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GENERALIZATION OF EF-BASED ASSIGNMENT STRATEGIES FOR CYCLE TIME OPTIMIZATION AT COMPLEX WET STATIONS

Anna Rotondo

Irish Manufacturing Research
Aerodrome Business Park
Rathcoole, D24 WC04, IRELAND

John Geraghty
Paul Young

Enterprise Research Centre
Dublin City University
Collins Avenue
Dublin, D09 W6Y4, IRELAND

ABSTRACT

When solution approaches are developed to facilitate decision processes in real manufacturing systems, fundamental information constraints may apply. The data required by theoretically efficient decision support tools may not be available or accessible; as a consequence, the possibility of implementing the solutions developed is compromised. In this paper, assignment strategies subjected to information constraints and previously developed for a particular wet station are generalized to wet stations characterized by different tool configurations and production recipes. These strategies have been designed to be integrated with data management systems and make use of real time data to minimize the stations' average cycle time. The experiments run aim at supporting the hypothesis that progressive incorporation of details on the system status in assignment strategies enhances the strategies' performance. The relevance of data-driven simulation-based decision support is demonstrated with reference to wet stations operating in a real semiconductor manufacturing facility.

1 INTRODUCTION

The importance of incorporating problem-specific knowledge into the behaviour of any optimization algorithm is well explicated by the No Free Lunch (NFL) theorems developed by Wolpert and McReady (Wolpert and Macready 1997). In order to be effective in generating optimal solutions, an algorithm should be tailored to the specific problem analyzed and incorporate information on the contingent scenario observed when the solution is generated. This concept can be certainly extended to decision support tools that are designed to be adopted in a specific manufacturing environment to facilitate real-time decisions related to production issues. In general, a detailed knowledge of the system where the issue is experienced is fundamental to provide effective decision support; moreover, relevant data on the system's current status should be available and accessible in order to offer automated real-time prescriptive solutions. Information constraints introduce relevant challenges for the development of successful solution approaches since limited amount of real-time data could mean that the decision process is based on partial information and this may affect the quality of the solutions obtained (Kusiak 2006).

In this study, assignment strategies previously developed for a specific wet station configuration operating in a real semiconductor fabrication plant (Rotondo et al. 2014) are generalized to more complex production scenarios, from both a tool configuration and operations perspective, with the aim to demonstrate that manufacturing data available in information systems can effectively support optimal assignment decisions in real-time and that the quality of the assignment decision improves with the meaningfulness of the data considered during the decision process. As a result, the impact of information quality and quantity on the performances of different assignment strategies applied to wet stations operating in a real semiconductor manufacturing facility is investigated. In this context, data quality refers to the accuracy and meaningfulness of the data available in terms of the amount of information on the system status that can be extracted from them. More specifically, the problem of scheduling a wet station including multiple wet tools, each consisting of an automated handling system, multiple tanks containing etch chemicals or deionized water, and an internal buffer is analyzed with the objective of minimizing the average cycle time at the station. Considering that the tools avail of an internal scheduling system that cannot be modified without incurring considerable software update costs, scheduling optimization is realized by optimizing the assignment of batches of lots to specific wet tools within the station. The assignment strategies considered are inspired by an efficient assignment concept based on the shortest completion time (Earliest Finish concept) (Hsieh et al. 2002). The original EF concept would require detailed information on the system's current status; however, due to limited access to the tools' internal database, fundamental information constraints apply. Taking these constraints into account, the three alternative strategies developed progressively enlarge the information domain on which the assignment decisions are based and consider more sophisticated look-ahead logics: one that examines the status of all chemical stations, one that considers the availability of the dryer station, and one that considers the dryer and repour times. The results obtained could be used by production management to perform trade-off analyses between information costs and cycle time performances.

It is worth noting that although more advanced single wafer wet processing technology has been recently introduced and adopted by companies at the cutting edge of the semiconductor industry, the multi-chamber batch technology is still in use in the industry (i.e. for test wafers regeneration); hence the assignment strategies suggested here are still relevant and will be for at least a decade. Moreover, the assignment problem in single wafer wet processing becomes even more critical since, when this technology is used, the wet station fleet size typically increases, and assignment decisions become more complex and should be driven by dynamic data-based approaches.

This paper is organized as follows; Section 2 reviews relevant literature on wet station scheduling, Section 3 describes in detail the wet station initially modelled. In Section 4, the scheduling algorithm is illustrated. The assignment strategies are described in Section 5. Section 6 reports the results obtained and conclusions are drawn in Section 7.

2 Literature Review

Wet stations represent critical production steps for the semiconductor wafer manufacturing process (Aydt et al. 2008). A wet station usually consists of several identical tools that operate in parallel. In batch chamber wet tools, batches of wafers made of one or two lots are processed at wet tools; the process consists of immersing a batch into consecutive chemical and water tanks available within the tools. As for most batch chamber tools (Lee 2008) subjected to peculiar scheduling constraints, wet tools are generally difficult to model (Govind and Fronckowiak 2003). Simulation approaches have been developed to perform what-if analyses and evaluate the effect of modifications of operational settings on the tools' performance (Noack et al. 2008). Simulation has also been coupled with optimization approaches to identify efficient strategies for operational planning and control of wet-etch tools; maximum waiting time for batching operations (Govind and Fronckowiak 2003), virtual queue capacity (Govind and Fronckowiak 2003; Noack et al. 2008), recipe dedication (Aydt et al. 2008; Te Quek et al. 2007) have been subject of simulation-based optimization studies on wet tools. A fundamental feature of wet tools and, more generally, integrated or cluster tools (Niedermayer and Rose 2003) consists of parallel processing; this transforms the inversely proportional relationship between cycle time and throughput (Mauer and Schelasin 1993) so that higher CTs can also generate increases in throughput and reductions of overall run time. The presence of parallel processing and the variety of operations performed at a wet tool enables the improvement of the tools performance by means of efficient assignment strategies and sequencing optimization. Mathematical programming approaches (Bhushan and Karimi 2004; Karimi et al. 2004; Aguirre et al. 2011; Castro et al. 2011; Zeballos et al. 2010; Novas and Henning 2012; Castro et al. 2012) and heuristics (Bhushan and Karimi 2004; Geiger et al.

1997) have been extensively used for solving sequencing and scheduling optimization problems at wet stations. For these problems, as a result of managements suggestions, makespan minimization represents the most common objective function (Zeballos et al. 2010). This is because makespan reductions lead to throughput increases and reduce the likelihood that wet tools could constitute a constraint to the factory output (Geiger et al. 1997). Reducing the makespan also supports an increase in tool capacity and, hence, minimizes the number of tools needed, with obvious advantages in terms of occupied clean room floor space (Geiger et al. 1997). Moreover, decreasing the makespan leads to a lower inventory and contamination and results in greater profits (Bhushan and Karimi 2003). The observed research trend on wet stations sequencing and scheduling optimization is towards the development of approaches able to deliver nearly optimal solutions in a reasonable time for increasingly larger sized problems (Karimi et al. 2004; Castro et al. 2011; Castro et al. 2012). More recent studies also focus on the introduction of modelling details, such as those regarding the material handling system, so that more realistic assumptions are considered in the solutions developed (Aguirre et al. 2011; Lee et al. 2007).

As a further effect of parallel processing and recipes variety, dispatching and assignment strategies also impact cycle time at wet tools (Govind and Fronckowiak 2003; Noack, Gan, Lendermann, and Rose 2008; Te Quek, Gan, Tan, Peng, and vd Heijden 2007). The assignment concept (i.e. Earliest Finish, EF) that has inspired the definition of the assignment strategies illustrated in this paper presents similarities with the concept developed in Hsieh et al. (2002); the fundamental differences between the two assignment approaches concern the underlying equations that support the choice of the optimal tool in the station. Hsieh et al. (2002) adopt an approximated procedure for calculating the processing completion time of a batch at the different tools available in a station whereas a rigorous algorithmic procedure based on valid governing equations is adopted in this study. Moreover, in Hsieh et al. (2002), delays caused by maintenance operations within a tool are considered *a posteriori* whereas, in the analysis proposed here, events that could delay a batch processing are concurrently considered during the calculation of the assignment decision variable. A concept similar to EF is also used in Noack et al. (2008) where it is applied to establish the order with which batches assigned to a tool will be processed, that is, it is used as a sequencing strategy rather than an assignment strategy. Similarly, Te Quek et al. (2007) analyze the combined effect of assignment and dispatching on wet stations capacity.

In this study, the simulation algorithm used to support assignment decisions is based on a trial and error approach; scheduling logics and applicable constraints captured in the algorithm faithfully reproduce those observed at wet stations operating in a real semiconductor fabrication facility. The development of the algorithm has been based on a detailed analysis of the tools manufacturing data; data analyses have been conducted to characterize the tools behaviour as the internal scheduling logic was proprietary to the tools vendor. An accurate representation of the tools behaviour is achieved as several recipes, bi-directional production flows (Lee et al. 2007) and correct robot transfer movements (Novas and Henning 2012) can be simulated. This also ensures that the scheduling optimization problem at wet tools is not reduced to a flowshop permutation scheduling problem (Bhushan and Karimi 2004; Aguirre et al. 2011) and the property of parallel processing, which is typical of a batch chamber tool, is fully exploited in the assignment procedure. The assignment strategies investigated in this study adopt the same scheduling algorithm so that the sole effect of the assignment decisions are analyzed. The strategies originally developed for a particular wet station characterized by a relatively simple recipe mix have been generalized to be applicable to more complex production scenarios. A recipe describes the order with which a batch visits tanks; an operation establishes the processing times in each tank. Further experiments have also been conducted to investigate both the impact of the *a priori* exclusion of tools subjected to preventive maintenance from the list of eligible tools at a station and the impact of recipe dedication policies on cycle time performances.

3 System Description

In the wet station initially considered in this study, four identical tools operate in parallel; these tools present a typical batch chamber tool layout (Fig. 1). In each tool, the 6 tanks (T1-T6 in Fig. 1) are

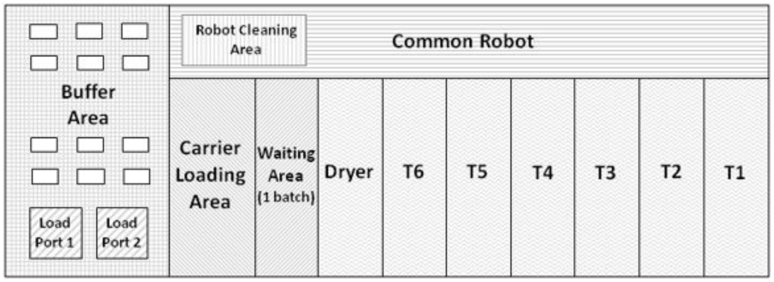


Figure 1: Schematic representation of the wet tools modelled.

alternately filled with chemical etchants and deionized water. The chemical etchants are used to etch away the exposed photo-resist from the wafer layers; the etchant action is terminated by immersing the wafers into the consecutive water tank. As an over-exposure of the wafers to a chemical etchant will most likely damage the wafers, a Zero Wait (ZW) constraint is applied to the chemical tanks; this constraint forces a batch to leave the tank once the prescribed processing time is reached and implies that both the associated rinse tank and the robot are available at that time. In order to satisfy the ZW constraint and also to guarantee that a temporary storage is available in case of a sudden chemical tank operational failure, the rinse tank associated with a chemical tank is required to be available and idle while a batch is being processed in the chemical tank. No intermediate buffer is available between any two consecutive tanks; this generates a further scheduling constraint, usually called No-Intermediate Storage (NIS). The NIS constraint requires that before a batch can leave a tank, the following tank in its recipe is available. The tanks subjected to the ZW constraint will be considered unsafe, whereas the remaining tanks will be considered safe tanks since a sensible overexposure time will not damage the wafers. The maximum overexposure time in a rinse tank varies according to the etchants in the associated chemical tank. Safe tanks can occasionally be used as local storage when the following tanks or the material handling system are not available.

The tools modelled avail of an automated material handling system. A common robot moves the batches across the tanks, whereas, internal handlers at each tank perform vertical movements so that a batch can be transferred from the robot into the tank. The internal handler at unsafe tanks also transfers batches to the associated rinse tanks. Pre-emptive robot assignment rules are implemented in the internal scheduler control logic to increase the availability of the dryer; in particular, transfer of batches out of the dryer are prioritized over any other robot movement. Due to necessary and periodic repouring operations, the chemical tanks present a limited availability; during these operations, a tank is emptied and refilled with the appropriate chemicals whilst the other tanks in the same tool continue processing as usual. Regular preventive maintenance is also performed at the wet tools. A common buffer upstream of the wet station gathers all the lots that require processing at the station. In the buffer, batching is performed so that lots with compatible operations are virtually batched and immediately made available to the assignment system that selects the wet tool that will process the batch. Each operation is characterized by a maximum waiting time (MWT) in the buffer; if a lot in the upstream buffer remains single for the MWT, it will be processed as a single lot. Two assignment rules are generally considered in the plant where the tools operate. The Emptiest-Oldest (EO) strategy assigns batches to the tools with the lowest number of batches currently assigned. In case of equally loaded tools, the tool with the oldest last arrival is selected. On the contrary, if the Oldest Time Out (OTO) strategy is implemented, the tool with the oldest last batch exiting the tool is selected. The OTO strategy is adopted in the wet station initially modelled. Once in a wet tool, the lots are logged in the internal scheduler that generates fully feasible schedules based on the recipe and the robot and tanks availability. The schedule details the times in and out of each tank. At the prescribed time, the lots are loaded by a mechanical device onto a carrier and moved by the robot following the schedule generated by the internal scheduler. If the first tank to be visited is occupied, the carrier is left in the internal waiting area. Before leaving the tool every batch visits the dryer, then the lots are unloaded from the carrier and return into the internal buffer.

4 System Modelling

In order to investigate the impact of different assignment strategies on cycle time at the wet station investigated, a simulation model was developed. The model presents a modular structure so as to enhance its flexibility; the most relevant modules for the analysis presented here consist of the assignment algorithm and the scheduling algorithm. The assignment algorithm verifies the inventory status at regular time intervals and based on the lots available creates virtual batches, if possible. When lots ready to be assigned are available, the algorithm identifies the tool to which the lot will be routed based on the assignment strategy applied. Different versions of this algorithm have been developed for simulating the different strategies investigated here. The scheduling algorithm generates detailed schedules for the lots to be processed based on deterministic input data. The scheduling logic used is inspired by the behaviour of the internal scheduler of the tools analyzed; the control logic applied in the real plant is proprietary to the tools' vendor and cannot be modified without incurring significant software update costs. Communication with the production engineers involved in this research and analyses of historical data helped develop an adequate understanding of the tools control logic so that it could be accurately modelled. Historical manufacturing data generated by the internal scheduler were analyzed over a 15 day period to gain an understanding of the scheduling logic and validate the production engineers' knowledge regarding the tools behaviour. In particular, the batch progression within the tools was analyzed in order to identify scheduling constraints and pre-emptive rules governing the material handling system. As an interesting outcome of this process, it was found that the internal waiting area that is interposed between the carrier loading area and the tanks (Fig. 1) does not constitute a bottleneck for the tool as initially thought. This assumption had influenced the tools management, especially with regards to the assignment logic.

The tools' control logic described in the previous section has been reproduced in a scheduling algorithm based on a trial and error approach with a backward correction procedure. The algorithm utilizes availability matrices for both tanks and robot at each tool while it progressively builds the schedules in order to confirm or reject a tentative resource request for a certain time interval. Once the batch schedule is confirmed, the robot and tanks availability are updated. Further details on the modelling assumptions, scheduling logic, and the inherent governing equations are detailed in (Rotondo et al. 2015) where the model validation process using real data is also discussed. The algorithm has been coded in MATLAB v9 and it has proven to be computationally efficient as detailed batch schedules are generated in less than 0.01 seconds per batch, on average. For bigger problem sizes, the computational time increases slightly more than linearly; 120 seconds are needed to generate feasible schedules for 6200 lots when the assignment strategy adopted in the plant is applied. For the most computational intensive strategy investigated in this study, the same problem was solved in 130 seconds. The experiments were run on a 2.4 GHz INTEL Core Duo processor.

5 Generalized Assignment Strategies

The assignment strategies initially developed adapted the EF strategy to the information constraints observed in the real plant and specifically to the recipes structure of the wet station modelled. In that station, referred to as Station A hereinafter, the tools included two identical chemical tanks able to satisfy the demand for higher volume operations (Table 1). In the tanks rows of Table 1, the first letter suggests if the tank is filled with a chemical etchant (C) or deionised water (R), the second letter represents a chemical identifier, the third letter refers to the tank classification (e.g. whether safe (S) or unsafe (U)). All the recipes performed at Station A prescribe to visit one chemical tank, the associate rinse tank and the dryer (Table 2).

The simple recipe structure allowed for straightforward adaptations of the EF strategy to less information based strategies. The alternative strategies developed incorporate progressive information details on the tools status and, as a consequence, require progressive implementation efforts.

The first variant, the Tank Check (TC) strategy, requires the least amount of information as it is based on the current status of each single chemical tank excluding the dryer. Tanks with actual or virtual queue assigned to them are immediately excluded from the pool of eligible tanks and the remaining tanks are

Table 1: Wet station and tools' configuration.

Station		A		B	C	
# tools		2	2	7	2	1
Tanks	T1	C b - U	C b - U	C d - U	C c - U	C c - U
	T2	R b - S	R b - S	R d - S	R c - S	R c - S
	T3	C a - U	C b - U	R e - S	C c - U	NA
	T4	R a - S	R b - U	C e1 - S	R c - S	NA
	T5	C a - U	C a - U	C e2 - S	C a - U	C a - U
	T6	R a - S	R a - S	R e - S	R a - S	R a - S

Table 2: Recipes performed at the three wet stations.

Station	Recipe ID	# Op	Recipe					
A	A1	9	C a	R a	Dryer			
	A2	6	C b	R b	Dryer			
B	B1	14	C e1	C e2	R e	Dryer		
	B2	7	C d	R d	C e1	C e2	R e	Dryer
	B3	4	C d	R d	Dryer			
C	C1	7	C c	R c	C a	R a	Dryer	
	C2	2	C a	R a	C c	R c	Dryer	
	C3	1	C c	R c	Dryer			
	C4	5	C a	R a	Dryer			

sorted based on the time at which they become available, this information is provided by the tools' internal scheduler. The virtual queue includes all batches that have been virtually assigned to a tool based on the schedule generated theretofore.

The second variant, the Tank & Dryer (TD) strategy, includes information on the dryer availability; the dryer represents a critical element of a wet tool as all recipes require a final visit to the dryer. The time at which the dryer becomes available is derived based on the tools' actual and virtual workload and compared with the expected Time Out from the rinse tank; transport times are of the order of seconds and hence are neglected in the calculations.

The last variant developed, the Tank & Dryer with Repour Check (TDR) strategy, slightly modifies the TD strategy as it incorporates information on the tanks availability with respect to repouring operations. This variant implements an *a priori* exclusion of all tanks that are or will be subjected to repours within a sensible time interval. The exclusion time interval is based on considerations on the travel time between the upstream buffer and the tool, and the typical waiting time within the tool.

When the recipes consist of visiting more than one chemical tank, the exclusion of tanks that already present a virtual queue, as requested by the TC, TD and TDR strategies, would mean drastically reducing the possibility of making assignment decisions as most tools would be excluded from the remaining decision steps. For this reason, the strategies have been generalized so that they could be applied to wet stations with more complex recipe mixes, such as Stations B and C (Table 1). These stations present the same layout as Station A (Fig. 1); however, the succession of chemical and rinse tanks differs for the three stations. Table 1 illustrates the wet station and tools configuration. Station B configuration suggests that it is possible that a chemical tank is considered safe from a scheduling perspective and that the rinse tanks physically precede the associated chemical tanks; this means that bi-directional flow can exist in a real wet tool. Moreover, in Station B, the two safe chemical tanks are coupled; this means that a batch has to visit them consecutively and suggests that the succession of chemical and rinse tanks is not necessarily alternating as reported in most research studies (Bhushan and Karimi 2004; Zeballos et al. 2010; Geiger et al. 1997). As regards Station C, due to the peculiar recipe mix that determines a non-unidirectional production flow within a tool, a recipe dedication policy is applied so that, at any time, a tool in the station is dedicated to process batches of a specific recipe; the tools' dedication to a specific recipe is rotated at regular time intervals. Due to low capacity requirements, two tanks in one of Station C's tools are left empty. The choice of focusing on the wet tool configurations and recipe structures that characterize Stations A, B and C derives from the observations of these stations in the real manufacturing facility where the analysis reported in this paper has been conducted. Within that facility, alternative tool configurations and recipe mixes for wet stations did not exist.

For more complex recipe mixes such as those of Stations B and C, the assignment strategies have been adapted as illustrated in this section; based on the generalization approach illustrated here, adaptations to other various recipes different to those performed in Stations B and C can be derived.

In the TC strategy, the assignment decision is based on the lowest Time In for the last chemical tank in the recipe; this Time In is calculated with a procedure similar to the calculation of the Time In for the dryer for the TC strategy. The pseudo-code that illustrates the generalized TC strategy assignment logic is reported below.

```
for each batch k to be assigned:
  retrieve recipe r and chemical tanks (t's) required by the recipe
  for each t in r:
    for each tool m that can process r:
      cumulativePT(m,0) = Time_Log_In (k)
      for each t in r:
        if t > 1:
          cumulativePT(m,t) = cumulativePT(m,t-1) + RinseT(k,t-1)
        for each tank h with chemical t:
          retrieve TimeOut*(h) of batch currently processed
          virtualQueue_PT(h) = 0
          for each batch v in virtualQueue(h):
            virtualQueue_PT(h) = virtualQueue_PT(h) + PT(v,t)
          minTimeInTank(k,h) = max{cumulativePT(t), TimeOut*(h) +
          + virtualQueue_PT(h)}
        cumulativePT(m,t) = min_h(minTimeInTank(k,h))+PT(k,t)
  select tool m* | cumulativePT(m*,t_Last)=min_m(cumulativePT(m,t_Last))
  if more than one m* exists:
    select m** | # batches in m** since m** last shut down is min
```

The earliest time at which the last chemical tank in the recipe becomes available (TimeOut$^*(h)$ + virtualQueue_PT(h)) is compared with the cumulative sum of the time at which the previous chemical tanks become available plus the required processing and transportation times to reach the last chemical tank (cumulativePT(m^*, t_{Last})); the maximum value between these two predictions represents the predicted TimeIn for the last chemical tank at the corresponding tool. The time at which a tank becomes available consists of the TimeOut of the batch currently processed in that tank if there is no virtual queue (TimeOut$^*(h)$); on the contrary, when a virtual queue exists at that tank a penalty time is applied. The consideration of a penalty time avoids the exclusion of the tank and the associated tool from further decision steps. The penalty time consists of the processing times and setup times of the batches virtually assigned to the tanks. It is worth noting that for ease of representation, terms such as setup times or travel times are not reported in the pseudo-code above but are considered in the assignment algorithm. If more than one tool present the same minimum Time In for the last chemical tank, the tool with the fewest number of batches processed

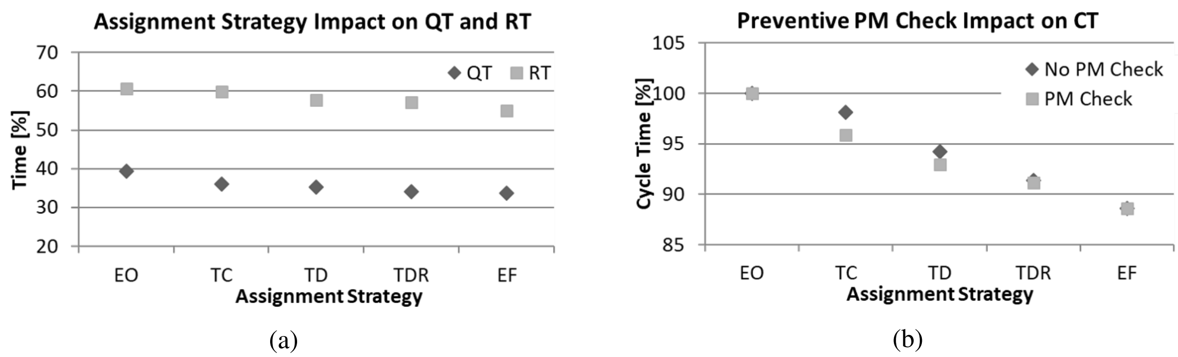


Figure 2: Impact of assignment strategies on QT and RT (a) and on CT for alternative PM check policies (b) at Station B.

since its last shut down is chosen. The TD and TDR strategies incorporate the variations made to the TC strategy with respect to the calculation of the earliest Time In of the chemical tanks; moreover, for the TDR strategy, following the same logic as the TC strategy, tanks subjected to repours within sensible time intervals are given a penalty time but are not excluded from the consecutive procedures steps.

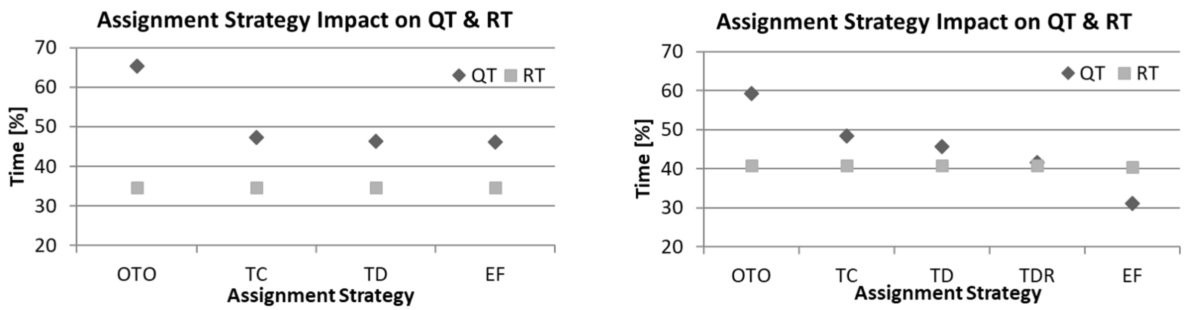
6 Results

The efficacy of the strategies' variants described above has been tested on both stations B and C in terms of its impact on Cycle Time (CT). CT is considered as the sum of two components, namely Queuing Time (QT) and Run Time (RT). QT is intended as the time elapsing between the lot arrival at the buffer and the time at which the lot leaves the interval buffer of a wet tool in order to be processed; this means the waiting time within the tool is also included in QT. RT is intended as the time that a lot spends inside a wet tool, excluding the waiting time in the internal buffer. The experimental results show that for both Station B and Station C, CT progressively reduces as the strategies applied incorporate more information on the tools status. This is especially evident at Station B, where both CT components benefit from the implementation of information-based assignment strategies (Fig. 2a). In this case, RT reductions are also possible due to both the relatively high number of operations performed at the station (See Table 2) and the classification of chemical tanks as safe tanks (e.g. T4-T5 in Table 1). Indeed, a better allocation of batches to tools prevents safe tanks from being used as local storage and, as a result, RT is reduced.

The impact of information quality on CT performance has been further investigated at Station B; the effects of the *a priori* exclusions of tools subjected to preventive maintenance (PM) at the moment of the assignment decision or tools with maintenance operations scheduled within a sensible time interval have been compared with the original case when no check for ongoing preventive maintenance operations is performed (Fig. 2b). The results show that the introduction of this exclusion rule is more effective on the TC strategy, which is the one based on poorer information. As the level of information increases, the impact of the exclusion rule on CT reduces. In the TDR and EF strategy the exclusion rule does not impact CT as these strategies are not substantially modified; indeed, repours occur during PM and, as a consequence, tools undergoing maintenance operations are automatically penalized by the TDR logic. Moreover, the EF strategy does not apply any *a priori* exclusion rule because, by its nature, all the tools are considered for the assignment decision, so effectively, no modification has been made to the EF strategy.

As regards Station C, interesting results are obtained as the TC and TD strategies generate significant QT reductions that are of the same order of those obtained when the EF strategy is implemented (Fig. 3a).

The limited number of tools available (e.g. three tools operate in Station C) that is further reduced by the recipe dedication policy applied is the reason for this result. As happens in Station A (Fig. 3b), RT are not affected by the assignment strategy due to both the recipes' structure and the presence of unsafe



(a) Station C (b) Station A

Figure 3: Impact of assignment strategies on QT and RT at Station C (a) and Station A (b).

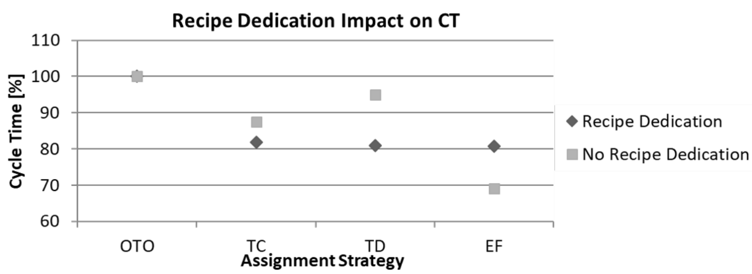


Figure 4: Impact of assignment strategies on CT under two recipe dedication policies.

tanks. It is worth noting that the application of the TDR strategy has not generated sensible results at this station; as a consequence, the TDR strategy's results have been omitted in Fig. 3a. This is probably due to the limited number of tools available and the recipe dedication policy applied; moreover, at this station, repours are performed at quite high frequency so that the high penalty times assigned to the tools delay the assignment decision and, as a consequence, increases in QT are observed.

The impact of the recipe dedication policy on the efficacy of the assignment strategies has also been analyzed at this station; simulation experiments have been conducted to investigate the effect of a non-dedication policy on CT for the TC, TD and EF strategies. In these experiments all the three tools at Station C are considered available for processing batches of any recipe. The alternative strategies still generate CT reductions (Fig. 4) with respect to the strategy currently adopted (e.g. OTO); however, for the TC and TD strategy, CT increases with respect to the corresponding Recipe Dedication scenarios. This is because, in the tool previously dedicated to one recipe (e.g. recipe C1 which constitute 77% of the production volume at Station C) the non-dedication policy makes the production flow asynchronous and conflicts for the tanks utilization cause processing delay. In this case, an assignment decision based on a complete knowledge of the tools status (e.g. EF strategy) can compensate for this issue and generate even more significant CT reductions as the absence of a dedication policy increases the number of tools eligible for the assignment decision. In other words, when the strategy is based on poorer information, sensible constraints that make the production flow synchronous and limit the search domain could facilitate an efficient assignment decision; on the contrary, for strategies based on good quality information, any unnecessary constraint reduces the strategy's efficiency.

Finally, the strategies illustrated here have been assessed by the industrial engineers involved in this study and positive feedback on the results obtained has been obtained. The strategies development has been guided by their knowledge on the stations control system and the possibility to access relevant data. Since significant modifications to both the data management system and the control system are required to implement these strategies, preliminary investigations are currently being carried out internally at the company to assess the applicability of similar assignment concepts to other stations operating in the plant that comprise parallel batch chamber tools. Positive results would support the final decision to allocate resources for the strategies adoption in the plant. In this regard, it is worth noting that, modifications of scheduling related control parameters that were suggested based on experimental results and required no implementation cost have been trialled in the plant. As a result, significant CT reductions, in the order of 10%, have been obtained; the parameters modified included the tools' virtual buffer capacity and MWTs for different operations.

7 Conclusion

The assignment problem at wet stations presents relevant challenges as the variety of recipes performed and the peculiar scheduling constraints applied generate an asynchronous production flow within the tools that makes their efficient utilization a difficult task. By generalizing assignment strategies previously developed to more complex tools' and recipes' configurations, this study demonstrates that when the assignment decision is based on accurate information on the tools' status, the choice of the tool is made more effectively and, as a result, the tools are better utilized. This concept has been inspired by the No Free Lunch theorems that state the importance of incorporating problem-specific knowledge into optimization and search algorithms. Following the latest trends in data analytics, data available in the manufacturing system should be exploited to extract information, refine the industrial practitioners knowledge on the system behaviour and support optimal decisions. However, especially for decision support tools based on real-time data, the presence of information constraints should never be neglected as access to relevant data required by the solution algorithms may not be possible. Four assignment strategies previously developed have been generalized to more complex wet tool configurations and recipe structures. The strategies consider the effects of a progressive introduction of information quantity and quality into the assignment decision process as an efficient assignment concept is adapted to applicable information constraints. The analysis has been carried out using a scheduling algorithm based on the scheduling logics observed at real wet stations. The algorithm generates feasible schedules in short computational times and is integrated with an assignment module that implements the four strategies analyzed. The results obtained show that, generally, queuing times benefit most from the application of information-based assignment strategies as a more efficient workload distribution among the tools available generates additional effective capacity at no investment cost. This happens especially when the recipe mix performed at the station consists of quite short recipes. When the recipes prescribe to visit more than one chemical tank and several unsafe tanks operate in the tools, run times also reduce when the quantity of information on which the assignment decision is based increases. Further experiments have been run to show that the introduction of further details, such as Preventive Maintenance related information, in the assignment decision process can also improve the results obtained. It has also been observed that the presence of assignment constraints intended to optimize the tools' utilization by making the production flow synchronous (e.g. recipe dedication policy) has a positive impact on CT performance when the assignment decision is based on partial information on the tools' status; however, when a complete knowledge of the system status is possible (i.e. EF strategy can be fully implemented), this assignment constraint significantly limits the decisions efficiency and should be avoided. As shown in this study, the introduction of additional details on a problem instance in corresponding solution algorithms is likely to generate output improvements; however, it is expectable that exceptions to this generic concept exist. An obvious reference would be to the tool/recipe configuration used for Station C; in this case, the TDR strategy, which incorporates more problem specific knowledge, generates higher cycle times than less knowledge-intensive strategies (i.e., TC and TD). Further investigations will be conducted to analyze to which extent the hypothesis that information-based assignment strategies are likely to generate considerable productivity improvements can be considered valid. For instance, EF-based approaches will be further generalized to be applicable to single wafer wet processing technology and will also be tested within the context of more generic assignment and/or scheduling problems.

REFERENCES

Aguirre, A. M., V. G. Cafaro, and C. A. Méndez. 2011. "Simulation-based Framework to Automated Wet-Etch Station Scheduling Problems in the Semiconductor Industry". In *Proceedings of the 2011 Winter Simulation Conference (WSC)*, edited by S. Jain, R. Creasey, J. Himmelspach, K. White, and e. M. Fu, 1816–1828. IEEE.

Aguirre, A. M., C. A. Méndez, and P. M. Castro. 2011. "A Novel Optimization Method to Automated Wet-Etch Station Scheduling in Semiconductor Manufacturing Systems". *Computers & Chemical Engineering* 35(12):2960–2972.

Aydt, H., S. J. Turner, W. Cai, M. Y. H. Low, P. Lendermann, and B. P. Gan. 2008. "Symbiotic Simulation Control in Semiconductor Manufacturing". In *International Conference on Computational Science*, edited by M. B. et al., 26–35. Springer: Springer-Verlag Berlin Heidelberg 2008.

Bhushan, S., and I. Karimi. 2003. "An MILP Approach to Automated Wet-Etch Station Scheduling". *Industrial & Engineering Chemistry Research* 42(7):1391–1399.

Bhushan, S., and I. Karimi. 2004. "Heuristic Algorithms for Scheduling an Automated Wet-Etch Station". *Computers & Chemical Engineering* 28(3):363–379.

Castro, P. M., A. M. Aguirre, L. J. Zeballos, and C. A. Méndez. 2011. "Hybrid Mathematical Programming Discrete-Event Simulation Approach for Large-Scale Scheduling Problems". *Industrial & Engineering Chemistry Research* 50(18):10665–10680.

Castro, P. M., L. J. Zeballos, and C. A. Méndez. 2012. "Hybrid Time Slots Sequencing Model for a Class of Scheduling Problems". *AIChE Journal* 58(3):789–800.

Geiger, C. D., K. G. Kempf, and R. Uzsoy. 1997. "A Tabu Search Approach to Scheduling an Automated Wet Etch Station". *Journal of Manufacturing Systems* 16(2):102–116.

Govind, N., and D. Fronckowiak. 2003. "Process Equipment Modeling: Resident-Entity Based Simulation of Batch Chamber Tools in 300mm Semiconductor Manufacturing". In *Proceedings of the 35th Winter Simulation Conference (WSC)*, edited by D. F. S. Chick, P. J. Sanchez and D. J. Mornce, 1398–1405: IEEE.

Hsieh, M., A. Lin, K. Kuo, and H. Wang. 2002, December 11. "A decision support system of real time dispatching in semiconductor wafer fabrication with shortest process time in wet bench". In *Semiconductor Manufacturing Technology Workshop, 2002*, 286–288. Hsinchu, China: IEEE.

Karimi, I., Z. Y. Tan, and S. Bhushan. 2004. "An Improved Formulation for Scheduling an Automated Wet-Etch Station". *Computers & Chemical Engineering* 29(1):217–224.

Kusiak, A. 2006. "Data Mining: Manufacturing and Service Applications". *International Journal of Production Research* 44(18-19):4175–4191.

Lee, T.-E. 2008. "A Review of Scheduling Theory and Methods for Semiconductor Manufacturing Cluster Tools". In *Proceedings of the 40th Winter Simulation Conference (WSC)*, edited by S. J. Mason, R. R. Hill, L. Mnch, O. Rose, T. Jefferson, and J. W. Fowler, 2127–2135. IEEE.

Lee, T.-E., H.-Y. Lee, and S.-J. Lee. 2007. "Scheduling a Wet Station for Wafer Cleaning with Multiple Job Flows and Multiple Wafer-Handling Robots". *International Journal of Production Research* 45(3):487–507.

Mauer, J. L., and R. E. Schelasin. 1993. "The Simulation of Integrated Tool Performance in Semiconductor Manufacturing". In *Proceedings of the 25th Winter Simulation Conference*, edited by G. Evans, E. R. M. Mollaghasemi, and W. Biles, 814–818. ACM.

Niedermayer, H., and O. Rose. 2003. "A Simulation-based Analysis of the Cycle Time of Cluster Tools in Semiconductor Manufacturing". In *Proceedings of the 15th European Simulation Symposium*, edited by A. Verbraeck and V. Hlupic, 349–354: SCS European Council.

Noack, D., B. P. Gan, P. Lendermann, and O. Rose. 2008. "An Optimization Framework for Waferfab Performance Enhancement". In *Proceedings of the 40th Winter Simulation Conference (WSC)*, edited by S. J. Mason, R. R. Hill, L. Mnch, O. Rose, T. Jefferson, and J. W. Fowler, 2194–2200. IEEE.

Novas, J. M., and G. P. Henning. 2012. "A Comprehensive Constraint Programming Approach for the Rolling Horizon-based Scheduling of Automated Wet-Etch Stations". *Computers & Chemical Engineering* 42:189–205.

Rotondo, A., P. Young, and J. Geraghty. 2014. "EF-based Strategies for Productivity Improvements at Wet-Etch Stations". *Production Planning & Control* 25(11):958–968.

Rotondo, A., P. Young, and J. Geraghty. 2015. "Sequencing Optimisation for Makespan Improvement at Wet-Etch Tools". *Computers & Operations Research* 53:261–274.

Te Quek, P., B. P. Gan, S. L. Tan, C. L. Peng, and B. vd Heijden. 2007, October 15-17. "Analysis of the Front-End Wet Strip Efficiency Performance for Productivity". In *International Symposium on Semiconductor Manufacturing, 2007. ISSM 2007.*, 1–4. Santa Clara, CA: IEEE.

Wolpert, D. H., and W. G. Macready. 1997. "No Free Lunch Theorems for Optimization". *IEEE transactions on evolutionary computation* 1(1):67–82.

Zeballos, L. J., P. M. Castro, and C. A. Méndez. 2010, September 6-9. "A CP-based Approach for Scheduling of Automated Wet-Etch Stations". In *Proceedings of the 2nd International Conference on Engineering Optimisation*. Lisbon, Portugal.

Zeballos, L. J., P. M. Castro, and C. A. Mendez. 2010. "Integrated Constraint Programming Scheduling Approach for Automated Wet-Etch Stations in Semiconductor Manufacturing". *Industrial & Engineering Chemistry Research* 50(3):1705–1715.

AUTHOR BIOGRAPHIES

ANNA ROTONDO is an optimization Scientist at Irish Manufacturing Research. She holds a MS degree in management engineering from Politecnico di Bari (Bari, Italy) and received her PhD in manufacturing engineering from Dublin City University (Dublin, Ireland). The focus of her research for her PhD theses was on the prediction of quality risk associated with sampling strategies in semiconductor fabrication systems. Her research interests include analysis, modelling and optimization of complex manufacturing systems. Her email address is anna.rotondo@imr.ie.

JOHN GERAGHTY is an Assistant Professor in the School of Mechanical and Manufacturing Engineering at Dublin City University, Ireland. He holds a B.Eng., a M.Eng. (by research) and a PhD in Industrial Engineering from the University of Limerick, Ireland. The focus of his research for both his M.Eng. and PhD theses was on inventory and production control strategies in manufacturing systems subject to variability in production time and demand distributions. His research interests include modelling and analysis of semi-conductor fabrication systems, lean manufacturing, supply-chain management and operations excellence. His email address is john.geraghty@dcu.ie.

PAUL YOUNG is the Director of the Enterprise Process Research Centre at Dublin City University, Ireland. His PhD (Trinity College Dublin, 1991) concerned condition monitoring of turning and was followed by the measurement and modeling of vehicle HVH in Japan. The design, analysis, modeling and monitoring of manufacturing processes was the main focus of his Post-Doctoral research work with the Advanced Manufacturing Research Centre in University College Dublin. In 1998 he was appointed to the faculty in Dublin City University where, since 2001, his research is mainly in the application of modeling and analysis to improve the performance of complex manufacturing systems, while maintaining some machine design and modelling. His email address is paul.young@dcu.ie.