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MAINTENANCE WITH PRODUCTION PLANNING CONSTRAINTS IN SEMICONDUCTOR MANUFACTURING

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ABSTRACT

In semiconductor manufacturing, as in most manufacturing contexts, preventive maintenance is required to avoid machine failures and to ensure product quality. In this paper, we are interested in optimally planning maintenance operations given a production plan that must be satisfied. Two Integer Linear Programming models are proposed that aim at completing as many maintenance operations as possible and as late as possible, while respecting their deadlines and the capacity constraints on machines. Computational experiments on industrial data are presented and discussed.

1 INTRODUCTION

1.1 Overview

Semiconductor manufacturing requires very complex and expensive machines to produce integrated circuits. Thus, machines should be used as much and as effectively as possible. Although they are time-consuming and usually require machines to be stopped, Preventive Maintenance (PM) operations are necessary to prevent machine failures and ensure product quality. Each maintenance operation must be planned within a given time window, and if possible, as close to the last period of the time window as possible. This is because postponing a maintenance operation on a machine means postponing the next maintenance operation on the machine, and thus reducing the idle time of the machine.

Usually, maintenance is planned first, and then production is planned with the remaining capacity on the machines. In this paper, we consider that the production plan is first given as workloads (also called Work-In-Process, WIP) to be processed on families of identical machines per period on a given horizon. Then, maintenance operations are planned on the machines with the remaining capacity, but the production workload can still be balanced between machines in the same family. In this way, maintenance does not negatively impact production and thus the global efficiency of the manufacturing facility (fab). Unlike the work of (Kalir, Rozen, and Morrison 2017) which considers the impact of maintenance on the availability of machines, our model is not explicitly taking Critical Queue Time restrictions into account, because the production plan is given and must satisfy queue time constraints. Moreover, our goal is to use the availability of machines in the production plan to plan the maintenance operations and avoid impacting production.

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1.2 Literature Review

Most of the time, both in industry and in research, maintenance and production are planned independently, either maintenance first and the production or the opposite. In the former case, maintenance operations are first planned, and then production is planned by reducing the capacity of the machines accordingly (Christ, Dauzère-Pérès, and Lepelletier 2019). In the second case, production quantities are first planned, and then maintenance operations by considering production constraints. These two cases do not always lead to an optimal use of the machines, but they help to solve the overall maintenance and production-planning problem. However, the flexibility at both decision levels is not used to improve both the maintenance plan and the production plan.

There are already some papers that have studied the integration of production and maintenance planning decisions. (Abdelrahim and Vizvári 2017) are focusing on the scheduling of production and preventive maintenance operations. (Pan, Liao, and Xi 2012) propose a model to optimize the scheduling of production and maintenance operations on one machine subject to degradation. In his Ph.D thesis, (Cai 2008) studies the scheduling of production and maintenance operations on a single machine with two recipes. The large number of machines and recipes in a semiconductor manufacturing facility makes the integrated scheduling problem very complex. Therefore, the approaches proposed in the literature are often not feasible in this context. Moreover, as maintenance operations need to be planned in advance, maintenance and production schedule do not support medium-term planning. Hence, production planning on a longer horizon at the tactical level is also very relevant.

The joint planning of maintenance and production is studied in (Alaoui-Selsouli, Mohafid, and Najid 2012) and (Cheng, Zhou, and Li 2017). (Davenport 2010) presents a mixed-integer linear programming model for predictive maintenance planning. The model aims at resource leveling of the maintenance technicians and at minimizing the impact of maintenance operations on the production while respecting maintenance constraints as much as possible. A simulation is used to predict the workload on each machine into one-hour periods. According to the author, the model can be used on a horizon of two weeks. (Assid, Gharbi, and Hajji 2015) are proposing joint production and maintenance policies for one machine. A discrete-event simulation is used in (Scholl, Mosinski, Gan, Lendermann, Preuss, and Noack 2012) to know when some machines will be less loaded and then plan the maintenance. The results of the short-term model provide a forecast of the workload of each machine in the following week. Also, maintenance operations are not automatically planned. Moreover, it is not possible to know how to consolidate preventive maintenance operations. (Chang, Ni, Bandyopadhyay, Biller, and Xiao 2007) describe how to use opportunity windows to plan maintenance in order to have as much production time as possible. (Yao, Fu, Marcus, and Fernandez-Gaucherand 2001) present a model that schedules preventive maintenance tasks to increase the availability of machines. In our paper, instead of using the workload for each machine, the workload of each family of identical machines is considered, and thus can be balanced to free machines. (Chan, Tan, Subramaniam, and Ong 2006) propose a control system to know when is the best time to perform maintenance according to the forecast of the workload of the machine. (Yao, Fernández-Gaucherand, Fu, and Marcus 2004) present a mixed-integer linear programming model to plan preventive maintenance, that is able to consolidate preventive maintenance operations.

(Kalir 2013) and (Kalir, Rozen, and Morrison 2017) explicitly consider the impact on machine availability of joint production and maintenance policies in a G/G/*m* system. Our context is very different, since we are considering production planning with a dynamic demand on a finite planning horizon, and that each maintenance operation requires a given processing time, i.e., the time that the associated machine must be stopped, and must be performed within a given time window.

1.3 Contributions and Organization of the Paper

Our goal is to propose a model that optimizes the periods in which preventive maintenance operations are performed on machines in a workshop on a planning horizon, with an application to semiconductor manufacturing. Preventive maintenance operations must be planned when machines are available, i.e., not used for production, to avoid impacting the production plan. Maintenance operations are also constrained by a time window in which they must be planned, and as late as possible.

This paper is organized as follows. Section 2 introduces the optimization model. Then, in Section 3, computational results on industrial data from a 300mm wafer manufacturing facility are presented and discussed. Section 4 concludes the paper and proposes some perspectives.

2 MATHEMATICAL MODELING

2.1 Problem Description

Our goal is to plan O preventive maintenance operations on M machines grouped in F families (machines in a family are identical) and on a planning horizon of P periods. Each maintenance operation o requires d_o time units and must be performed on machine m_o in family f_o after period e_o and before period l_o. An operation o can only be planned in period p if $c_{m_o,p}$, the production capacity of machine m_o in period p, is not violated, i.e., if $d_o \leq c_{m_o,p}$.

The operational planning tool presented in (Christ, Dauzère-Pérès, Lepelletier, and Vialletelle 2018) is used to determine the production workload (or WIP) $w_{f,p}$ on machine family f in each period p of the planning horizon. Hence, operation o can only be planned in period p if the production capacity of machine family f_o in period p is not violated, i.e., if $w_{f_o,p} + d_o \leq \sum_{m=1;f_m=f_o}^{M} c_{m,p}$, where f_m denotes the family of machine m. The important characteristic of our problem is that the workload of identical machines in a family can be balanced to free (totally or partially) a machine and allow one or more maintenance operations to be performed.

2.2 Notations

The parameters of our mathematical models are listed below:

- P: Number of periods in the planning horizon,
- M: Number of machines,
- F: Number of machine families,
- f_m: Family of machine m,
- $w_{f,p}$: Production workload (or WIP) on machine family f in period p,
- $c_{m,p}$: Production capacity of machine m in period p,
- O: Number of maintenance operations,
- m_o: Machine on which maintenance operation o should be performed,
- d_o: Processing time of operation o,
- e_o: Earliest period in which operation o can be planned,
- l_o: Latest period in which operation o can be planned,
- ω_o: Weight of operation o, the larger ω_o the more important is the maintenance operation.

The following decision variables are used in the mathematical models:

- $S_{o,p} \in \{0,1\}$: Is equal to 1 if operation o is performed in period p, and to 0 otherwise,
- $I_o \in \{0,1\}$: Is equal to 1 if operation o is not planned, and to 0 otherwise.

2.3 Integer Linear Programming (ILP) Models

First, the approach introduced in (Christ, Dauzère-Pérès, Lepelletier, and Vialletelle 2018) is used to determine the values of the production workloads $w_{f,p}$, which are inputs of our maintenance planning model (MPM1) formalized below:

$$\min \sum_{o=1}^{O} \left(P^2 \omega_o I_o + \sum_{p=e_o}^{l_o} (l_o - p)^2 S_{o,p} \right) \tag{1}$$

$$\sum_{o=1;\ m_o=m}^{O} d_o S_{o,p} \leq c_{m,p} \qquad \forall p \in \{1,\dots,P\}, \forall m \in \{1,\dots,M\} \tag{2}$$

$$\sum_{o=1;\ f_{m_o}=f}^{O} d_o S_{o,p} \leq \sum_{m=1;\ f_m=f}^{M} c_{m,p} - w_{f,p} \qquad \forall p \in \{1,\dots,P\}, \forall f \in \{1,\dots,F\} \tag{3}$$

$$\sum_{p=e_o}^{l_o} S_{o,p} + I_o = 1 \qquad \forall o \in \{1,\dots,O\} \tag{4}$$

$$S_{o,p} \in \{0,1\} \qquad \forall o \in \{1,\dots,O\}, \forall p \in \{1,\dots,P\} \tag{5}$$

$$I_o \in \{0,1\} \qquad \forall o \in \{1,\dots,O\} \tag{6}$$

The objective function (1) first aims to maximize the number of planned operations, i.e., for all variables I_o to be equal to 0, and then to minimize the earliness of maintenance operations. The parameter P^2 ensures that minimizing $\sum_{o=1}^{O} I_o$ is prioritized. A quadratic penalty is used because two maintenance operations early by one day is preferred to one maintenance operation early by two days. In other words, maintenance operations that are too early should be avoided. The weight ω_o is used to prioritize some maintenance operations. The earliness is weighted by $(l_o - p)^2$, i.e., the quadratic difference between the latest period to plan o and the period in which o is performed, to avoid a linear penalty. More precisely, completing two maintenance operations 3 periods before their latest periods is preferable than completing one operation 6 periods before its latest period and one operation exactly at its latest period. Constraints (2) ensure that it is not possible to plan more maintenance operations on a machine than the production capacity of the machine in each period. Constraints (3) ensure that it is not possible to plan more maintenance operations on the machines in a family than the production capacity of the family in each period. This production capacity is the sum of the production capacity of all the machines in the family minus the production workload on the family. Hence, it is possible to increase the workload of one machine in a family to free another machine in the family for a maintenance operation, as long as the overall production capacity of the family is satisfied. Constraints (4) guarantee that either maintenance operation o is planned between e_o and l_o, i.e., $\sum_{p=e_o}^{l_o} S_{o,p} = 1$, or is not planned, i.e., $I_o = 1$. Constraints (5) and (6) are the integrality constraints.

In our computational experiments, we also investigate a second maintenance planning model (MPM2) by relaxing Constraints (2) and (3). We now consider that the maintenance capacity can be distributed on non-overlapping pairs of consecutive periods, i.e., on periods 1 and 2, on periods 3 and 4 and so on until periods $P-1$ and P. Without loss of generality, we are assuming that the number of periods P is even. Capacity constraints (2) and (3) in (MPM1) are replaced by the following constraints. In this model, there is still no trade-off with manufacturing performance. A maintenance operation can start at the end of a period and be completed at the beginning of the next period.

$$\sum_{o=1;\ m_o=m}^{O} d_o (S_{o,2p-1} + S_{o,2p}) \leq c_{m,2p-1} + c_{m,2p} \qquad \forall p \in \{1,\dots,\frac{P}{2}\}, \forall m \in \{1,\dots,M\} \tag{7}$$

$$\begin{aligned} &\sum_{o=1;\ f_{m_o}=f}^{O} d_o (S_{o,2p-1} + S_{o,2p}) \\ &\qquad \leq \sum_{m=1;\ f_m=f}^{M} (c_{m,2p-1} + c_{m,2p}) - w_{f,2p-1} - w_{f,2p} \qquad \forall p \in \{1,\dots,\frac{P}{2}\}, \forall f \in \{1,\dots,F\} \end{aligned} \tag{8}$$

Constraints (2), resp. (3), ensure that the production capacity is satisfied at machine level, resp. at machine family level, on all pairs of periods $(2p-1,\, 2p)$, $\forall p \in \{1,\ldots,\frac{P}{2}\}$.

3 COMPUTATIONAL EXPERIMENTS

3.1 Design of Experiments

The proposed integer linear programming models have been implemented with Python 3.7 using Pulp 1.6.8 with IBM ILOG CPLEX 12.8 on a computer with a CPU Intel(R) Core (TM) i5-7200U at 2.7 GHz and 8 GB of RAM.

The production plans and the data related to the maintenance operations were obtained from our industrial partner and used to generate 12 different instances. For all instances, the planning horizon is equal to 60 periods of 24 hours, and only preventive maintenance operations of machines in the same workshop are considered. Because the industrial data were extracted at least a week apart, the number of maintenance operations differs from one instance to another. In this preliminary investigation, the weight ω_o is fixed to 1 for each maintenance operation o. The impact of selecting different values ω_o is an interesting perspective.

We assume that each machine is fully available for maintenance in each period, i.e., $c_{m,p} = 24$ hours $\forall p \in \{1,\ldots,P\}$, $\forall m \in \{1,\ldots,M\}$. The capacity constraints associated to manufacturing the quantities in the production plan, i.e., to the production workloads $w_{f,p}$, are on the machine families as shown in Constraints (3) and (8).

3.2 Numerical Results

The production plan is first generated for the 12 instances using the approach summarized in (Christ, Dauzère-Pérès, Lepelletier, and Vialletelle 2018) to initialize the values of $w_{f,p}$. For each instance, the CPU times to optimally solve the maintenance planning models are always smaller than 1 second although the models are quite large. As an example, for the first instance, there are close to 4,400 decision variables and 5,200 constraints in (MP1), and 2,200 decision variables and 2,700 constraints in (MP2). The small CPU times are probably related to the limited degree of flexibility, which is due to many periods when machines are not available enough to perform any maintenance operation.

Figure 1 is used to illustrate the problem and the optimal maintenance plan determined by model (MP1) for the first instance. Each row in the figure corresponds to a maintenance operation, and the label of each row should be read as follows: "Id of the maintenance operation (Family Id, Machine Id)". A box in a row which is not white means that the period is in the time window of the maintenance operation. For example, the time window of maintenance operation 5 ranges from periods 4 to 13. The box is black when there is not enough capacity in the period to plan the maintenance operation, and the box is gray if there is enough capacity. For example, maintenance operation 1 can be performed in any period in its time window, whereas maintenance operation 7 cannot be planned in its time window. A box with a "1" is the period in which the maintenance operation is planned in the optimized maintenance plan. Maintenance operation 19 is planned in period 2, whereas maintenance operation 23 is not planned. Maintenance operation 3 is not planned in the last period of its time window, because of a conflict with maintenance operation 8 that must be performed on the same machine. Maintenance operation 5 is planned after maintenance operation 2 on machine 1, because the objective function (1) prioritizes the maintenance operation in a period that is the furthest from the last period in its time window. Note that there is no conflict for machine family 14, because there are only few maintenance operations to perform in the next 60 periods. Thus, all the maintenance operations of machine family 14 are planned in the last period of their time windows.

The results for the 12 instances are summarized in Table 1. The first column corresponds to the instance number, and the second column to the number of maintenance operations to be planned in the instance. For each instance, there is one row for the results obtained with (MPM1) and one row for the results obtained with (MPM2). Column "Min." under "Unplanned (%)" is the percentage of maintenance operations that

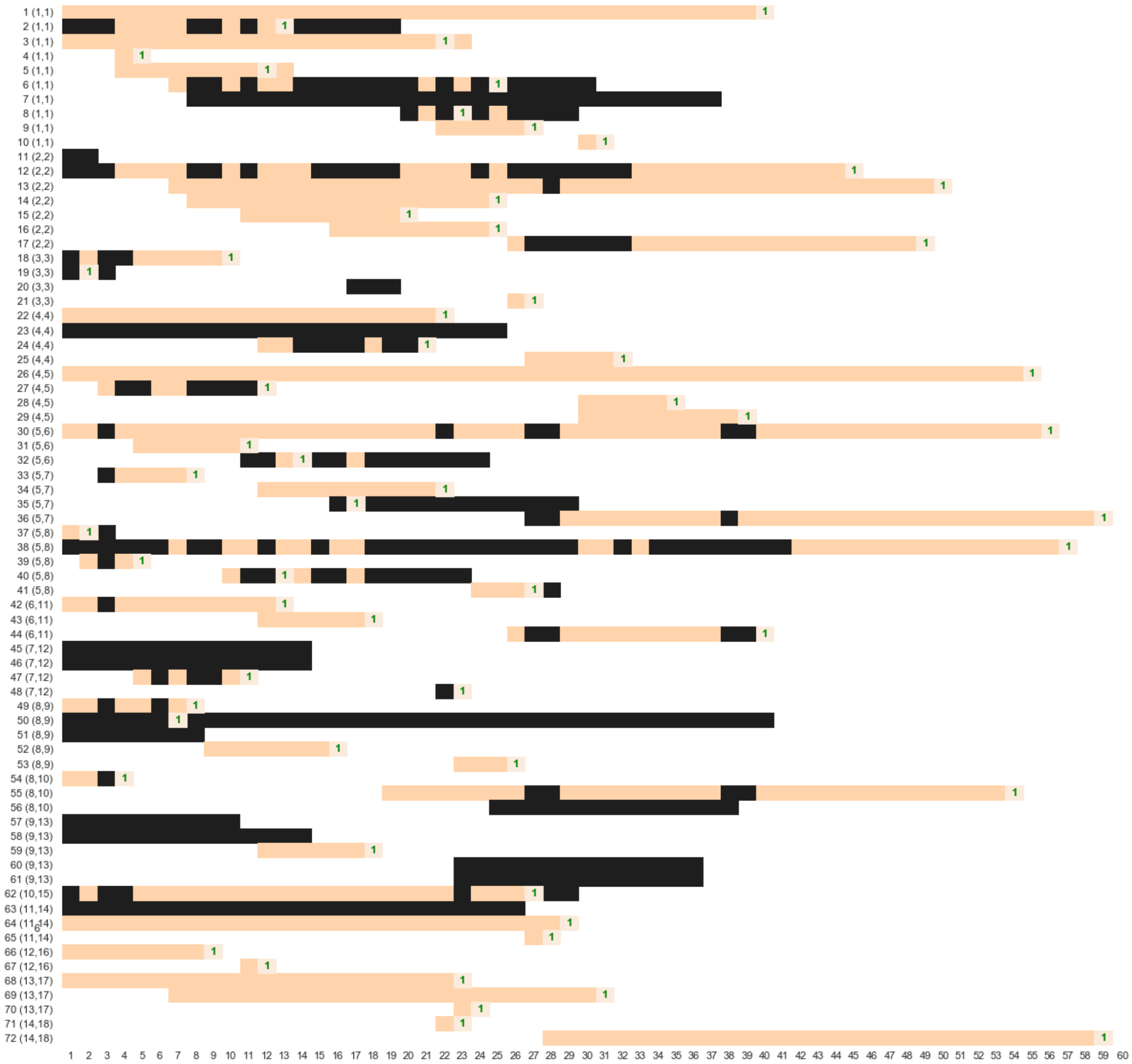

Figure 1: Optimal maintenance plan for instance 1 obtained with model (MPM1).

are known to be infeasible before starting the optimization. Indeed, some maintenance operations cannot be planned even though they do not compete with others, since there is never enough capacity in their time window. Column ”Optim.” under ”Unplanned (%)” is the percentage of maintenance operations after solving the optimization model. The percentage in Column ”Optim.” is thus always lower than or equal to the percentage in Column ”Min.” More precisely, when considering for example the first instance, 18.1% of the operations could not be planned when solving (MPM1) but also 18.1% could not be planned when calculating from the data by only checking Constraints (3) (Constraints (8) for (MPM2)). Hence, the value in the second column must be larger than the one in the first column. Note that there is a difference between the two columns only for Instances 7 and 10 for (MPM1). The three columns under ”Operations” provide the mean, minimum and maximum of the number of maintenance operations that are planned by period. The last column shows the total earliness of the maintenance operations, which is the sum of the differences between the latest period in which an operation is planned and the period in which it is actually planned, i.e., $\sum_{o=1}^{O}\sum_{p=e_o}^{l_o}(l_o-p)S_{o,p}$.

Table 1: Numerical results obtained with models (MPM1) and (MPM2) on 12 industrial instances.

			Operations					
			Unplanned (%)		**Planned by period**			**Earliness (days)**
Inst.	**O**	**Model**	**Min.**	**Optim.**	**Mean**	**Min**	**Max**	
1	72	(MPM1)	18.1%	18.1%	0.98	0	4	89
		(MPM2)	7.8%	7.8%	1.08	0	4	12
2	77	(MPM1)	39.0%	39.0%	0.78	0	6	38
		(MPM2)	7.8%	7.8%	1.18	0	5	12
3	82	(MPM1)	35.4%	35.4%	0.88	0	5	39
		(MPM2)	7.3%	7.3%	1.27	0	5	11
4	80	(MPM1)	38.8%	38.8%	0.82	0	2	27
		(MPM2)	7.5%	8.8%	1.22	0	5	11
5	81	(MPM1)	30.9%	30.9%	0.93	0	4	24
		(MPM2)	3.7%	3.7%	1.30	0	5	11
6	85	(MPM1)	22.4%	22.4%	1.10	0	5	41
		(MPM2)	4.7%	4.7%	1.35	0	6	9
7	84	(MPM1)	16.7%	17.9%	1.15	0	6	59
		(MPM2)	2.4%	2.4%	1.37	0	5	11
8	84	(MPM1)	14.3%	14.3%	1.20	0	7	40
		(MPM2)	3.6%	3.6%	1.35	0	7	19
9	87	(MPM1)	14.3%	19.5%	1.17	0	5	47
		(MPM2)	3.5%	3.5%	1.40	0	5	0
10	97	(MPM1)	16.5%	17.5%	1.33	0	5	43
		(MPM2)	1.0%	1.0%	1.60	0	9	2
11	88	(MPM1)	11.4%	11.4%	1.30	0	8	53
		(MPM2)	1.1%	1.1%	1.45	0	7	0
12	94	(MPM1)	10.6%	12.8%	1.37	0	6	70
		(MPM2)	0.0%	0.0%	1.57	0	6	5

Let us recall that using (MPM1), each maintenance operation cannot exceed one period, while for (MPM2), a maintenance operation can be planned on predefined and non-overlapping pairs of consecutive periods. Hence, because more flexibility and thus capacity is provided in (MPM2), the number of planned operations is always much larger with (MPM2) compared to (MPM1), but also the total earliness is significantly decreased with (MPM2). For example, for Instance 2, the number of unplanned operations, resp. the total earliness, decreases from 39% to 7.8%, resp. from 38 days to 12 days, when solving (MPM2) instead of (MPM1). Hence, the effect of relaxing Constraints (2) and (3) in (MPM2) is significant.

When some maintenance operations cannot be planned by the optimization model, but could be planned when only considering the data (such as in Instance 4 and (MPM2) with 7.5% in column "Data" and 8.8% in column "Model"), then prioritizing critical operations could be relevant. This can be done by increasing their weight ω_o in the objective function, thus ensuring that they will be more likely planned.

However, note that, even with (MPM2) and in all instances, there is only one with all maintenance operations that can be planned, although all maintenance operations have to be planned in practice. However, the proposed planning can still provide insights to the people in charge of maintenance planning. They can use the planning as a basis for discussion with the production planners. Our current research aims at proposing an integrated production and maintenance plan to ensure that all maintenance operations will be planned.

Another point is that the number of maintenance operations by period is not constrained in (MPM1) and (MPM2). This number reaches 9 in Instance 10 for (MPM2). Performing too many operations in a day could be a problem in days when there are not enough maintenance operators. Taking maintenance capacity into account is also part of our current research. A first approach consists in adding constraints in (MPM1) and (MPM2) that limit the number of operations per period.

4 CONCLUSIONS AND PERSPECTIVES

In this paper, we studied the problem of optimally planning preventive maintenance operations on a given time horizon, while satisfying the time windows of the maintenance operations and constraints induced by a production plan. The objective is primarily to plan as many operations as possible, and secondly to plan operations as late as possible in their time window. Because the production requirements in terms of workload are given for each family of machines and not for each machine, a machine can be freed to perform a maintenance operation by increasing the workload of another machine. Two integer linear programming models were proposed, the second one with more flexibility than the first one. Computational experiments on industrial data were discussed. The numerical results enabled the two mathematical models to be compared, showing that the second one provides much better maintenance plans, both in terms of number of unplanned maintenance operations and of total earliness.

This research opens various perspectives. As mentioned in Section 3.2, in our current research, we investigate how to take maintenance capacity into account and, more importantly, how to determine an integrated production and maintenance plan. To tackle the last point, the simultaneous optimization of maintenance and production criteria is required, and thus should lead to the development of multi-objective optimization approaches. Also, by changing the qualifications of machines, i.e., the set of products each machine is able to perform (see (Johnzén, Vialletelle, Dauzère-Pérès, Yugma, and Derreumaux 2008) and (Johnzén, Dauzère-Pérès, and Vialletelle 2011)), additional flexibility can be obtained, allowing for improved maintenance planning.

Another perspective is to consider some health indicators of the machines to adjust the maintenance time windows. For instance, (Munirathinam and Ramadoss 2014) present some methodologies on how to use machine data to determine a health score for machines that can help to better plan maintenance operations. Robust optimization approaches could be relevant since, as underlined in (Géhan, Castanier, and Lemoine 2014), the failures of machines can make the planning not reliable.

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