	**4**	**5**	**6**
Orig Caps ("1")	61%	47%	45%	61%	21%	43%
Poss Caps ("2")	18%	35%	34%	10%	22%	14%
Not Poss Caps ("0")	21%	18%	21%	29%	57%	43%
	100%	100%	100%	100%	100%	100%

As stated previously, 4,000 wafer alignments per week are presently processed in the existing system. For this experimentation three increased demand profiles are assessed (4500, 5000 & 5500 wafer alignments per week).

4.1 Results

For each run of the model, the average wait time (in minutes) (Appendix A) and the average utilization (Appendix B) of each tool is recorded. Each model run is simulated over 180 days with the statistical collection period beginning after the first 10 days (this allows the system to reach a steady state). In the case of the two new tools the wafers per hour was set to 45.

For the system evaluated, it is desirable to maintain the average wait times in front of tools at an acceptable level (this will come down to managerial judgment), while balancing the utilization of all tools. In this study the acceptable level of wait time has been set at two hours (120 minutes). The question is therefore, what action is most appropriate at each different demand level (where demand is expected to remain at this level in the medium to long term).

4.1.1 Wafer Alignments = 4,500

If demand is expected to rise to 4,500 wafer alignments per week and it remains at this level, then the original capabilities that are on the tools is sufficient to maintain an acceptable wait time in the system (Figure 8). However, there is a significant imbalance in tool utilization using these original capabilities (Figure 9). This can be addressed somewhat by adding the possible capabilities to the model. Taking these factors into consideration the best possible action is to maintain the original capabilities with the possibility of adding some select further possible capabilities to reduce the imbalance. In this case it is not necessary to consider the purchase of a new tool (tool 7), as this cost would not be warranted.

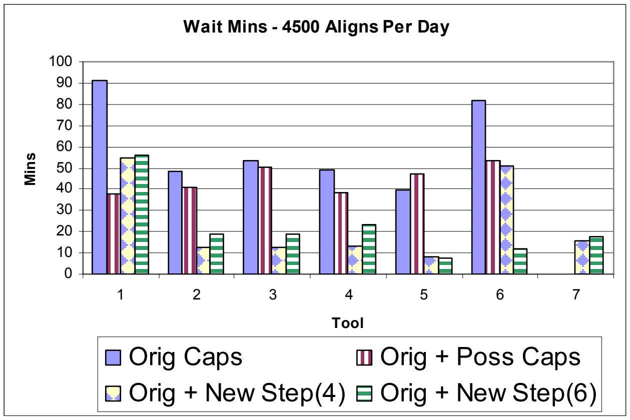

Figure 7: Wait minutes (4,500)

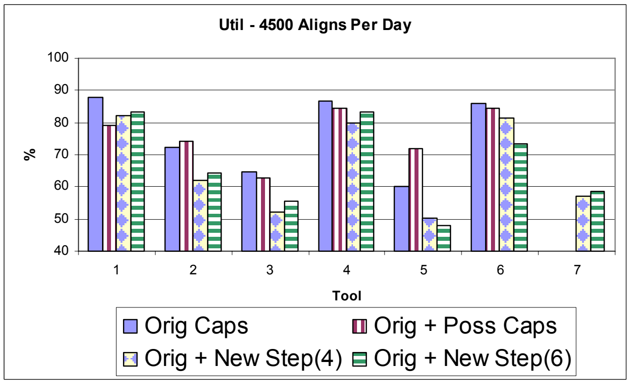

Figure 8: Tool utilization (4,500)

4.1.2 Wafer Alignments = 5,000

If demand is expected to rise to 5,000 wafer alignments per week and remain at this level, then the acceptable level of wait time is breached by two tools (see Figure 9) under the only the original capabilities. In this case, the addition of all possible capabilities reduces all tool wait times to an acceptable level while assisting in balancing tool utilization (Figure 10). Therefore, the appropriate action is to turn on all capabilities where possible. However, a note of caution should be attached to this as the overall tool utilization is increasing with tool six reaching 92% (see Figure 10). In some cases, this would be considered too high and the option of a new tool (tool 7) may have to be considered. The demand in this case would require further scrutiny to ensure it didn't creep above 5,000 wafer alignments per day as this could have significant impact on the systems operation pushing the acceptable wait time levels over the two hour mark (particularly on tool 6 - Figure 9).

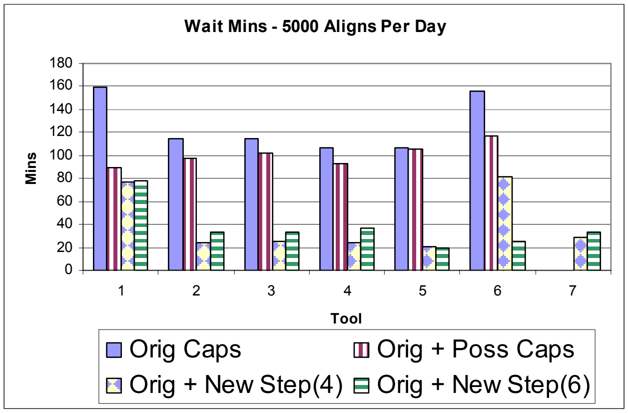

Figure 9: Wait minutes (5,000)

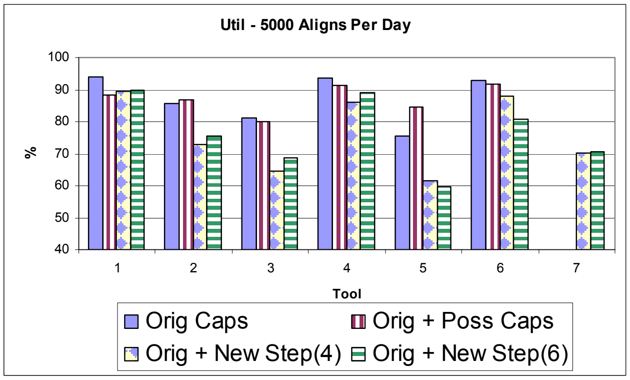

Figure 10: Tool utilization (5,000)

4.1.3 Wafer Alignments = 5,500

If demand is expected to rise to 5,500 wafer alignments per week and it remains at this level, then it is necessary to purchase a new tool (tool 7) based on both excessive average wait time (Figure 11) and tool utilization (Figure 12). In this case two tools have been reviewed. Each tool can process 45 wafers per hour. The new tools capabilities have been modeled on two of the most highly utilized existing tools. These two tools are tools 4 & 6. As illustrated in Figure 12 there is little to choose between these two new tools with respect to utilization balancing. However, the addition of a new tool 4 still breaches the two hour acceptable wait time standard, whereas a new tool 6 does not. In addition to balancing tool utilization, a new tool 6 also better balances the tool wait minutes across all tools. Taking these factors into consideration the best possible action in this case is to purchase a new tool based on the capabilities of the current tool 6.

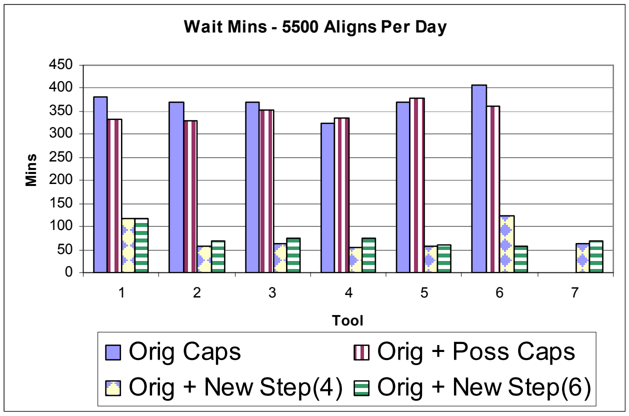

Figure 11: Wait minutes (5,500)

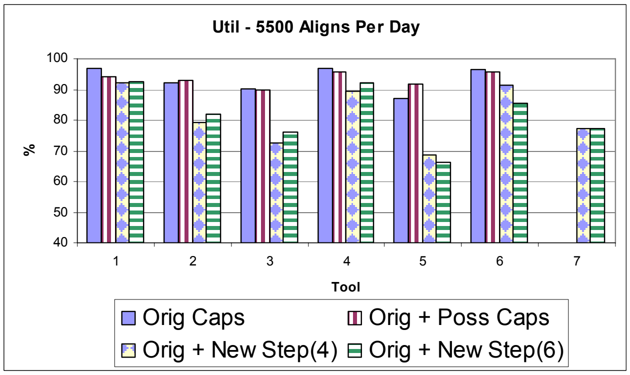

Figure 12: Tool utilization (5,500)

5 CONCLUSIONS

Photolithography is one of the most complex and constraining sectors in semiconductor wafer fabrication, and has a significant impact on fab cycle-times. Cycle time management in this area is crucial to balance the trade-off between tool utilization and cycle time. Too many tools leads to under utilization of these tools and unnecessarily short cycle times, with too few tools leading to over utilization of the tools and excessively long cycle times

This paper reviews and models the photolithography section of a fab with high product variety and low production volumes. The fab is expecting increased demand for its products over the medium to long term. This paper examines potential demand trends and analyzes appropriate courses of action using discrete event simulation for decision support. In all cases the goal is to maintain average wait times, in front of all tools, to under two hours while balancing tool utilization, and minimizing capital spend.

A summary of the proposed actions are illustrated in Table 4. Depending on the expected level of increased demand, different courses of action are appropriate. For example, if further demand studies are carried out and it is expected that demand will rise to 4,700 – 4,800 wafer alignments per day in the medium to long term then commissioning of all possible capabilities in this case is sufficient.

Table 4: Summarized actions

Demand	Proposed Action
4,500	Current Situation + Selected New Capabilities
5,000	All Possible Capabilities to be Turned on (Note: Utilization is High and New Tool may be Required)
5,500	Purchase New Tool (6)

A APPENDIX: TOOL WAIT MINS

Table 5: Tool wait minutes (4,500)

	Tool						
	1	2	3	4	5	6	7
Orig Caps	91	48	53	49	40	82	-
Orig + Plan Caps	38	41	50	38	47	54	-
Orig + New Step(4)	55	13	13	13	8	51	15
Orig + New Step(6)	56	19	19	23	7	12	18

Table 6: Tool wait minutes (5,000)

	Tool						
	1	2	3	4	5	6	7
Orig Caps	159	115	114	107	107	156	-
Orig + Plan Caps	89	98	102	93	105	117	-
Orig + New Step(4)	77	24	25	24	20	82	28
Orig + New Step(6)	78	33	33	37	20	26	33

Table 7: Tool wait minutes (5,500)

	Tool						
	1	2	3	4	5	6	7
Orig Caps	380	370	369	325	371	408	-
Orig + Plan Caps	332	328	352	336	377	361	-
Orig + New Step(4)	117	58	62	54	56	123	64
Orig + New Step(6)	117	70	75	73	59	57	70

B APPENDIX: TOOL UTILIZATION (%)

Table 8: Tool percentage utilization (4,500)

	Tool						
	1	2	3	4	5	6	7
Orig Caps	88	72	65	87	60	86	-
Orig + Plan Caps	79	74	63	84	72	85	-
Orig + New Step(4)	82	62	52	80	50	81	57
Orig + New Step(6)	83	64	56	83	48	73	59

Table 9: Tool percentage utilization (5,000)

	Tool						
	1	2	3	4	5	6	7
Orig Caps	94	86	81	94	76	93	-
Orig + Plan Caps	88	87	80	91	84	92	-
Orig + New Step(4)	89	73	65	86	61	88	70
Orig + New Step(6)	90	75	69	89	60	81	70

Table 10: Tool percentage utilization (5,500)

	Tool						
	1	2	3	4	5	6	7
Orig Caps	97	92	90	97	87	97	-
Orig + Plan Caps	94	93	90	96	92	96	-
Orig + New Step(4)	92	79	73	89	69	91	77
Orig + New Step(6)	93	82	76	92	66	85	77

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