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Predicting the Mean Cycle Time as a function of Throughput and Product Mix for Cluster Tool Workstations using EPT-based Aggregate Modeling

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***Abstract*—Predicting the mean cycle time as a function of throughput and product mix is helpful in making the production planning for cluster tools. To predict the mean cycle time, detailed simulation models may be used. However, detailed models require much development time, and it may not be possible to estimate all model parameters. Instead of a detailed simulation model, we propose to use a so-called aggregate model to predict the mean cycle time as a function of throughput and product mix. The aggregate model is a lumped-parameter representation of the queueing system. We estimate the parameters of the aggregate model from arrival and departure data using the Effective Process Time (EPT) concept. The proposed method is illustrated for a simulation test case and a Crolles2 cluster tool workstation. The method accurately predicts the mean cycle time in a region around the workstations' operational product mix.**

***Index Terms*—cycle time, simulation, CT-TH-PM surfaces, manufacturing performance, factory dynamics**

I. INTRODUCTION

For capacity planning in semiconductor manufacturing, it is useful to predict the mean cycle time of lots as a function of workstation throughput, and product mix. Cycle time is the sum of queue time and process time of a lot at a particular workstation. With throughput we mean the number of lots processed per time unit. The product mix is the pie chart (in percentages) of the various product types, each of which has a different process recipe. Machines may be qualified to process only a subset of product recipes. A so-called Cycle Time-Throughput-Product Mix (CT-TH-PM) surface can be used to predict the mean cycle time as a function of the throughput and the product mix.

CT-TH-PM surfaces may be calculated from detailed models representing the factory floor. The detailed simulation model then should include all relevant details of the considered workstation to arrive at an accurate CT-TH-PM surface. For example [Yan07] used progressive model fitting to derive CT-TH-PM surfaces from a detailed simulation model. However, the development of such a detailed simulation model may involve considerable effort. It may also be difficult to obtain all model parameters.

In this paper we propose to use an aggregate model to calculate the CT-TH-PM surface. The aggregate model is a lumped-parameter representation of the workstation only covering the elementary queueing aspects. Our starting point is a G/G/m queueing approximation (see e.g. [Sak77],[Whi93],[Hop08]). The G/G/m approximation models each machine in the workstation as a single server with mean process time t_e and coefficient of variability of the process time c_e.

Hopp and Spearman [Hop08] referred to G/G/m parameters t_e and c_e as the mean Effective Process Time (EPT), and the coefficient of variability of the EPT, respectively. Hopp and Spearman calculate t_e and c_e from distribution parameters of the raw process time, preemptive and non-preemptive outages. Jacobs et al. [Jac03] follow a different approach. They do not quantify the factors that may contribute to the effective process time. Instead, they calculate EPT realizations directly from arrivals and departures of lots at the workstation. Jacobs et al. use the mean and the coefficient of variability of the measured EPT distribution in a G/G/m queueing approximation of the workstation to predict the mean cycle time as a function of the throughput.

The G/G/m queueing approximation assumes that machines process one lot at a time. However, in semiconductor manufacturing many machines are integrated processing machines (e.g. cluster tools), which may process multiple lots at the same time in the various machine chambers. To model integrated processing machines, Kock [Koc08] developed a G/G/m type of aggregate model with workload-dependent process times, which are determined using the EPT concept. Veeger et al. [Vee08b] showed that the method of Kock accurately estimates the mean cycle time as a function of the throughput for workstations in a semiconductor environment. In [Vee08a] we extended our EPT-based aggregate modeling method such that it can predict the mean cycle time as a function of the throughput, ánd the product mix.

Continuing on our previous work [Vee08a], we present new results in this paper of our efforts to extend our aggregate modeling method. In particular we consider here the application to workstations consisting of one or more cluster tools in a semiconductor environment. Our aggregate model of the workstation consists of an infinite buffer, and several parallel servers. Each server represents one integrated

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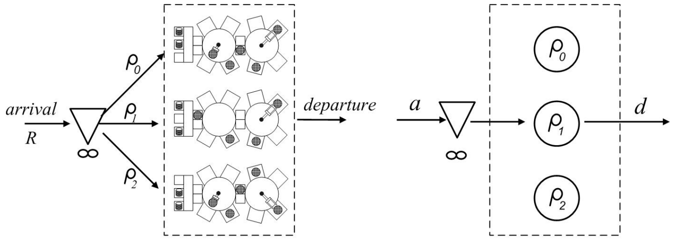

(a) (b)

Fig. 1. Workstation with three parallel cluster tools, with each tool qualified for a subset of process recipes (a), and the proposed aggregate model (b)

processing machine, and has the same recipe qualification as its real counterpart. The process time of a lot at an aggregate server is sampled from an EPT distribution. The EPT distribution parameters depend on the momentary workload, and the process recipe of the lot. We measure EPT distributions from lot arrivals and departures. The measured EPTs include time losses due to raw process time, machine downs, setups, and operator behaviour, which are not modeled explicitly in the aggregate model. Time losses due to machine qualification are not included in the EPT, for in the aggregate model product mix, and recipe qualification are modeled explicitly.

To show that accurate CT-TH-PM surfaces can be generated for cluster tool type of workstations, we present a simulation test case and a case based on data from an operational cluster tool workstation at the Crolles2 wafer fab. The simulation test case provides insight in the throughput and product mix range in which our method provides accurate mean cycle time estimations. The Crolles2 test case demonstrates how the method can be used in practice.

The outline of the paper is as follows: the EPT-based aggregate modeling method of [Vee08a] is summarized in Section 2. We test our method on a cluster tool simulation test case in Section 3. Subsequently, we test the method on a Crolles2 cluster tool workstation in Section 4. Finally, we present our conclusions in Section 5.

II. EPT-BASED AGGREGATE MODELING METHOD

We consider an infinitely buffered workstation, which has one or multiple parallel machines. Each machine may have multiple process chambers, which means that multiple lots can be in process simultaneously. Let R be the set of process recipes r that can be processed by the machines in the workstation. Each machine m in the workstation is qualified for a subset $\rho_m \subseteq R$. We assume that after service, the processed lot can always leave the system (no blocking after service). As example of such a system, a workstation with three parallel cluster tools is shown in Figure 1(a).

A. The aggregate model

The aggregate model is shown in Figure 1(b). It consists of M parallel servers with M equal to the number of machines in the real workstation. Lots arrive according to some arrival process in an infinite buffer that feeds the parallel servers. Each aggregate server in the model corresponds to a machine and is qualified for the same subset of process recipes as its real counterpart. The difference with reality though is that the aggregate server processes one lot at a time. Furthermore, in the model we assume that service starts if a machine is, or becomes, idle and lots are present in the system for which the machine is qualified (non-idling assumption). The process time of a lot is sampled from a distribution at the moment it starts processing in the aggregate model. Two dispatching rules apply. When a lot arrives and multiple machines are idle and qualified, the lot is sent to the machine that is qualified for the least amount of recipes. If a machine becomes idle, and there are multiple queued lots for which the machine is qualified, the lot that arrived first is sent to the machine (FIFO assumption).

The process time distribution depends on three variables: workload, recipe, and start of service. The workload upon process start of lot i is the number of lots in the aggregate system for which the aggregate server serving lot i is qualified (including lot i itself). This workload is denoted by sw_i. The second variable is the process recipe of lot i, which is denoted by r_i. The third variable is the event type sev_i (arrival or departure), upon which lot i starts being served in the aggregate model: sev_i is 'A' if lot i starts processing on an aggregate server immediately upon arrival in the system (which happens if, upon arrival, an idle server is qualified for lot i); sev_i is 'D' if lot i starts upon departure of another lot (i.e. lot i was queued before starting service).

We define process time buckets. Each bucket is identified by recipe r, number of lots sw, and event type sev. In the aggregate model, the process time of lot i is sampled from a gamma distribution with distribution parameters (mean and variance) corresponding to bucket (r_i, sw_i, sev_i). We assume that the process time distributions for each bucket are independent. To limit the number of buckets, we define a highest value of sw being N. Buckets (r, N, sev) contain all process times of buckets (r, sw, sev) for $sw \geq N$.

The input of the model consists of EPT distributions for each bucket. To determine these EPT distributions, arrival and departure data is used. For each lot i departing from the considered workstation, departure time d_i is collected, as well as the corresponding arrival time a_i of the lot in the buffer of the workstation. The arrival and departure data is translated into EPT-realizations using an EPT algorithm.

B. EPT algorithm

The input of the EPT algorithm is a list of events, each event consisting of event time τ, lot identifier (lot ID) id, event type ev, and lot recipe r. The events are sorted in increasing time order. Additionally, algorithm input consists of the number of servers M, and a user-defined function `qual`, in which the recipe qualification of each server is defined.

The EPT algorithm takes the aggregate model viewpoint. The algorithm reconstructs the EPT realizations from the measured list of arrival and departure events as follows. The algorithm reads arrival and departure events in time order. The start of an EPT realization may occur in either of two cases:

1) A lot arrives while, according to the aggregate model, there is an idle qualified machine.
2) A lot departs from a machine and, according to the aggregate model, at least one lot is waiting in the queue for which the machine is qualified.

An EPT realization ends if a lot departs. Upon departure of lot i, the algorithm calculates EPT_i by subtracting the EPT start time of lot i from its departure time. EPT_i is assigned to bucket (r_i, sw_i, sev_i). In reconstructing EPTs, it may occur that a lot i departs that has not yet started an EPT according to the aggregate model. This may occur if lot i in reality overtook several other lots. Note that the aggregate model works on FIFO basis. When an EPT start is not available, an EPT start is randomly chosen from all available EPT starts with the same recipe r as the departing lot. If there is no EPT start available with recipe r, an EPT start is chosen randomly from all available EPT starts. The selected EPT start time is assigned to lot i to calculate the EPT. For a lot from which the EPT start has been taken, the EPT start is reset to the present time. The algorithm in pseudo-code is presented in [Vee08a].

C. Example

Suppose we have two workstations that provide us with a list of events, visualized in Figure 2. Figure 2a shows four lots that do not overtake, and Figure 2b shows four lots with overtaking. We approximate both workstations with the aggregate model shown in Figure 1b, with $R = \{A, B\}$, $\rho_0 = \rho_1 = \{A, B\}$, and $\rho_2 = \{A\}$.

The EPT realizations that follow using the EPT algorithm are depicted in the Figure 2. The bucket recipe of each EPT realization is indicated between parenthesis. Bucket value sw (number of lots in the system upon the EPT start for which the aggregate server is qualified), is indicated between square brackets. The event upon which the EPT started is indicated between curly brackets. In Figure 2a, Lot 1,2, and 4 start an EPT upon arrival, because at least one machine is idle and qualified for the lot type. Lot 3 does not start an EPT upon arrival, because the idle machine (the third machine) is not qualified for type B. Lot 3 starts an EPT upon departure of lot 1, for a machine qualified for type B becomes idle. Lot 1, 2 and 3 are processed on the first two aggregate servers, which are qualified for recipe A and B. Hence, values sw are equal to the total number of lots in the system (1, 2 and 3 respectively). Lot 4 is processed on the third aggregate server, which is only qualified for recipe A lots. Therefore, value sw is equal to the number of recipe A lots in the system (which is 1 in this case).

In Figure 2b, lots 1, 2, and 3 start an EPT upon arrival. Lot 4 does not start an EPT upon arrival, but departs before lots 1, 2, and 3. Hence, the EPT start of lot 4 is not available when lot 4 departs. Instead, an EPT start of another lot is used. In this case, the EPT start of lot 3 is used, because lot 3 has the same recipe as lot 4 (being type A). The EPT start of lot 3 is restarted.

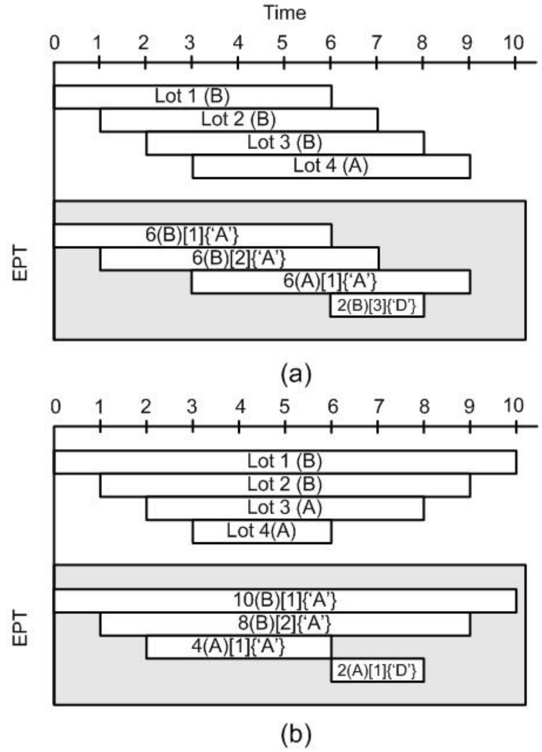

Fig. 2. Lot-time diagrams of arrivals and departures and the calculated EPT realizations (a) without overtaking, (b) with overtaking.

III. SIMULATION TEST CASE

Consider a simulation test case of a cluster tool workstation. We investigate the throughput and product mix range for which our method provides accurate mean cycle time predictions. Simulation results were generated using the language χ [Hof07].

A. Simulated cluster tool workstation

The simulation test case is shown in Figure 1(a), with $R = \{A, B\}$, $\rho_0 = \rho_1 = \{A, B\}$, and $\rho_2 = \{A\}$. The arriving product mix is denoted by p_A, which is the fraction of arriving recipe A lots. Accordingly, $1 - p_\mathrm{A}$ is the fraction of arriving recipe B lots. The test case system consists of three semiconductor cluster tools, which share one infinite buffer. Lots arrive at the workstation buffer according to a Poisson process; each lot contains 25 wafers. Each cluster tool has three load ports, which may hold one lot each. After a lot has been placed on the load port, its wafers are processed inside the cluster tool. Once all wafers of a lot are finished, the lot is taken from the load port and leaves the workstation. Lots are processed in FIFO order taking into account the machine qualification. If more than one qualified machine is available for processing we look at the amount of empty load ports and the machine qualification. The first criterion is that a lot is assigned to the machine that has the most empty load ports. The second criterion is that a lot is assigned to the machine that is qualified for the least amount of recipes.

The wafer flow inside the cluster tool is modeled as a tandem flow line, see Figure 3. The flow line consists of 8 processes; for each process one or two parallel servers are available. The servers correspond to the process chambers in the cluster tool. The constant process times are given in Table I. The process times of recipe A and B are equal in all process steps, except in process 6. After all processes are finished, the wafers return to their lot on the loadport. Once process 1 has finished the last wafer of a lot, it continues with the first wafer of the next lot. Hence, wafers of multiple lots can be in the system simultaneously. In the cluster tool model, wafers are not allowed to overtake via parallel servers. Wafer transport between servers does not require time.

B. EPT distribution parameters

The aggregate model that we use to approximate the test case system is depicted in Figure 1(b), again with $R = \{A, B\}$, $\rho_0 = \rho_1 = \{A, B\}$, and $\rho_2 = \{A\}$. Each cluster tool is modeled as a wip-dependent single-lot server, with the same recipe qualification as its real counterpart. We calculated EPT realizations from arrivals and departures generated by simulating the test system. The arrivals and departures of 10^5 simulated lots were obtained for product mix $p_{\text{A}} = 0.75$ and throughput ratio $\delta/\delta_{\text{max}} = 0.8$. We set N (user defined maximum value of sw) to 10. The EPT realizations were assigned to buckets as explained in the previous section. For each bucket, the mean EPT and the coefficient of variation of the EPT were calculated. Figure 4 shows the mean EPT t_{e} as a function of the number of lots sw in the system upon the EPT start for which the aggregate server is qualified. The left plot in Figure 4 shows the mean EPT $t_{\text{e,a}}$ of EPTs that started upon arrival of a lot, for recipes A and B. The right plot in Figure 4 shows the mean EPT $t_{\text{e,d}}$ of EPTs that started upon departure of a lot.

The left-most plot of Figure 4 shows that the mean EPT for lots that started their EPT upon arrival is 8.95 for recipe A lots, and 22.55 for recipe B lots. This corresponds to the process time that a 25-wafer lot takes to be processed. Recipe B lots take longer because the wafers have a non-zero process time in process 6, other than the wafers of a recipe A lot. Up to three lots may be in the system upon an EPT start (including the arriving lot), so sw is 3 at most.

For EPTs that started upon departure of a lot, the mean approximates 7.2 for increasing sw, and 21.2 for recipe B. This corresponds to the mean interdeparture time of lots at each machine, when the machine is working at its full speed. The interdeparture time of a recipe A lot depends on the recipe of the previous lot. In case the preceding lot is also of recipe A, the interdeparture time is 7.5. However, if the previous lot is of recipe B, the interdeparture time is lower. This is because recipe B wafers need an extra process step 6, and recipe A lots are not allowed to overtake recipe B wafers. The interdeparture time of a recipe B lot is 20.0 if the previous lot was also of recipe B, but higher if the previous lot was of recipe A. For the product mix at which we measured EPTs ($p_{\text{A}} = 0.75$) the first two cluster tools switch frequently between recipe A and B lots. Hence, the mean EPT at high buckets is lower than 7.5 for recipe A and higher than 20 for recipe B.

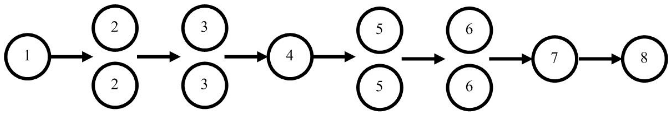

Fig. 3. Cluster tool simulation model

TABLE I
PROCESS TIMES CLUSTER TOOL SIMULATION MODEL

Process	Process Time A	Process Time B
1	0.1	0.1
2	0.3	0.3
3	0.5	0.5
4	0.0	0.0
5	0.6	0.6
6	0.0	1.6
7	0.15	0.15
8	0.1	0.1

For EPTs of recipe A lots that started upon departure, the minimum value of sw equals 1. $sw = 1$ may occur if a recipe A lot starts on the third aggregate server, after being the only recipe A lot in the queue. The third server is only qualified for recipe A, so only counts A lots in determining sw, so $sw = 1$. For recipe B lots, $sw \geq 2$. Recipe B lots are processed on the first 2 servers, that count all lots in the system in determining sw. At least 2 lots have to be in the system upon the EPT start, which are the lot starting the EPT itself, and a lot that is in process on the other server that can process recipe B lots.

C. CT-TH-PM surface

Figure 5 depicts cross-sections of the CT-TH-PM surface for various levels of p_{A} (fraction of recipe A lots). The solid lines represent the mean cycle times φ calculated by the test case system, and the dashed lines represent the mean cycle times estimated by the aggregate model. Figure 5 shows that the mean cycle times are accurately predicted by the aggregate model for product mixes near the working point product mix ($p_{\text{A}} = 0.75$).

For product mixes far from the working point, in particular at $p_{\text{A}} = 0.0$ and 1.0, the predicted mean cycle time less accurate. This is because at the working point $p_{\text{A}} = 0.75$

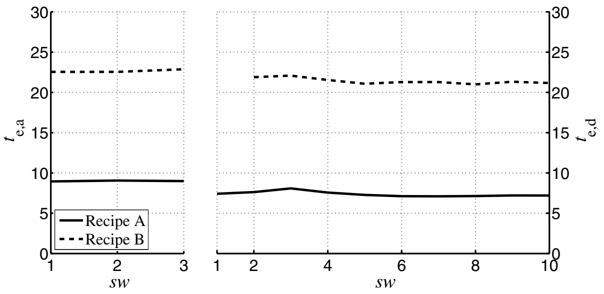

Fig. 4. Mean EPT t_{e} of simulated cluster tool workstation

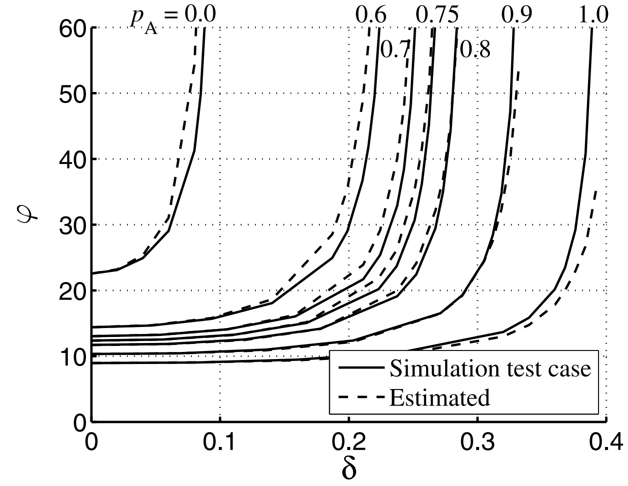

Fig. 5. Cross-sections of the CT-TH-PM surface of simulated cluster tool workstation

the first two machines switch between recipe A and B lots. Switching results in a lower mean EPT for recipe A, and a higher mean EPT for recipe B (as shown in Figure 4), in comparison with the case in which the server does not switch between recipes. Hence, the measured mean EPT at $p_{\mathrm{A}} = 0.75$ is too high for $p_{\mathrm{A}} = 0.0$, and too low for $p_{\mathrm{A}} = 1.0$. As a result, the mean cycle time is overestimated for $p_{\mathrm{A}} = 0.0$, and underestimated for $p_{\mathrm{A}} = 0.0$.

IV. CROLLES2 CASE

Next, CT-TH-PM surfaces are determined for a cluster tool workstation in the Crolles2 wafer fab. Crolles2 is a multi-product 300mm fab in which both high volume products as well as small series and prototype products are produced. Standard production lots, so-called FOUPs (Front Opening Unified Pods), contain 25 wafers. In this section, we first describe the Crolles2 cluster tool workstation for which the CT-TH-PM surface is calculated. Subsequently, we explain how arrival and departure data was obtained and filtered. Next, we calculate EPT-realizations and estimate EPT-distributions. Finally, the CT-TH-PM surface is estimated using the EPT-based aggregate model.

A. Considered cluster tool workstation

The considered cluster tool workstation consists of three cluster tools, which are used to deposit metal layers. The third cluster tool can only deposit titanium nitride layers, which are required for recipe A lots. Cluster tool 1 and 2 can deposit aluminum and titanium nitride layers. This means that besides recipe A lots, also recipe B lots can be processed, which need both aluminum and titanium nitride layers. Note that the amount of machines in the workstation, their recipe qualification, and their working principle is the same as in our simulation test case system.

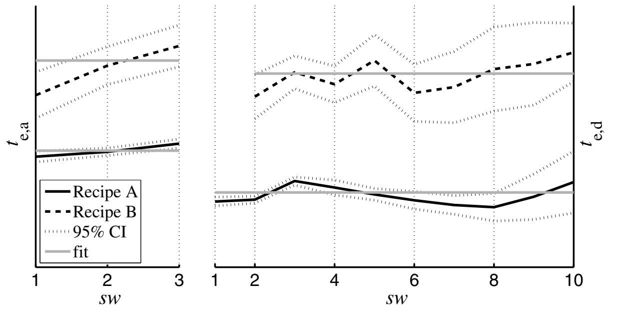

Fig. 6. Measured mean EPT and fits for the Crolles2 cluster tool workstation

B. Estimating EPT-distribution parameters

At the Crolles2 site, arrivals and departures of 5560 lots processed on the considered cluster tool workstation were obtained from the manufacturing execution system (MES). To obtain arrivals and departures, a data processing algorithm transforms MES data into arrivals and departures similar as in [Vee08b].

The EPT-algorithm as explained in Section II is used to reconstruct EPT-realizations of the considered cluster tool workstation for recipe A and recipe B lots. Departures that have corresponding arrival times outside the measurement period and vice versa, are treated using the procedure as explained in [Vee08b]. The aggregate model representation we use is the same as in the simulation test case system, and depicted in Figure 1b.

The left side of Figure 6 shows the measured $t_{\mathrm{e,a}}$ values for recipe A (solid black line) and recipe B lots (dashed black lines), as a function of sw. The right side of Figure 6 shows the measured $t_{\mathrm{e,d}}$ values for recipe A and B lots as a function of sw. For reasons of confidentiality, no values on the y-axes are given. Additionally, Figure 6 shows the 95% confidence intervals (dotted).

Again similar to [Vee08b] we fit curves to the measured EPT parameters for recipe A and B (the grey solid lines in Figure 6 represent the curve fits). We choose constant functions for $t_{\mathrm{e,a}}$ and $t_{\mathrm{e,d}}$. This implies that their is no dependency on sw for this cluster tool workstation. For $c_{\mathrm{e,a}}$ and $c_{\mathrm{e,d}}$ (not shown in Figure 6) we also fit constant functions.

C. CT-TH-PM surface

Cross-sections of the generated CT-TH-PM surface for the considered Crolles2 workstation are shown in Figure 7. The curves represent the estimated mean cycle time as a function of the throughput for various product mixes. The x-axis denotes the ratio of throughput δ and throughput at the working point δ^*. The y-axis represents the ratio between estimated mean cycle time $\hat{\varphi}$ and mean cycle time at the working point φ^*. This implies that point (1,1) is the working point of the workstation during the measurement period (indicated by the plus sign). The working point product mix is 74% recipe A, and 26% recipe B lots ($p_{\mathrm{A}} = 0.74$). Figure 7 shows that the

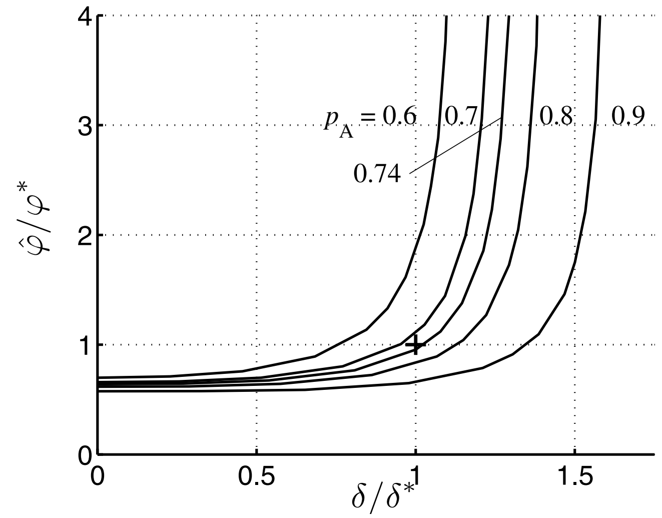

Fig. 7. Cross-sections of the CT-TH-PM surface of Crolles2 cluster tool workstation

mean cycle time is predicted accurately at the working point, $\hat{\varphi}$ is about 5% lower than real cycle time at the working point φ^*. Figure 7 shows that the maximum throughput of the system increases for increasing values of p_A. This is because the mean EPT of recipe A is lower than the mean EPT of recipe B (as can be observed in Figure 6). Additionally, for recipe A all three cluster tools can be used, whereas for recipe B only the first two cluster tools can be used.

We can only verify the accuracy of the estimated CT-TH-PM surface at the working point. On the basis of the simulation test case described in Section III, which is very similar to the considered Crolles2 workstation, we estimate that the product mix can be varied between $p_\mathrm{A} = 0.6$ and $p_\mathrm{A} = 0.9$. For product mixes further away from the working point, the accuracy of the mean cycle time prediction is expected to deteriorate.

V. CONCLUSION

This paper studies an EPT-based aggregate modeling method to calculate CT-TH-PM surfaces of cluster tool workstations. Machines may be qualified for a subset of process recipes. The new method approximates the workstation by an m-server parallel workstation, in which each server is qualified for the same set of recipes as in the original system. In the aggregate m-server workstation, each server processes just a single lot at a time. The process time distribution of the servers depends on the lot recipe, the workload, and the condition upon which the lot starts processing. The process time distributions are measured directly from lot arrivals and departures using an EPT algorithm.

The proposed EPT-based aggregate modeling method was illustrated by means of a simulation test case representing a cluster tool workstation. The mean cycle time was accurately predicted in the vicinity of the working point of the system. For product mixes far from the working point, the accuracy of the mean cycle time deteriorates. The reason is that at the working point, lots of different recipes influence each other's effective process times. For other product mixes further away from the working point, this mutual influence is different.

As an industry case, the proposed aggregate modeling method was tested on a Crolles2 metal cluster tool workstation. At the working point, the predicted mean cycle time was within 5% of the real cycle time. The results of the simulation test case suggest that accurate mean cycle time predictions for the Crolles2 case can be obtained for product mix changes up to ± 0.15.

The proposed aggregate modeling method includes the product mix explicitly. Other effects affecting the queueing performance are aggregated in the wip-dependent effective process time distributions. If besides the product mix other aspects play a crucial role, one may consider to also model these explicitly to obtain an accurate prediction for sufficiently large product mix ranges. The product mix dependence of the EPT is one example. Setup time for switching between recipes is another.

VI. ACKNOWLEDGMENT

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