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STUDY OF RELATIONSHIPS BETWEEN SCHEDULING OBJECTIVES IN SEMICONDUCTOR MANUFACTURING

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ABSTRACT

In semiconductor manufacturing, scheduling problems addressed at the operational level involve a rich set of constraints and criteria. As a result, multi-objective optimization algorithms are increasingly preferred over dispatching rules, especially in complex manufacturing areas. This article investigates the relationships between several scheduling objectives considered in the photolithography area. The criteria are first presented and then compared two by two. To this effect, the notion of dominated objective function is used. Various relationships are shown in the general case along with different counterexamples. In addition, an experimental analysis is proposed based on industrial optimization computations of the photolithography area to assess the conflict level between objectives, but also to confirm the relevance of a multi-objective approach. Finally, some perspectives are provided.

1 INTRODUCTION

(Mönch et al. 2011) and (Mönch et al. 2012) showed that the performances of the semiconductor industry highly relies on the use of effective scheduling approaches in wafer fabrication facilities. The latter include the most complex manufacturing processes, with various objectives to be considered. Thanks to increasing computational capabilities and algorithmic progress, optimization methods tend to supplant dispatching rules in scheduling decisions. However, optimizing several criteria remains computationally expensive since each single objective scheduling problem is must often already difficult to solve.

Operations scheduling in some manufacturing areas at *STMicroelectronics* relies on real-time multi-objective optimization engines. Among all work areas of front-end manufacturing processes, photolithography is central, and is therefore considered as a reference area in this paper. Due to the various industrial requirements in this area, no less than 8 different objectives are currently considered sequentially in the scheduler, with time limitations that do not always allow a proper optimization. Though each objective is defined by experts, no global comprehensive analysis has been conducted. This work aims at investigating the relationships between these objectives in order to rule out potential redundancies among them.

Objectives considered in the following are described in Section 2, and are positioned with respect to the literature in Section 3. Section 4 introduces the dominance relation, and a pairwise comparison of objectives is conducted in Section 5, with some proofs and numerous counterexamples. Finally, Section 6 proposes an experimental assessment of the conflict intensity between objectives considered in the photolithography area, with interesting results complementing the formal study of the previous sections.

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2 OVERVIEW OF THE OBJECTIVES

Scheduling decisions consists in assigning each of the lots to be processed, called job, to one of the area machine in such a way that one or several objective functions are optimized. In every work area, some specific operational constraints must also be enforced, for instance a non-preemptive processing on machines, some setup times between different recipes, or a serial or parallel batching of lots. The resulting optimization problems are especially tougher to solve given that machines usually have various characteristics, such as unrelated processing times or different list of eligible jobs.

In the following, some of the objectives are classical ones, such as the minimization of the weighted sum of completion times or the minimization of the makespan. Other criteria are derived from them:

- **Minimization of the sum of the setup times** *or* **Minimization of the total number of setups.** Several lots can be processed with different recipes on the same machine. Changing the recipe on the machine induces a sequence-dependent cost: a waste of time but also a waste of consumables along with some manual operations, which are rarely formally modelled in scheduling models.
- **Maximization of the number of jobs completed before a certain time horizon.** Because of the high volume of lots in the manufacturing areas, schedules generally stretch over several hours. Over this period, various uncertainties, like machine failures or process drifts, generally occur. Moreover, additional lots will be released in the area, that should be scheduled before lots already available. Hence, only the first hours of the schedule are more likely to be executed. For this reason, this objective is introduced in order to complete as many lots as possible (potentially weighted by their priority) before a given time horizon. This time horizon is set by experts, and ranges from one to four hours depending on the situation of the photolithography area.

Finally, some objectives are more specific to semiconductor manufacturing:

- **Risk minimization for maximum time lags constraints.** The time spent by some lots between two operations (that are not necessarily consecutive) must not exceed a certain duration. This time constraint aims at reducing the risk for lots of being discarded due to some physical and chemical reasons. Such time constraints are generally treated as constraints called maximum time lags constraints. In the real application, many lots are already under time constraint at the beginning of the schedule, which make some constraints unsatisfiable. Besides, the duration of such constraints is only empirically estimated and their violation does not automatically lead to yield loss or lot scrapping. For these two reasons, maximum time lag constraints are turned to an objective that minimizes the time spent by the lot outside the time constraint.
- **Length maximization of serial batches of jobs.** Serial batches consist of jobs belonging to the same recipe group, i.e. having no setup times in between. In some work area, maximizing the length of serial batches is thereby used to reduce the number of setup times in the schedules.
- **Minimization of total number of moves of auxiliary resources.** In the photolithography area, processing of lots on machines requires an auxiliary resource called reticles, that have to be moved from one machine to another by machine operators. Because the workforce in the area is limited and to avoid unnecessarily reticles moves, this number of reticle moves must be minimized.
- **Minimization of X-factor.** This criterion aims at reducing the total cycle time of lots. For a given lot, the X-factor is the total staying time of the lot in the area over its processing time.

When scheduling in manufacturing areas such as photolithography, several of these objectives need to be considered at the same time, which imposes a multi-objective approach.

3 LITERATURE REVIEW

Some objectives are extensively treated in the literature, in particular in the semiconductor industry. The minimization of the sum of completion times is tackled in (Pickardt et al. 2010) for dispatching rules and (Hochbaum and Landy 1997) for scheduling semiconductor burn-in operations. Regarding the photolithography area, (Bitar et al. 2016) proposes a memetic algorithm to optimize this criterion. The makespan minimization is discussed by (Sung and Choung 2000) for single burn-in ovens in the wafer fabs, just like (Lee and Kim 2016) for lot switching period in cluster tools. In the photolithography area, (Madathil et al. 2018) use this criterion to schedule a photolithography area containing cluster tools. Apart from the semiconductor industry, numerous discussions on classical objectives can be found, for instance in (Pinedo 2012) or (Baker and Trietsch 2013).

On the other hand, other objectives seem to be less addressed in the literature. Thought the reduction of setup times is investigated by (Allahverdi and Soroush 2008), this objective along with the length maximization of serial batches of jobs are rarely especially considered in the scheduling literature of semiconductor manufacturing. The maximization of the number of jobs completed before a certain time horizon is discussed in (Bitar et al. 2021). Nevertheless, this latter can be seen as a special case of late work minimization (optimized in (Gupta and Sivakumar 2006)). Regarding objectives that are specific to wafer fabrication, maximum time constraints are usually defined as model constraints, e.g. in (Klemmt and Mönch 2012). (Lima et al. 2017) also analyzes different dispatching policies for probability estimation in time constraint tunnels. In their work, (Díaz et al. 2005) highlight the impacts of reticle requirements in the photolithography area in their work, what motivates some publications to integrate them in the scheduling decision, like (Cakici and Mason 2007). However, number of auxiliary resources has been more recently embedded in optimization model as an objective function, like in (Bitar et al. 2021) or in (Yepes-Borrero et al. 2020). Finally, in the semiconductor industry, the minimization of the X-factor is often used: we can mention method of tool planning proposed by (Ozawa et al. 1999), or the batch optimization solver for diffusion area developed by (Artigues et al. 2006) that both use the X-factor as objective.

Literature in multi-criteria scheduling in the semiconductor is quite diversified, with numerous bi-objective problems (see for instance (Rocholl et al. 2020)). (Pfund et al. 2008) and (Min and Yih 2003) both propose a multi-criteria approach for scheduling semiconductor wafer fabrication facilities. A multi-objective optimization approach for complex flexible job-shop scheduling problems is proposed in (Tamssaouet et al. 2022). For the photolithography area, (Zhu and Tianyu 2019) developed a mathematical model to simultaneously minimize the total weighted completion times and the total energy consumption. However, to the best of our knowledge, no scientific research was conducted to formally compare all these scheduling objectives.

4 DOMINANCE RELATION

This section formalizes the dominance relation between objective functions, which is then applied in Section 5 for the single machine and the parallel machine scheduling problems.

In order to compare two objective functions f and g of the same vector of discrete variables $x = (x_k)_{k\in\mathbb{N}^*}$, let us introduce the notion of dominance. In the following, let us assume without loss of generality that f and g both need to be minimized over the same set of feasible solutions $\mathscr{X}$. Their respective set of optimal solutions is denoted $\mathscr{X}_f^* \subseteq \mathscr{X}$ and $\mathscr{X}_g^* \subseteq \mathscr{X}$.

Definition 1 (Dominance between objective functions) Objective function f dominates objective function g over a set of feasible solutions $\mathscr{X}$ if:

$$\mathscr{X}_f^* \subseteq \mathscr{X}_g^*$$

For instance, if $f(x) = x$ and $g(x) = -x^2$, then f dominates g over $[-1,1]$ as $\mathscr{X}_f^* = \arg\min\{f(x) \mid x \in [-1;1]\} = \{-1\} \subset \mathscr{X}_g^* = \arg\min\{g(x) \mid x \in [-1;1]\} = \{-1,1\}$.

Furthermore, when two functions dominate each other, they are said to be equivalent.

Definition 2 (Equivalence between objective functions) Objective functions f and g are equivalent over a set of feasible solutions $\mathscr{X}$ if:

$$\mathscr{X}_f^* = \mathscr{X}_g^*$$

For example, if $f(x) = -|x|$ and $g(x) = -x^2$, then f dominates g over $[-1,1]$ as $\mathscr{X}_f^* = \arg\min\{f(x) \mid x \in [-1;1]\} = \{-1,1\} = \arg\min\{g(x) \mid x \in [-1;1]\} = \mathscr{X}_g^*$.

The dominance relation is a quasiorder, i.e. a reflexive and transitive binary relation. However, this relation is not antisymmetric, as Proposition 1 below proves. Indeed, every linearly and positively dependent pair of objective functions are equivalent.

Proposition 1 (Linearly dependent functions) If f and g are two objective functions defined over a set of feasible solutions $\mathscr{X}$, then:

$$\exists(a,b) \in]0,+\infty[\times \mathbb{R} \text{ such that } \forall x \in \mathscr{X} \ f(x) = a \cdot g(x) + b \implies \mathscr{X}_f^* = \mathscr{X}_g^*$$

Proof. $\mathscr{X}_f^* = \arg\min_{x\in\mathscr{X}} f(x) = \arg\min_{x\in\mathscr{X}} (a \cdot g(x) + b) = \arg\min_{x\in\mathscr{X}} g(x) = \mathscr{X}_g^*$. ■

For the sake of completeness, let us introduce Lemma 1, that is used in Section 5 to demonstrates that no dominance relationship exists between two objective function f and g.

Lemma 1 (Absence of dominance between objective functions) There exists no dominance relationship between two objective functions f and g over a set of feasible solutions $\mathscr{X}$ when:

$$\exists(x_f^*, x_g^*) \in \mathscr{X}_f^* \times \mathscr{X}_g^* \text{ such that } \begin{cases} f(x_g^*) > f(x_f^*), \\ g(x_f^*) > g(x_g^*). \end{cases}$$

Proof. Indeed, $f(x_g^*) > f(x_f^*) \implies x_g^* \notin \mathscr{X}_f^* \implies X_g^* \not\subset X_f^*$. Similarly, $g(x_f^*) > g(x_g^*) \implies X_f^* \not\subset X_g^*$. ■

For instance, if $f(x) = |x|$ and $g(x) = -x^2$, then there is no dominance relation between f and g over $[-1,1]$. Indeed, $x_f^* = 0$ and $x_g^* = 1$ (or -1), but $f(x_g^*) = 1 > f(x_f^*) = 0$ proves that $\mathscr{X}_g^* \not\subset \mathscr{X}_f^*$, and $g(x_f^*) = 0 > g(x_g^*) = -1$ demonstrates that $\mathscr{X}_f^* \not\subset \mathscr{X}_g^*$.

5 STUDY OF DOMINANCE RELATIONS BETWEEN SCHEDULING OBJECTIVES

Although scheduling problems in the semiconductor industry most often include multiple machines, single machine scheduling problems are first considered in Section 5.1 and 5.2 to eliminate several dominance relationships between objectives. Then, parallel machines are considered in Section 5.3.

5.1 Single Machine Scheduling Problem

In this section, only one machine is considered, with scheduling constraints derived from those of the photolithography area: Processing of lots on the machine is not preemptive, and only one job can be processed at the same time. Moreover, all jobs must be scheduled. Using the notation introduced by (Graham et al. 1979), such a problem is denoted $1||\text{opt}f$ where $\text{opt}f \in \{\min f, \max f\}$ and f refers to any objective function previously defined.

If $\min\sum_j \omega_j C_j$ denotes the minimization of the weighted sum of completion times, an optimal solution to problem $1||\min\sum_j \omega_j C_j$ is provided by the Smith's rule (see for instance (Pinedo 2012)).

Theorem 1 (Smith's rule) Consider a set $\mathscr{J}$ of jobs to be scheduled. Let us denote $p_j \in \mathbb{R}^{+*}$ and $\omega_j \in \mathbb{R}^{+*}$ the processing time and the weight of job $j \in \mathscr{J}$, respectively. Then, scheduling jobs by increasing value of $\frac{p_j}{\omega_j}$ provides an optimal solution to $1||\min\sum_j \omega_j C_j$.

Corollary 1 If $\min C_{max}$ denotes the makespan minimization, $1||\min\sum_j \omega_j C_j$ dominates $1||\min C_{max}$.

Proof. Using theorem 1, any optimal schedule for $1||\min\sum_j \omega_j C_j$ is non-delayed, which means that the makespan is also minimized, whatever the values of ω_j. Hence, $\min\sum_j \omega_j C_j$ dominates $\min C_{max}$ in the single machine scheduling problem. ■

Notice that the reciprocal of Corollary 1 is false, as all job permutations of the optimal schedule for problem $1||\min\sum_j \omega_j C_j$ are an optimal solution of problem $1||\min C_{max}$ (see Figure 2 below for a counterexample).

Consider now the maximization of the number of jobs completed before a time horizon H, denoted by $\max\sum_{C_j \leqslant H} 1_j$. With any value of $(\omega_j)_{j\in\mathscr{J}}$, no dominance relationship exists between $\max\sum_{C_j\leqslant H} 1_j$ and $\min\sum_j \omega_j C_j$, nor between $\max\sum_{C_j\leqslant H} 1_j$ and $\min C_{max}$. Indeed, Figure 1 shows a simple counterexample with three lots generating distinct optimal schedules for each of the two pairs of objectives.

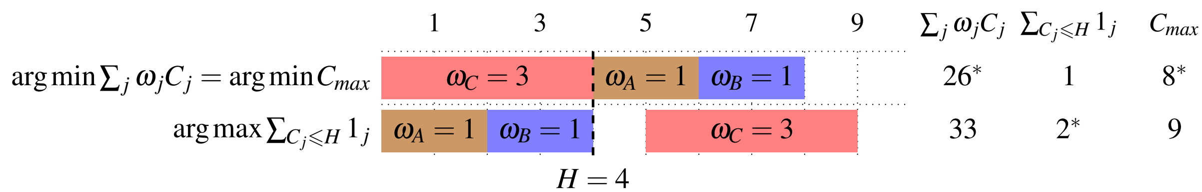

Figure 1: Counterexample of a dominance relationship between any pair of objectives $(\min\sum_j \omega_j C_j, \max\sum_{C_j\leqslant H} 1_j)$ and $(\min C_{max}, \max\sum_{C_j\leqslant H} 1_j)$ for scheduling problem $1||\text{opt} f$, using three lots A, B and C.

However, in the specific case where the set of jobs ordered by decreasing weights w_j is the same as the set of jobs obtained by ordering the jobs by increasing processing times p_j, then the maximization of the number of jobs completed before a time horizon H is dominated by the minimization of the weighted sum of completion times.

Theorem 2 Let us denote $\mathscr{J}$ the set of jobs to be scheduled, and $p_j \in \mathbb{R}^{+*}$ and $\omega_j \in \mathbb{R}^{+*}$ the processing time and the weight of job $j \in \mathscr{J}$, respectively. With these notations, if $\forall (j,j') \in \mathscr{J}^2, p_j \leqslant p_{j'} \implies \omega_j \geqslant \omega_{j'}$, then $1||\min\sum_j \omega_j C_j$ dominates $1||\max\sum_{C_j\leqslant H} 1_j$.

Proof. Let the bijection $S^* : \mathscr{J} \leftrightarrow [\![1, |\mathscr{J}|]\!]$ be an optimal positional schedule for $1||\min\sum_j \omega_j C_j$. By applying the above assumptions to the optimality criterion of Theorem 1, we obtain that $\frac{p_j}{\omega_j} \leqslant \frac{p_{j'}}{\omega_{j'}} \implies p_j \leqslant p_{j'}$ $\forall (j,j') \in \mathscr{J}^2$ such that $S^*(j) < S^*(j')$, which is optimal for $1||\max\sum_{C_j\leqslant H} 1_j$. ■

Regarding the risk minimization of maximum time lag constraints, it is assumed for the sake of simplicity and without loss of generality that the corresponding objective function aims at completing as soon as possible the time constraint, which means that the sum of the difference between the completion of the job starting the constraint and the completion time of the job ending the constraint has to be minimized. In brief, let us refer to this objective as $\min\sum_{(j,j')}(C_{j'} - C_j)$. Figure 2 proves that no dominance is possible between $1||\min\sum_j \omega_j C_j$ and $\min\sum_{(j,j)}(C_{j'} - C_j)$, but also between $\min C_{max}$ and $\min\sum_{(j,j)}(C_{j'} - C_j)$, and between $\max\sum_{C_j\leqslant H} 1_j$ and $\min\sum_{(j,j')}(C_{j'} - C_j)$.

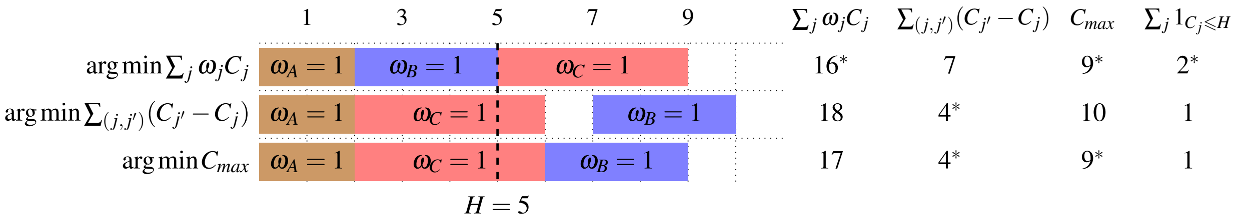

Figure 2: Counterexample of a dominance relationship between any pair of objectives $(\min \sum_j \omega_j C_j, \min \sum_{(j,j')}(C_{j'} - C_j))$, $(\min C_{max}, \min \sum_{(j,j)}(C_{j'} - C_j))$ and $(\max \sum_{C_j \leqslant H} 1_j, \min \sum_{(j,j')}(C_{j'} - C_j))$ for problem $1||\text{opt} f$ with three lots A, B and C and a maximum time lag between A and C.

Figure 3 summarizes the dominance relationships among the considered objectives for the single machine scheduling problem.

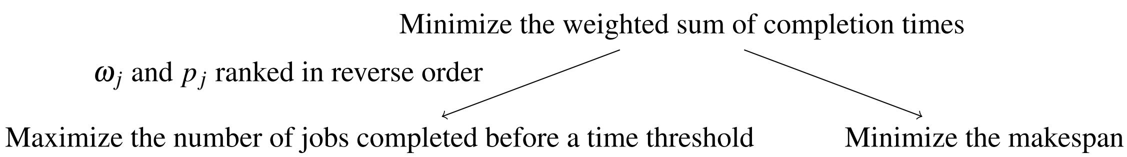

Figure 3: Dominance relationships between objectives in the single machine scheduling problem $1||\text{opt} f$.

5.2 Single Machine Scheduling Problem with Sequence Dependent Setup Times

In this section, sequence-dependent setup times $s_{j,j'} \in \mathbb{R}^*$ are added to the single machine scheduling problem, henceforth denoted $1|s_{j,j'}|\text{opt} f$. Firstly, let us show that the previously proven relationships do not hold. Indeed, by considering objective $\min \sum_j C_j$, the specific case of $\min \omega_j \sum_j C_j$ with $\omega_j = 1\ \forall j \in \mathscr{J}$, scheduling problem $1|s_{j,j'}|\min \sum_j C_j$ does no longer dominate $1|s_{j,j'}|\max \sum_j 1_{C_j \leqslant H}$ nor $1|s_{j,j'}|\min C_{max}$, as Figures 4 and 5 respectively show.

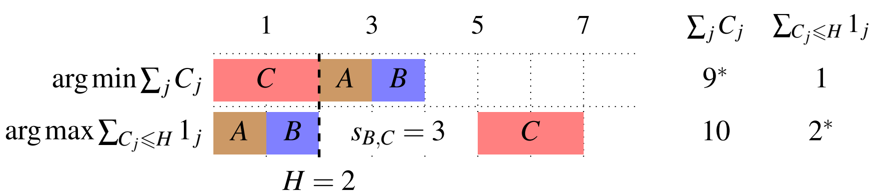

Figure 4: Counterexample for a dominance relationship between problems $1|s_{j,j'}|\min \sum_j C_j$ and $1|s_{j,j'}|\max \sum_{C_j \leqslant H} 1_j$ using three lots A, B and C such that $s_{A,B} = s_{B,A} = s_{C,A} = s_{C,B} = 0$ and $s_{A,C} = s_{B,C} = 3$.

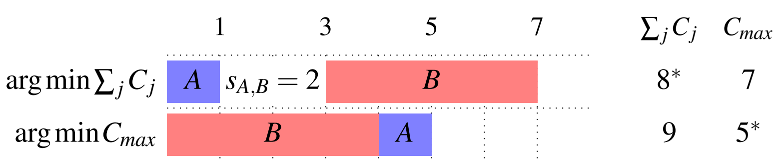

Figure 5: Counterexample for a dominance relationships of problem $1|s_{j,j'}|\min \sum_j C_j$ over problem $1|s_{j,j'}|\max \sum_j 1_{C_j \leqslant H}$ using two lots A and B such that $s_{A,B} = 2$ and $s_{B,A} = 0$.

Consider now the three objectives integrating sequence-dependent setups, namely:

- Minimization of the sum of the setup times, denoted by $\min \sum_{(j,j')} s_{j,j'}$,
- Minimization of the number of setups, denoted by $\min \sum_{(j,j')} 1_{s_{j,j'}>0}$,
- Length maximization of serial batches of jobs, denoted by $\max \sum_{(j,j')} |B_{j,j'}|$.

Theorem 3 If $1|s_{j,j'}|\text{opt} f$ denotes any single machine scheduling problem with sequence-dependent setup times $s_{j,j'} \in \mathbb{R}^{+*}$, and C_{max} and $\min \sum_{(j,j')} s_{j,j'}$ denotes the makespan minimization and the minimization of the sum of the setup times, respectively, then $1|s_{j,j'}|C_{max}$ dominates $1|s_{j,j'}|\min \sum_{(j,j')} s_{j,j'}$.

Proof. Let the bijection $S^*_{C_{max}} : [\![1, |\mathscr{J}|]\!] \leftrightarrow \mathscr{J}$ be an optimal schedule for $1|s_{j,j'}|C_{max}$. Then:

$$\begin{aligned}
\min C_{max} &= \min \sum_{k=1}^{|\mathscr{J}|-1} \left(p_{S^*_{C_{max}}(k)} + s_{S^*_{C_{max}}(k), S^*_{C_{max}}(k+1)} \right) + p_{S^*_{C_{max}}(|\mathscr{J}|)} && \text{Definition of } C_{max} \\
&= \min \left(\sum_{k=1}^{|\mathscr{J}|-1} s_{S^*_{C_{max}}(k), S^*_{C_{max}}(k+1)} + \sum_{k=1}^{|\mathscr{J}|} p_{S^*_{C_{max}}(k)} \right) && \text{Separate } s_{j,j'} \text{ from } p_j \\
&= \min \sum_{k=1}^{|\mathscr{J}|-1} s_{S^*_{C_{max}}(k), S^*_{C_{max}}(k+1)} && \sum_j p_j \text{ is constant} \\
&= \min \sum_{(j,j')} s_{j,j'} && \text{Minimization of setup times}
\end{aligned}$$

■

However, no dominance relationship can be found between $\min C_{max}$ and $\min \sum_{(j,j')} 1_{s_{j,j'}>0}$, as Figure 6 shows. By noting that $\min \sum_{(j,j')} 1_{s_{j,j'}>0}$ is a special case of $\min \sum_{(j,j')} s_{j,j'}$ where $s_{j,j'} = 1$, Figure 6 proves that $\min \sum_{(j,j')} s_{j,j'}$ does not dominate $\min C_{max}$, but also that the dominance relation does not hold between $\min \sum_{(j,j')} 1_{s_{j,j'}>0}$ and $\min \sum_{(j,j')} s_{j,j'}$. Regarding the minimization of the weighted sum of completion times, it is also sufficient to produce a counterexample between problems $1|s_{j,j'}|\max \sum_{(j,j')} 1_{s_{j,j'}>0}$ and $1|s_{j,j'}|\min \sum_j C_j$ to conclude for the weighted case (that is more general) and the criteria $\max \sum_{(j,j')} s_{j,j'}$. Figure 6 proposes such a schedule. Finally, note that the first schedule of Figure 6 constructs the longest serial batch ($\max \sum_{(j,j')} |B_{j,j'}|$), but this solution is neither optimal for objectives $\min \sum_j C_j$ or $\min C_{max}$, nor for objective $\sum_{(j,j')} s_{j,j'}$ as the second schedule proves.

	1	3	5	7	9	$\sum_{(j,j')} 1_{s_{j,j'}>0}$	C_{max}	$\sum_{(j,j')} s_{j,j'}$	$\sum_j C_j$
$\arg\min \sum_{(j,j')} 1_{s_{j,j'}>0}$	B A		$s_{A,C} = 7$		C	1^*	10	7	13
$\arg\min C_{max}$	A $s_{A,B} = 2$	B	$s_{B,C} = 2$	C		2	7^*	5^*	12^*

Figure 6: Counterexample of a dominance relationship of $\min \sum_{(j,j')} s_{j,j'}$ over $\min C_{max}$, and between pairs of objectives $\left(\sum_{(j,j')} 1_{s_{j,j'}>0}, \min \sum_{(j,j')} s_{j,j'}\right)$, $\left(\min \sum_{(j,j')} 1_{s_{j,j'}>0}, \min \sum_j C_j\right)$, $\left(\max \sum_{(j,j')} |B_{j,j'}|, \min \sum_j C_j\right)$, $\left(\max \sum_{(j,j')} |B_{j,j'}|, \min \sum_{(j,j')} s_{j,j'}\right)$ and $\left(\max \sum_{(j,j')} |B_{j,j'}|, \min C_{max}\right)$ for scheduling problem $1|s_{j,j'}|\text{opt} f$ using three lots A, B and C such that $s_{A,B} = s_{B,C} = 2$, $s_{B,A} = 0$, $s_{A,C} = 7$ and $s_{C,A} = s_{C,B} = 10$.

Note that the above counterexamples are based on asymmetric setup times. Besides, triangle inequalities for setup times are not always verified to produce the counterexamples (see Figure 6). A perspective is to investigate how special structures of the setup matrix impact the proposed dominance relations.

5.3 Parallel Machine Scheduling Problem

In this last section, the case with unrelated parallel machines is studied. The corresponding Graham notation is $R||\text{opt}f$. With this setting, the minimization of the total number of mask moves between machines, denoted by $\min \sum_r \mu_r$ where $\mu_r \in \mathbb{R}^{+*}$ represents the move duration of reticle r between any pair of distinct machines, can be considered. Figure 7 demonstrates that the set of optimal solutions for problem $R|| \min \sum_r \mu_r$ is disjoint from that of all objectives studied in Section 5.1, to wit, problems $R|| \min \sum_j C_j$, $R|| \min \sum_j C_{max}$, $R|| \max \sum_{C_j \leqslant H} 1_j$ and $R|| \min \sum_{(j,j')} (C_{j'} - C_j)$.

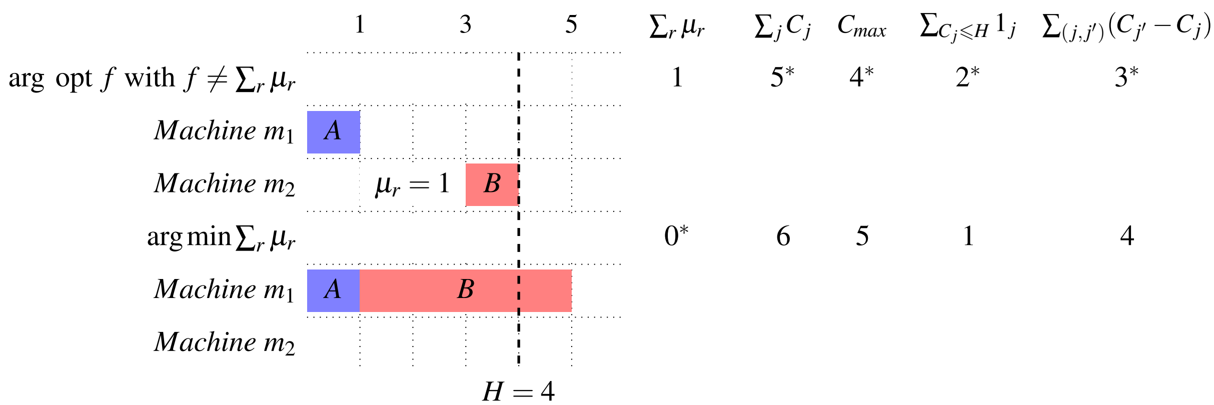

Figure 7: Counterexample of a dominance relationship between objective $\min \sum_r \mu_r$, and objectives $\min \sum_j C_j$, $\min \sum_j C_{max}$, $\max \sum_{C_j \leqslant H} 1_j$ and $\min \sum_{(j,j')} (C^*_{j'} - C^*_j)$ for scheduling problem $R||\text{opt}f$ using two lots A and B, two machines m_1 and m_2 and one reticle r, with $\mu_r = 1$, $p_{A,m_1} = p_{B,m_2} = 1$ and $p_{A,m_2} = p_{B,m_1} = 4$.

Besides, if setup times are added to this parallel machine scheduling problem, then problem $R|s_{j,j'}|C_{max}$ does not dominate problem $R|s_{j,j'}| \sum_{(j,j')} s_{j,j'}$, as illustrated in Figure 8.

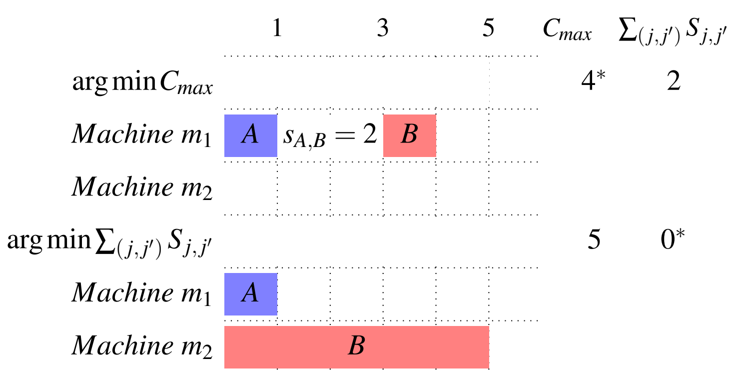

Figure 8: Counterexample of a dominance relationship between objectives $R|s_{j,j'}| \min C_{max}$ and $R|s_{j,j'}| \min \sum_{(j,j')} S_{j,j'}$ with two lots A and B and two machines m_1 and m_2 such that $p_{A,m_1} = p_{B,m_2} = 1$, $p_{A,m_2} = p_{B,m_1} = 5$ and $s_{A,B} = s_{B,A} = 2$.

6 EXPERIMENTAL STUDY

In this section, some results of the scheduler currently used in the photolithography area in a factory of *STMicroelectronics* are exploited in order to complete the dominance study. Section 6.1 describes the considered objectives and selected methodology, and the results are presented and analyzed in Section 6.2.

6.1 Experimental Setting

The considered scheduling engine uses a constraint programming paradigm combined with a lexicographical handling of the multi-objective optimization. The following objectives are successively considered:

1. Minimization of the total number of reticle moves: $\min \sum_r \mu_r$;
2. Maximization of the length of serial batches: $\max \sum_{(j,j')} |B_{(j,j'}|$;
3. Minimization of the risk for maximum time lags constraints: $\min \sum_{(j,j')} (C_{j'} - C_j)$;
4. Maximization of the weighted X-factor: $\min \sum_j \omega_j \frac{C_j}{p_{j,m}}$.

To investigate the relationships between objectives, 5,000 schedules, obtained in 4 consecutive months, are analyzed using the metric introduced in Definition 3. Note that, in these 5,000 schedules, the number of machines and jobs are about 20 and 400, respectively. Each schedule was obtained in a computational time of at most 5 minutes.

Definition 3 (Empirical measure of conflict between objective functions) Consider two objective functions f and g of a lexicographical optimization approach where f is optimized before g. Let us denote by f_k^i and g_k^i the respective objective value of f and g at the end optimization phase $k \in \mathbb{N}$ for instance $i \in \mathscr{I}$, where $\mathscr{I}$ is a set of instance indices. Besides, the optimization phases of objective f and g are denoted by k_f and k_g, respectively. Then, the conflict level of f over g can be empirically estimated for instance i by measuring the following gap:

$$\delta^i_{g|f^*} = \frac{g^i_{k_f} - g^i_{k_g}}{g^i_{k_g}} \qquad \forall i \in \mathscr{I}$$

For a set of representative instances, the distribution of gaps $(\delta^i_{g|f^*})_{i\in\rangle}$ for any pair of objectives (f,g) provides a good insight of how objective f conflicts with g, especially through the mean, standard deviation and extrema.

6.2 Numerical Results

Using the metric described in Definition 3, the scheduler calculations are analyzed: the values of $\delta^i_{g|f^*}$ are computed for every execution i and every relevant pair of objectives (f,g), namely:

- $\min \sum_r \mu_r$ on criteria $\sum_{(j,j')} (C_{j'} - C_j)$ and $\sum_j \omega_j \frac{C_j}{p_{j,m}}$;
- $\max \sum_{(j,j')} |B_{(j,j'}|$ on criteria $\sum_{(j,j')} (C_{j'} - C_j)$ and $\sum_j \omega_j \frac{C_j}{p_{j,m}}$;
- $\min \sum_{(j,j')} (C_{j'} - C_j)$ on criterion $\sum_j \omega_j \frac{C_j}{p_{j,m}}$.

Some of the pairs of criteria cannot be considered due to the lexicographical approach, as the value of criterion g is fixed by a constraint for all iterations $k > k_g$. Hence, only the impact of an objective f preceding g in the lexicographical order can be considered to estimate the impact of f_{k_f} on g_{k_f}. Additionally, it is worth noting that the values of criterion $\max \sum_{(j,j')} |B_{j,j'}|$ have not be saved in the archives, which explains that the effect of criterion $\min \sum_r \mu_r$ on criterion $\sum_{(j,j')} |B_{j,j'}|$ has not been studied in the following.

Table 1 summarizes the main trends of the distribution of $(\delta^i_{g|f^*})_{i\in\mathscr{I}}$, namely the average, the standard deviation and the extrema. Firstly, a global analysis of the gap provides some evidence that none of the considered objectives in the photolithography area is redundant, as optimizing one criterion leads to both a large maximal and average deteriorations of the other criteria. Indeed, the maximum gap over all pairs (f,g) is higher that 48%, and exceeds 24 times the value g_{k_g} when $g = \sum_{(j,j')} (C_{j'} - C_j)$). Similar trends can be noticed for the average gap, which is in the order of 15% for $\sum_j \omega_j \frac{C_j}{p_{j,m}}$ and 115% for $\sum_{(j,j')} (C_{j'} - C_j)$. However, minimal values of the gap, that are close to zero, show that, even when no general dominance between the criteria holds, some configurations of the work in progress and of the area make the criteria almost not conflicting. Thus, a more in-depth analysis of instances with zero gap might help to identify potential restrictive criteria leading to a dominance relation between criteria.

Regarding the relationships between the considered objectives, Table 1 provides some useful indications on a potential rework of the lexicographic order. On the one hand, note that optimizing the area efficiency by minimizing the number of reticle moves or maximizing the length of serial batches of jobs leads to a strong risk of deteriorating the value of the maximum time lag constraints, as illustrated by the the very scattered values of the gap with a large average. This result encourages to minimize the risk of maximum time lag constraint earlier in lexicographic order. On the other hand, it can be seen that $\max \sum_{(j,j')} |B_{(j,j'}|$, $\min \sum_{(j,j')}(C_{j'} - C_j)$ and, to a lesser extent, $\min \sum_r \mu_r$ have a more moderate impact on the X-factor.

Table 1: Main trends of the distribution of $(\delta^i_{g|f^*})_{i\in\mathscr{I}}$ for pairs of successive criteria (f,g) computed over a set with 5,132 computations.

Criteria (f,g)		Main trends of the gap distribution $\delta_{g\|f^*}$			
Objective f	Criterion g	Min.	**Average**	*Std dev.*	Max.
$\min \sum_r \mu_r$	$\sum_{(j,j')}(C_{j'} - C_j)$	0%	**126%**	*255%*	2448%
$\min \sum_r \mu_r$	$\sum_j \omega_j \frac{C_j}{p_{j,m}}$	1%	**17%**	*9%*	72%
$\max \sum_{(j,j')} \|B_{j,j'}\|$	$\sum_{(j,j')}(C_{j'} - C_j)$	0%	**109%**	*238%*	2400%
$\max \sum_{(j,j')} \|B_{j,j'}\|$	$\sum_j \omega_j \frac{C_j}{p_{j,m}}$	0%	**12%**	*6%*	58%
$\min \sum_{(j,j')}(C_{j'} - C_j)$	$\sum_j \omega_j \frac{C_j}{p_{j,m}}$	1%	**13%**	*6%*	48%

7 CONCLUSIONS AND PERSPECTIVES

In this paper, a list of scheduling objectives currently used in the semiconductor industry are presented and positioned with respect to the literature and classical objectives. In order to analyze the efficiency of multi-criteria schedulers, a formal analysis of the relationships between the criteria is conducted by introducing the notion of dominance between criteria. The resulting study demonstrates that no dominance relation holds in wafer fabrication facilities. This formal analysis is then completed by an experimental study of the conflict level between the criteria considered in the photolithography area. Numerical results validate that no redundancy can be found among several criteria, but that local dominance exists under certain conditions. Some useful indications regarding the lexicographical order of criteria are also derived from the statistical measures.

The experimental study can be extended to separately study every pair of criteria outside the real-time optimization conditions. By computing the Pareto frontier, dominance and conflict level between criteria can be better assessed using correlation and the area below the front, but such experiments are considerably more costly from a computational perspective.

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