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AN OPTIMIZATION MODEL FOR QUALIFICATION MANAGEMENT IN WAFER FABS

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ABSTRACT

The individual tools of a tool group need to be qualified to run lots of certain families in wafer fabs. A qualification time window is associated with each family and each tool. This window lasts typically from a couple of days to few weeks. The time window can be re-initialized with separate qualification effort on a need by basis and can be extended by on-time processing of qualifying families. In this paper, we propose a mixed integer programming formulation for this problem assuming a given demand for a planning horizon of several periods. The objective function takes into account qualification costs, backlog costs, and inventory holding costs among others. Results of computational experiments based on randomly generated problem instances are presented that demonstrate that a tradeoff between production objectives and qualification costs can be reached by an appropriate configuration of the model.

1 INTRODUCTION

Semiconductor manufacturing deals with producing integrated circuits, so called chips, on thin wafers made from silicon. The corresponding processes are considered as the most complex existing manufacturing processes. Chips are produced in semiconductor wafer fabrication facilities (wafer fabs). Lots are the moving entities in wafer fabs. Each lot consists of a certain number of wafers. A large number of expensive machines, also known as tools that are organized in groups of parallel tools and a mix of different process types, among them single wafer and batch processes, are typical for wafer fabs. Here, a batch is a set of lots that are processed at the same time on a single tool. Moreover, wafer fabs are highly reentrant systems, i.e., a single tool group is visited by the same lot up to 40 times. Frequent tool breakdowns occur in wafer fabs (cf. Mönch *et al.* 2013 for a detailed discussion of the process conditions in wafer fabs).

Qualification issues are crucial in wafer fabs since the tools have to be qualified before running lots of a specific family. A high utilization of the expensive tools can be ensured by appropriate tool-operation qualifications. At the same time, qualifications are expensive (cf. Johnzén *et al.* 2011). Despite its importance, qualification problems are rarely discussed in the literature. In the present paper, we study a qualification management problem that arises in wafer fabs. A qualification time window is associated with each family and each tool. This window lasts typically from a couple of days to a few weeks. The time window can be re-initialized with separate qualification effort on a need by basis and can be extended by on-time processing of qualifying families. The qualification management problem can be considered as a planning version of more detailed scheduling models for the stepper tool group in wafer fabs (cf. Mönch and Yugma 2015).

The paper is organized as follows. The problem is described in the next section. In addition, related work is discussed. A mixed integer programming (MIP) formulation for the problem is proposed in Section 3. The results of computational experiments based on randomly generated problem instances are presented in Section 4. Finally, conclusions and future research directions are provided in Section 5.

2 PROBLEM SETTING

2.1 Problem

In this paper, we consider the stepper tool group. Steppers transfer the circuit pattern from a mask to the wafers using exposure based on ultraviolet light. Because steppers belong to the most expensive equipment found in wafer fabs, this tool group often forms a planned bottleneck (cf. Mönch *et al.* 2001).

All lots from the same product and mask layer form a family. A finite planning horizon of length T that is divided into discrete equidistant periods is assumed. Targets for each family, i.e. the number of wafers to be manufactured, are known for each period. Backlog and inventory is possible in each period that carries over to the next period. The processing times of the lots on the steppers depend on the family and the tool. Deterministic processing times are assumed. In addition, the capacity of each tool in a certain period is deterministic and known. Although masks, i.e. reticles, are an important secondary constraint for the stepper tool group they will not be modeled in this paper since we consider periods of appropriate size. Therefore, because we do not make detailed scheduling decisions we can assume that enough reticles exist within all periods. This assumption is also supported by the computational experiments in Section 4. Note that this assumption is not reasonable in detailed scheduling models (cf. Mönch 2004, Mönch and Yugma 2015).

The following restrictions have to be ensured for the qualification management problem:

1. The finite capacity of the tools has to be respected.
2. Tool dedications occur, i.e., tools might be inappropriate for processing wafers from certain families.
3. Tools have to be qualified for a certain family to process wafers from this family on this tool.
4. A qualification time window Δ_{fk} is associated with each family f and each tool k. The length of this time window is an integer multiple of the period length. If no wafers from a family are processed on a qualified tool within the time window, the qualification will be lost.
5. The qualification time window for a certain family can be extended by on-time processing of wafers that belong to this family. If a wafer of a family f is processed on a tool k in period t inside the time window the tool is qualified until period $t + \Delta_{fk}$.
6. A tool can be re-qualified for a certain family by carry out qualification activities.

Since qualification and re-qualification activities are expensive, we are interested in performing a small number of such activities. At the same time, the backlog quantities should be as small as possible since we strive to fulfill the given targets for each family and period. We try to avoid large inventory values because they lead to expensive capital commitments. We are interested in a balanced workload of all the tools. On the one hand, this might require additional qualification of less utilized tools. On the other hand, an increased execution flexibility is the result of a balanced workload.

We see that the objectives of minimizing qualification costs and backlog and inventory holding costs are in conflict. Therefore, we look for an appropriate tradeoff that might be obtained by choosing appropriate cost values.

2.2 Discussion of Related Work

Scheduling problems for the stepper tool group in wafer fabs that take qualification issues into account are discussed by Mönch (2004) and Mönch and Yugma (2015). Send-ahead wafers are used to re-qualify steppers. Qualification time windows are considered. In the present paper, however, we are not interested in detailed scheduling decisions for the next shift. Instead of this, we strive for qualification decisions that take into account target WIP quantities for the next days or weeks. The importance of integrated scheduling and advanced process control decisions is mentioned by Yugma *et al.* (2015). Klemmt *et al.* (2010) and Klemmt (2012) propose a hierarchical decomposition scheme to make scheduling decisions for the stepper tool group in a wafer fab. The upper levels of the hierarchy restrict the possible decision alternatives on the subsequent levels. The resulting optimization models can be solved in a sequential manner. Tool qualification-related decisions are included. However, qualification time windows are not considered.

Flexibility measures are introduced by Johnzén *et al.* (2011) to quantify the advantage of different qualification strategies. Additional flexibility measures that take the capacity of a tool group into account are proposed by Rowshannahad *et al*. (2015). However, periods are not considered and qualification time windows are not modeled in these papers. A load-balancing problem for parallel machines with qualification costs is discussed by Aubry *et al.* (2008). In contrast to the present paper, periods and capacity restrictions are not considered, and there are no time windows. It is shown that the load-balancing problem is NP-hard because the 3-partition problem can be reduced to it. A capacity allocation problem for the stepper tool group is discussed by Toktay and Uzsoy (1998) and by Akçali *et al.* (2005). Machine dedications, the presence of auxiliary resources, and setup times are considered. However, qualification-related constraints are not directly taken into account.

A binary program is proposed by Ignizio (2009) for an operation-to-tool qualification problem in the lithography area of a wafer fab. It is shown by simulation experiments that the qualification decisions obtained by the optimization model outperform decisions made by simple heuristics with respect to the overall cycle time in a wafer fab. A somewhat similar problem to our problem is discussed by Fu *et al.* (2010). A MIP is proposed that determines a tradeoff between backlog costs and qualification-related costs for a back-end facility. However, qualification time windows are not considered in contrast to the present paper. The deterministic MIP from Fu *et al.* (2010) is extended towards a two-stage stochastic tool qualification model where stochastic demand is assumed. The resulting model is solved by the L-shaped method and acceleration techniques.

3 MIP FORMULATION

The following sets and indices are used in the MIP model:

$f = 1,\dots,F$ family index

$k = 1,\dots,M$ tool index

$t = 1,\dots,T$ period index.

The following parameters will be used within the model:

D_{ft}: target for family f wafers in period t (in wafers)

C_{kt}: capacity of tool k in period t (in minutes)

p_{fk}: processing time of a single wafer from family f on tool k (in minutes)

Δ_{fk}: length of the qualification time window for family f on tool k (in periods)

q_{fk}: cost per qualification for family f on tool k

b_f: backlog cost for family f (per wafer)

h_f: inventory holding cost for family f (per wafer)

d: cost for the deviation of the load on a tool from the average load on the tools in a given period (per minute)

$$e_{fk} = \begin{cases} 1, & \text{if tool } k \text{ is able to process wafers of family } f \\ 0, & \text{otherwise.} \end{cases}$$

The following decision variables are used within the MIP:

x_{fkt}: number of processed wafers of family f on tool k in period t

Q_{fkt}: indicator for a performed qualification of family f on tool k in period t

B_{ft}: backlog quantity of family f in period t

I_{ft}: inventory quantity of family f in period t

$$y_{fkt} = \begin{cases} 1, & \text{if tool } k \text{ is qualified for family } f \text{ in period } t \\ 0, & \text{otherwise} \end{cases}$$

$$z_{fkt} = \begin{cases} 1, & \text{if wafers of family } f \text{ are processed on tool } k \text{ in period } t \\ 0, & \text{otherwise} \end{cases}$$

δ_{kt}: deviation of the load on tool k from the average load on the tools in period t (in minutes)

$\tilde{\Delta}_{fkt}$: remaining number of periods in period t until tool k will lose the qualification for processing wafers of family f .

Now the qualification management problem can be formulated as follows:

$$\min \sum_{t=1}^{T} \left(\sum_{f=1}^{F} \left(\sum_{k=1}^{M} q_{fk} Q_{fkt} + b_f B_{ft} + h_f I_{ft} \right) + d \sum_{k=1}^{M} \delta_{kt} \right) \tag{1}$$

subject to

$$\sum_{k=1}^{M} x_{fkt} + I_{f,t-1} + B_{ft} = I_{ft} + D_{ft} + B_{f,t-1} \qquad f = 1,\ldots,F,\ t = 1,\ldots,T \tag{2}$$

$$\sum_{f=1}^{F} p_{fk} x_{fkt} \le C_{kt} \qquad k = 1,\ldots,M,\ t = 1,\ldots,T \tag{3}$$

$$\left| \frac{1}{M} \sum_{f=1}^{F} \sum_{l=1}^{M} p_{fl} x_{flt} - \sum_{f=1}^{F} p_{fk} x_{fkt} \right| = \delta_{kt} \qquad k = 1,\ldots,M,\ t = 1,\ldots,T \tag{4}$$

$$y_{fkt} - y_{f,k,t-1} \le Q_{fkt} \qquad f = 1,\ldots,F,\ k = 1,\ldots,M,\ t = 1,\ldots,T \tag{5}$$

$$Q_{fkt} \le y_{fkt} \qquad f = 1,\ldots,F,\ k = 1,\ldots,M,\ t = 1,\ldots,T \tag{6}$$

$$y_{fkt} \le e_{fk} \qquad f = 1,\ldots,F,\ k = 1,\ldots,M,\ t = 1,\ldots,T \tag{7}$$

$$p_{fk} x_{fkt} \le C_{kt} z_{fkt} \qquad f = 1,\ldots,F,\ k = 1,\ldots,M,\ t = 1,\ldots,T \tag{8}$$

$$z_{fkt} \le x_{fkt} \qquad f = 1,\ldots,F,\ k = 1,\ldots,M,\ t = 1,\ldots,T \tag{9}$$

$$p_{fk} x_{fkt} \le C_{kt} y_{fkt} \qquad f = 1,\ldots,F,\ k = 1,\ldots,M,\ t = 1,\ldots,T \tag{10}$$

$$y_{fkt} \le \tilde{\Delta}_{fkt} \qquad f = 1,\ldots,F,\ k = 1,\ldots,M,\ t = 1,\ldots,T \qquad (11)$$

$$\tilde{\Delta}_{fkt} \le \Delta_{fk} y_{fkt} \qquad f = 1,\ldots,F,\ k = 1,\ldots,M,\ t = 1,\ldots,T \qquad (12)$$

$$\max\left(\Delta_{fk} Q_{fkt}, \Delta_{fk} z_{fkt}, \tilde{\Delta}_{f,k,t-1} - 1\right) = \tilde{\Delta}_{fkt} \qquad f = 1,\ldots,F,\ k = 1,\ldots,M,\ t = 1,\ldots,T \qquad (13)$$

$$x_{fkt}, Q_{fkt}, B_{ft}, I_{ft}, \delta_{kt}, \tilde{\Delta}_{fkt} \ge 0,\ y_{fkt}, z_{fkt} \in \{0,1\} \qquad f = 1,\ldots,F,\ k = 1,\ldots,M,\ t = 1,\ldots,T. \qquad (14)$$

The objective function (1) to be minimized is the sum of the qualification costs, backlog costs, inventory holding costs, and a term that penalizes the absolute deviation of the load on tool k from the average load on the tools in period t. Constraints (2) serve as inventory balance equations. A capacity restriction for each tool is formulated by constraints (3). The absolute deviation of the load on tool k from the average load on the tools in each period t is expressed by constraints (4). Constraints (5) and (6) ensure that the performed qualifications are correctly taken into account by the objective function while constraints (7) enforce dedications, i.e., a tool can only be qualified for a given family if it is allowed to run the family on the tool. Constraints (8) and (9) are used to set the values of the binary indicator variable z_{fkt} in a correct way. The correct value of the remaining length of the qualification time window is modeled by constraints (11)-(13) where constraints (13) ensure that either the qualification time window is set to the maximum value Δ_{fk} in the case of a re-qualification or the value of the previous period $\tilde{\Delta}_{f,k,t-1}$ is decremented by one. Constraints (14) are used to model that the real-valued decision variables are nonnegative and that the decision variables y_{fkt}, z_{fkt} are binary. The qualification management problem considered in this paper is NP-hard since we are able to obtain the load-balancing problem studied in (Aubry *et al.* 2008) by choosing large costs, large-sized qualification time windows, and by considering a single period with a large capacity.

4 COMPUTATIONAL EXPERIMENTS

4.1 Simulation Environment and Generation of Target Quantities

Targets for the different families are generated based on the MIMAC I model (cf. MIMAC I 2016). It contains two products with 210 and 245 process steps, respectively. The tools are organized into 84 tool groups. The stepper tool group, the planned bottleneck of the model, consists of six steppers. The two products have ten and seven mask layers, respectively. Therefore, we consider 17 different families in our computational experiments. Each lot contains 48 wafers. Exponential distributed tool breakdowns are included in the simulation model.

The target quantities are generated for each family as follows. We run simulations where we release lots in such a way that a planned bottleneck utilization is reached. The simulation stops periodically, i.e. monthly, and based on the work in process (WIP) lots at time t and lots to be released in future periods a forward termination is performed based on a flow factor (FF) that is randomly chosen for each lot. This means that we calculate the due date d_{ji} for each remaining process step i of lot j recursively according to

$$d_{ji} := d_{j,i-1,} + z_j p_{ji} \qquad (15)$$

where we have $d_{j0} = \max(t, r_j)$. Here, r_j is the release date of lot j and p_{ji} is the processing time of process step i of lot j. We choose the FF quantity z_j as a realization of a random variable $Z_j \sim U[1.6,1.9]$ and $Z_j \sim U[1.9,2.2]$ in the case of 70% and 90% planned bottleneck utilization, respectively. Here, $U[a,b]$ denotes a uniform distribution over the interval $[a,b]$. Moreover, 5% of all released lots are hot lots that are characterized by a FF value close to one, i.e., we use $z_j \equiv 1.3$ in this situation. If based on equation (15) the processing of a lot on a stepper has to be completed in a certain period, the target of the corresponding family and period is increased by 48 wafers. The processing times for the families are taken from the routes of the two products. The capacity of the steppers is corrected by the expected tool down times. The processing of WIP lots on steppers and the unavailability of tools due to breakdowns at the beginning of the first period is taken into account when the capacity for the initial period is set. We assume that the tools are unqualified for all families at the beginning of the first period.

4.2 Design of Experiments and Implementation Issues

We expect that the computational results depend on the number of periods, i.e. the length of the planning horizon, the planned bottleneck utilization, and the cost settings. A period length of four hours is considered within the experiments. Each family can be processed on three randomly selected tools in this series of experiments. The used design is summarized in Table 1 where $DU[a,b]$ is a discrete uniform distribution over the integer values $\{a,\dots,b\}$.

Table 1: Design of experiments.

Factor	Level	Count
Number of families	17	1
Length of the time window per family and tool (in periods)	$\Delta_{fk} \sim DU[6,18]$	1
Number of tools	6	1
Bottleneck utilization	70%, 90%	2
Number of periods	12, 24, 36	3
Cost scenarios	Moderate qualification costs (QM), High qualification costs (QH), Low qualification costs (QL)	3
Number of independent instances per factor combination	6	
	Total number of problem instances	108

The specific cost settings of the different scenarios are summarized in Table 2. We abbreviate the moderate qualification cost setting by QM and the high qualification cost setting by QH, whereas the low qualification cost setting is called QL in the rest of the paper.

Table 2: Cost settings.

Cost Scenario	q_{fk}	b_f	h_f	d
QM	100	2.5	1.0	0.6
QH	400	2.5	1.0	0.6
QL	25	2.5	1.0	0.6

We also consider 36 instances for twelve periods that are generated based on the design of experiments from Table 1. Each family can be processed on all steppers in these instances, i.e., no dedications occur.

We are interested in assessing the solution quality that is mainly characterized by the obtained MIP gap after a given amount of computing time. Therefore, we apply a maximum computing time of 30 minutes per instance except for instances with high qualification costs and 24 or 36 periods where a maximum computing time of 90 minutes per instance is allowed. Moreover, we are interested in a cost breakdown for the obtained solutions. Therefore, we will report the ratio of the performed number of qualifications and the maximum possible number of qualifications. The latter number is 51, since we have 17 families that can be processed at three different tools. The ratio is denoted by Q%. We will also present the sum of the backlog quantities over the periods of the planning horizon relative to the sum of the target quantities where the backlog from the previous period is taken into account as additional demand. The ratio is called BL%. A similar approach is used for inventory holding costs, i.e., the ratio of the sum of inventory holding costs over the different periods and the sum of the target quantities corrected by the inventory from the previous period is used. This performance measure is abbreviated by INV%. Finally, we are interested in the sum of the deviations of the load on a single tool from the average load on the tools over all periods of the planning horizon. We report the ratio of this quantity and the length of the planning horizon. This quantity is called LB%. The MIP model (1)-(14) is implemented using CPLEX 12.1.0. AutoSched AP 9.3.0 is the applied simulation engine. A blackboard-type data layer similar to the one described by Mönch (2007) is coded in the C++ programming language to allow for applying the notification functionality of AutoSched AP for the generation of target quantities. All the computational experiments are carried out on a PC with a quad core Intel Core i7 3.40 GHz processor and 16GB RAM.

4.3 Computational Results

The computational results for the 54 problem instances with a planned bottleneck utilization of 70% are shown in Table 3. Instead of comparing all problem instances individually, the problem instances are grouped according to the cost settings and the length of the planning horizon. For example, the results for QM and $T = 12$ in the first row imply that all other factors have been varied, but the length of the planning horizon is 12 periods and the moderate cost setting is used. The MIP gap value after 10, 20, and 30 minutes is shown. We report the number of solutions with a MIP gap smaller than 35% in the column #Solutions.

Table 3: Computational results for 70% planned bottleneck utilization.

Cost	T	Q%	BL%	INV%	LB%	Gap (in %)			# Solutions
						10 min	20 min	30 min	
QM	12	52	5	10	15	14	12	11	6
QM	24	66	3	8	10	71	33	21	6
QM	36	73	3	8	4	91	83	70	2
QH	12	35	8	16	57	23	19	18	6
QH	24	44	5	16	52	98	98	76	4
QH	36	55	2	12	25	98	98	98	5
QL	12	64	5	8	6	6	5	4	6
QL	24	78	2	6	3	16	9	8	6
QL	36	84	2	5	2	58	34	9	6

The corresponding results for a planned bottleneck utilization of 90% can be found in Table 4. Note that again 54 problem instances are considered. Results for the 36 problem instances without dedications are presented in Table 5. Note that the planning horizon is $T = 12$ for these instances.

Cost breakdowns for the three different cost settings and the different planning horizon lengths are depicted in Figure 1. Here, we aggregate over the two dedication settings and the two planned bottleneck utilizations.

Table 4: Computational results for 90% planned bottleneck utilization.

Cost	T	Q%	BL%	INV%	LB%	Gap (in %)			# Solutions
						10 min	20 min	30 min	
QM	12	51	8	10	8	9	7	6	6
QM	24	64	5	8	7	43	20	13	6
QM	36	70	7	13	6	72	58	41	2
QH	12	37	10	17	36	18	16	15	6
QH	24	46	7	16	43	69	56	47	5
QH	36	58	4	11	10	91	91	84	6
QL	12	60	8	8	4	4	3	2	6
QL	24	73	5	7	3	10	6	5	6
QL	36	82	3	7	2	29	15	7	6

Table 5: Computational results for the problem instances without dedications.

Cost	Q%	BL%	INV%	LB%	Gap (in %)			# Solutions
					10 min	20 min	30 min	
Bottleneck utilization 70%								
QM	56	4	10	9	70	42	31	5
QH	39	7	21	19	70	55	49	3
QL	67	5	7	4	36	17	16	6
Bottleneck utilization 90%								
QM	56	7	10	7	52	35	21	5
QH	39	9	17	21	54	47	39	2
QL	64	8	6	4	39	12	9	6

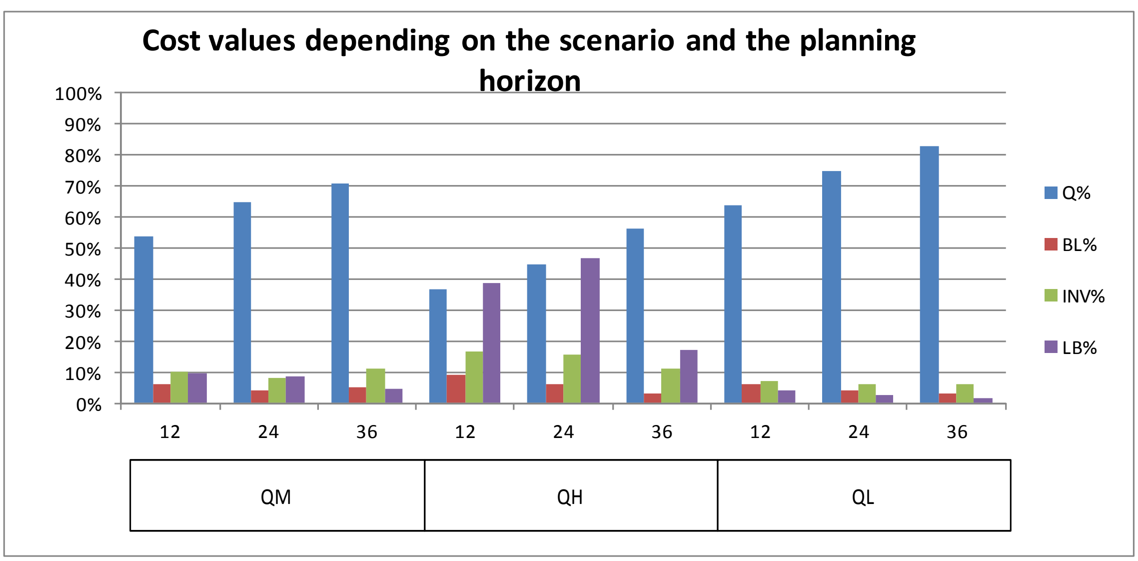

Figure 1: Cost breakdowns depending on the cost setting and the length of the planning horizon.

4.4 Analysis and Interpretation of the Results

Overall, we can see from the computational results that the computing times are fairly large due to the NP-hardness of the qualification management problem. Only a single instance is solved to optimality within the given amount of computing time. We are not able to determine feasible solutions for five problem instances out of the 144 instances.

We can see from Table 3 and 4 that an increasing length of the planning horizon leads to harder problem instances. This is an expected behavior since a larger planning horizon leads to more degrees of freedom for the optimization. Table 5 demonstrates that the instances without tool dedications are harder to solve since the room for optimization is larger because of the missing dedications. We also see from the Tables 3, 4 and 5 on the one hand that high qualification costs lead to larger computational burden compared to the moderate setting. On the other hand, low qualification costs lead to more tractable instances. This is again reasonable since binary decision variables are used to model the qualification-related decisions that are very important for high qualification costs.

The number of qualifications and the backlog and inventory holding costs associated with a certain solution strongly depend on the chosen cost setting. We see from the different tables and from Figure 1 that high qualification costs lead to a fairly small number of qualifications. However, the backlog and inventory holding costs are much larger compared to the moderate cost setting. The quality of the solutions is low with respect to the load balancing measure. A longer planning horizon results in more qualifications. Note that only a single qualification will be performed for $T = 12$ for most of the families if the QH setting is used.

The planned bottleneck utilization mainly impacts the backlog and the inventory holding costs. When the planned bottleneck utilization is 90% it is harder to meet the target quantities in the different periods due to the finite capacity of the tools. Therefore, larger backlog and inventory holding costs are observed in this situation.

5 CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

In this paper, we discussed a qualification management problem that arises in wafer fabs. An appropriate MIP formulation is proposed. Computational experiments were carried out on problem instances that are derived from the MIMAC I simulation model. We demonstrated that an appropriate configuration of the MIP model leads to the desired tradeoff between production and qualification costs.

There are several directions for future research. First of all, we are interested in proposing appropriate heuristics to tackle large-size instances of the MIP formulation (1)-(14) within a reasonable amount of computing time. As a second avenue for future research, we will incorporate the MIP formulation and the heuristics in a rolling horizon setting. This requires that the corresponding simulation-based performance assessment framework proposed by Mönch (2007) and by Ponsignon and Mönch (2014) has to be extended to deal with qualification management issues. At the same time, the simulation model has to be refined to allow for executing the qualification plans. We also believe that it is worthwhile to extend the proposed qualification model from a single to a multi-stage situation.

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