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OPTIMISATION OF SEQUENTIAL INSPECTION SCHEMA IN MULTI-COMPONENT DETERIORATING SYSTEM CONTEXT: HEURISTIC BASED APPROACH

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ABSTRACT: *This paper considers a condition-based maintenance policy for a system composed of m independent machines deteriorating system. Each machine is subject to stochastic degradation. The machines are maintained by spare parts provided either from supplier or from the remanufacturing centre. Three thresholds are used in our CBM policy, two for the corrective and preventive replacement and one for the order management. A new heuristic is proposed under two versions to calculate the sequential non-periodic inspection dates. A numerical example is presented to compare the proposed methods.*

KEYWORDS: *Inspection, Heuristic, Condition based maintenance, Remanufacturing, Spare parts.*

1 INTRODUCTION

For a production system that is subject to stochastic degradation, it is important to know the level of degradation of the system, in order to avoid failure and its possible negative effects, by preventive maintenances. For this reason, a maintenance policy known as the condition based maintenance has been developed (Grall et al., 2002) (Zhao et al., 2010). It is based on knowledge of the degradation level of the system in order to make decisions vis-a-vis the maintenance actions to carry out. The knowledge of the level of degradation is carried via a monitoring system. The system monitoring is made under different ways: continuous monitoring, periodic inspection or sequential inspection. The chosen monitoring type depends on the nature of the studied system. The continuous monitoring (Barata et al., 2002) is used in the case where monitoring can be implemented, to detect the degradation level, with a low cost. Generally, this type of monitoring is carried out by sensors, which automatically returns the information to a control computer. The Periodic (Wang et al., 2008) and the sequential (Castanier et al., 2003) (Golmakani and Moakedi, 2013) inspections are used in the case where the sensors cannot be implemented, which requires a human intervention.

The condition based maintenance is based on three parameters: degradation variation, degradation level monitoring and decision thresholds. According to the decision thresholds, the condition based maintenance may be applied under two different policies: control limit policy and multi-level control limit policy. The control limit policy (Saassouh et al., 2007) uses mainly two decision thresholds, one for the preventive maintenance management and the second one for the corrective maintenance

management. Another version of this policy may include a third threshold decisions, which manages the order of the spare part used for maintenance (Wang et al., 2009). The multi-level control limit policy (Castanier et al., 2005) uses several decision thresholds, some of them are used for inspection planning.

In this work, we address the problem of planning of inspection dates, for a system subject to a stochastic and monotone increasing degradation. The system is composed of m independent machines. Their maintenance requires spare parts, which is supplied set from two sources: the remanufacturing center or a supplier. The remanufacturing center uses the part recovered from the machines at the replacements in order to remanufacture them and reuse them in other replacements. Our objective is to propose a heuristic to calculate the intervention dates on machines. The heuristic is based on a heuristic proposed in (Boudhar et al., 2013), which was applied in the case of a single machine.

The remainder of the paper is organized as follows. Section 2 is dedicated to describe the problem in details. In the section 3 develop the adopted policies. A mathematical formulation and the proposed heuristic are presented in section 4. Section 5 is dedicated to a numerical example. Some concluding remarks are presented in section 6.

2 PROBLEM STATEMENT

2.1 System characteristics

We consider a production system consists of m independent machines M_i , $i=1...m$. Each machine is subject to a stochastic degradation, and can be maintained by preventive or corrective replacement. The spare parts used for the replacement are drawn from a

stock $S1$. For feeding the stock $S1$, we can order a spare part either from an external supplier or from the internal remanufacturing center. In order to meet orders, the remanufacturing center uses parts stored in the stock $S2$. These parts are retrieved from the machine at the replacement. Before being placed in the stock $S2$, the parts retrieved from the machine are classified according to their degradation level into n qualities. The parts of qualities $j=1\dots n-1$, are reusable and the parts of qualities n are intended for disposal. The remanufacturing center can carry out remanufacturing actions upon the selected part to improve its quality, by reducing its degradation level. Figure 1 describes the system components.

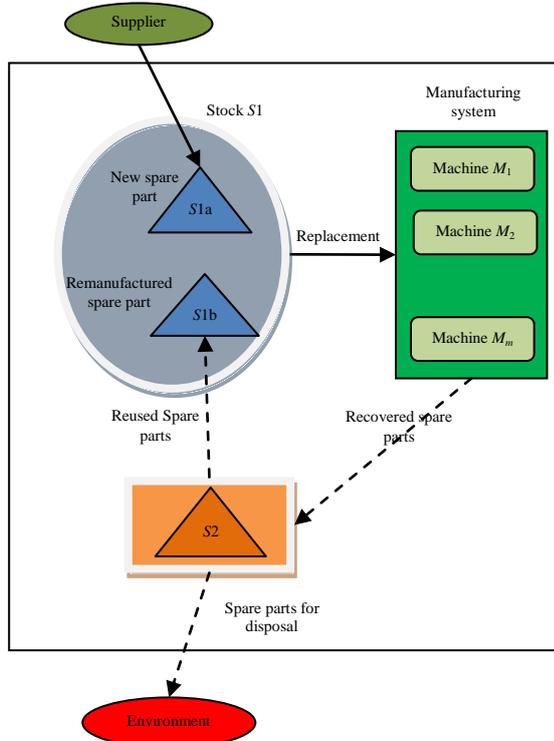


Figure 1: System description

Each machine is considered as a monolithic system, the spare part used for the replacement is the main part of the machine; therefore, the machines' state depends on the state of spare part. Let $d_i(t)$ the degradation level of the machine i at the time t . The machines degradation is supposed to be monotonically increasing. Between two times $t-1$ and t , the degradation level $d_i(t)$ of the machine i is incremented by a value a_j , where a_j is a uniform random variable that depends on the spare part quality. The degradation process is represented by the equation (1). We assume that degradation process accelerates when the quality level increases (Saassouh et al., 2007):

$$d_i(t) = d_i(t-1) + a_j, \quad i = 1, \dots, m \text{ and } j = 1, \dots, n-1 \quad (1)$$

Where: $a_j^{\min} \leq a_j \leq a_j^{\max}$ and $0 < a_j^{\max} \leq a_{j+1}^{\min}$.

3 THE CONDITION-BASED MAINTENANCE AND SPARE PARTS

3.1 Spare parts quality

The spare parts are classified into n qualities. This classification is correlated to the degradation level of the spare parts. Let $Q_j = [Q_j^{\min}, Q_j^{\max}]$ the degradation interval that defines the quality j . Therefore, as long as the part degradation level $d(t)$ belongs to the interval Q_j , the part is considered as of quality $j, j=0, \dots, n$.

3.2 Spare parts supply and remanufacturing process

The spare parts supply is done in two possible ways, either from an external supplier or from the internal remanufacturing center.

The spare parts coming from the supplier are of quality 0 (new spare parts). They are designed, manufactured and distributed according to forward supply chain schema. The spare parts coming from the remanufacturing center are of quality $j, j=1, \dots, n-1$. They follow a closed loop supply chain schema: from a machine to a machine, passing through the remanufacturing center. The parts recovered from the machine at the replacement are classified into two categories: reused parts and parts intended for disposal. The reused parts are likely to go through a remanufacturing process before being installed in the machine at the replacement. The remanufacturing process reduces the part degradation level reached at its recovery; therefore, its quality is improved. The remanufacturing process cannot make the part of quality 0, and the best quality that we can achieve with the remanufacturing is the quality 1. The remanufacturing degree decision is made when the choice of spare part used for replacement is made.

3.3 Decision thresholds

The adopted condition-based maintenance is a control limit policy, based on three thresholds: d_s , d_r and d_{max} . The threshold d_s is used for the order management: if the detected degradation level is bigger than or equal to the threshold d_s , an order is placed for a spare part (form supplier or form remanufacturing center). The threshold d_r is used for the preventive replacement management: if the detected degradation level is bigger than or equal to the threshold d_r without reaching the threshold d_{max} , a preventive replacement is carried out, with the proviso that the ordered spare part is delivered. The threshold d_{max} is used for the corrective replacement management: if the detected degradation level is bigger than or equal to the threshold d_{max} , with the proviso that the ordered spare part is delivered.

3.4 Inspection policy

The degradation level is quantified by a perfect inspection that is carried out by a maintenance operator. Intervention requires human and material resources, which depend on the number of the machine to be inspected. The intervention cost consists of fixed cost and an inspection unit cost per machine.

The inspections are carried out according to a sequential plan, where the inspection dates are determined by the heuristic which is the subject of this work. The heuristic is presented in the section 4.

4 MATHEMATICAL MODEL AND PROPOSED APPROACH

In this paper, we study a complex system that requires decision making on three different aspects. The first decision is based on the choice of the quality of the spare part to be ordered, therefore, the order cost depend on the choice to order from the supplier (manufacturing) or from the remanufacturing center (remanufacturing). The second decision is based on the thresholds d_s and d_r , which have an important role in minimizing the total cost. They are used to determine the ideal time to place the order and make a preventive replacement respectively, to establish a balance between the various decisions and minimize the total cost. The last decision is based on the intervention plan, which serves to steer the decisions made throughout the horizon. The interventions dates are divided into two categories: interventions for inspection T_{insp} and interventions for replacement $T_{replace}$. These interventions are planned according to a sequential policy that is used to determine the intervention dates on each machine. The aim of this work is to propose an inspection plan based on a new heuristic (Heuristic-2), which aims to group together the dates of interventions, in order to minimize the total cost. The choice of the quality of the spare parts and the thresholds (d_s , d_r) is considered as data. The total cost to optimize is represented as a function of T_{insp} and the set of the machine $IM_{T_{inspection}}$ to be inspected at T_{insp} , i.e.

$f(T_{inspection}, IM_{T_{inspection}})$ given as following:

$$\min f(T_{insp}, IM_{T_{insp}}) = C_{Ireplace} + C_{Iinsp} + C_{insp} + C_{or} + C_{pr} + C_{cr} + C_s + C_p + C_{disp} \quad (2)$$

The considered costs are related to: intervention cost for a replacement $C_{Ireplace}$, intervention cost for an inspection C_{Iinsp} , the inspection cost C_{insp} , order cost C_{or} , preventive replacement cost C_{pr} , corrective replacement cost C_{cr} , storage cost of the ordered spare part C_s , down time cost C_p and disposal cost C_{disp} .

$$C_{Ireplace} = CU_{Ireplace} \times NIR \quad (3)$$

$$C_{Iinsp} = CU_{Iinspection} \times NII \quad (4)$$

$$C_{insp} = \sum_{i=1}^{NII} CU_{insp} \times NI \quad (5)$$

$$C_{or} = \sum_{r=1}^{NR} x_{qp}^r \times (CU_{or}^{qp} + C_{use}^{qp}) + \sum_{r=1}^{NR} z^r \times CU_{or} \quad (6)$$

$q = 1, \dots, p; p = 1, \dots, 3$

$$C_{pr} = \sum_{r=1}^{NR} P_{pr} \times CU_{pr} \quad (7)$$

$$C_{cr} = \sum_{r=1}^{NR} P_{cr} \times CU_{cr} \quad (8)$$

$$C_s = \sum_{r=1}^{NR} P_s \times CU_s \times ST_r \quad (9)$$

$$C_p = \sum_{r=1}^{NR} P_{cr} \times CU_p \times DT_r \quad (10)$$

$$C_{disp} = \sum_{r=1}^{NR} P_{cr} \times CU_{disp} \quad (11)$$

Where:

NIR : The number of interventions for replacement.

NII : The number of intervention for inspection.

NI : The total number of the inspection carried out throughout the mission time T_{miss} .

$$x_{qp}^r = \begin{cases} 1 & \text{if the quality } q \text{ is used for the replacement } r \\ & \text{by remanufacturing a spare part of quality } p \\ 0 & \text{otherwise} \end{cases}$$

$$z^r = \begin{cases} 1 & \text{if a spare part of quality } 0 \text{ is used} \\ & \text{at the replacement } r \\ 0 & \text{otherwise} \end{cases}$$

NR : The total number of the replacement carried out throughout the mission time T_{miss} .

P_{pr} : The probability to carry out a preventive replacement.

P_{cr} : The probability to carry out a corrective replacement.

P_s : The probability to storage the ordered spare part.

ST_r : Time of storage before the replacement r

DT_r : Downtime before the replacement r

The proposed heuristic is an extension of the heuristic (Heuristic-1) presented in (Boudhar et al., 2013), which is used for a single machine. The Heuristic-1 is based on a characteristic of the degradation, such that the degradation is bounded by two degradations scenarios: the best and the worst degradation scenario. The scenarios are given by the following equations:

$$d_i^B(t) = d_i^B(t-1) + a^{Min_j}, \quad i=1, \dots, m \text{ and } j=1, \dots, n-1 \quad (12)$$

$$d_i^W(t) = d_i^W(t-1) + a^{Max_j}, \quad i=1, \dots, m \text{ and } j=1, \dots, n-1 \quad (13)$$

Where: $d_i^B(t)$ and $d_i^W(t)$ are the best and the worst degradation level at the time t respectively.

The inspection dates given by Heuristic-1 are calculated based on the worst degradation scenario. Each inspection date is determined according to the degradation level detected on the machines at the previous inspection.

In this paper, we deal with the case of m independent machines. The dates proposed by the Heuristic-1 can coincide; in this case, a single intervention is required to inspect all machines. The dates proposed by the Heuristic-1 can be different, which requires different intervention by inspection technicians, and other interventions for replacements.

The dates proposed by Heuristic-1 will be divided into two categories: intervention dates for inspection and intervention dates for replacement. An intervention for inspection is planned at dates that correspond to either the earliest date or the latest date, among those proposed by Heuristic-1 for each machine. Thus, Heuristic-2 is proposed in two versions: Heuristic-2 V1, where the grouping is made with the earliest date; Heuristic-2 V2, where the grouping is made with the latest date. Machines to be inspected at the same date will be determined according to the rules (Rules-V1 and Rules-V2):

Before presenting the rules, we define the following dates:

For the Heuristic-2 V1:

Let $T_l := T_{M_h}^W$ be the earliest date of inspection, among those proposed by Heuristic-1, which correspond to the time when the worst degradation scenario of the machine M_h crosses the threshold d_s or d_r .

Let $T_{M_h}^B$ be the time when the best degradation scenario of the machine M_h crosses the threshold d_s or d_r (M_h is the same machine that gives T_l).

Let $\{i_1, \dots, i_{mi}\}$ the set of the machine to inspect and IM the set of machines that have to be inspected at T_l .

T_l and $T_{M_h}^B$ are calculated from the last intervention date made on the machine M_h .

Rules-V1:

For all $i \in \{i_1, \dots, i_{mi}\}$

If $(T_{M_h}^B > T_{M_i} > T_l)$ **then**

The machine M_i is included in the set IM with a

$$\text{probability } P_{M_i}^I = \left(\frac{T_{M_i} - T_l}{T_{M_h}^B - T_l} \right)$$

End If

End For

For the Heuristic-2 V2:

Let $T_l := T_{M_h}^W$ be the latest date of inspection, among those proposed by Heuristic-1, which correspond to the time when the worst degradation scenario of the machine M_h crosses the threshold d_s or d_r .

Let $\{i_1, \dots, i_{mi}\}$ the set of the machine to inspect and IM the set of machines that have to be inspected at T_l .

Let $T_{M_i}^W$ be the time when the worst degradation scenario of the machine M_i crosses the threshold d_s or d_r .

Let $T_{M_i}^B$ be the time when the best degradation scenario of the machine M_i crosses the threshold d_s or d_r .

Rules V2:

For all $i \in \{i_1, \dots, i_{mi}\}$

If $(T_{M_i}^B > T_l > T_{M_i}^W)$ **then**

The machine M_i is included in the set IM with a

$$\text{probability } P_{M_i}^I = \left(\frac{T_{M_i}^W - T_l}{T_{M_h}^B - T_l} \right)$$

End If

End For

The steps of Heuristic-2 V1 (Heuristic-2 V2) are given as follow:

1. Using Heuristic-1: Calculate the intervention dates for each machine.
2. Divide the dates proposed by Heuristic-1 into two categories: intervention dates for inspection and intervention dates for replacement.
3. Plan interventions for replacement at date given by Heuristic-1.
4. Plan an intervention for inspection at date that corresponds to the earliest date among those proposed by Heuristic-1.
5. Apply the rules Rules-V1 (Rule-V2) on the machines.
6. Repeat 1-5.

In the next part of the paper, we want to compare the Heuristic-2 with its version and the case when we don't apply the Heuristic-2.

The following figure illustrates the results of the application of the three methods on the same example, with two machines:

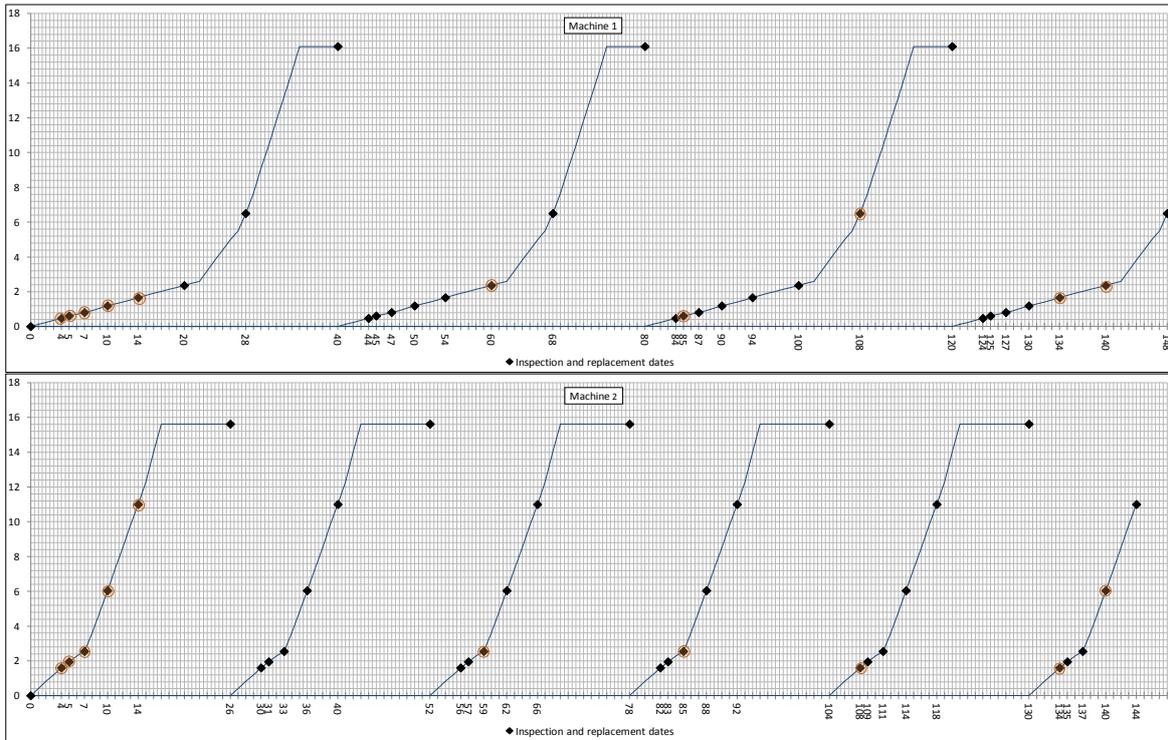


Figure 2a: Inspection and replacement dates without Heuristic-2

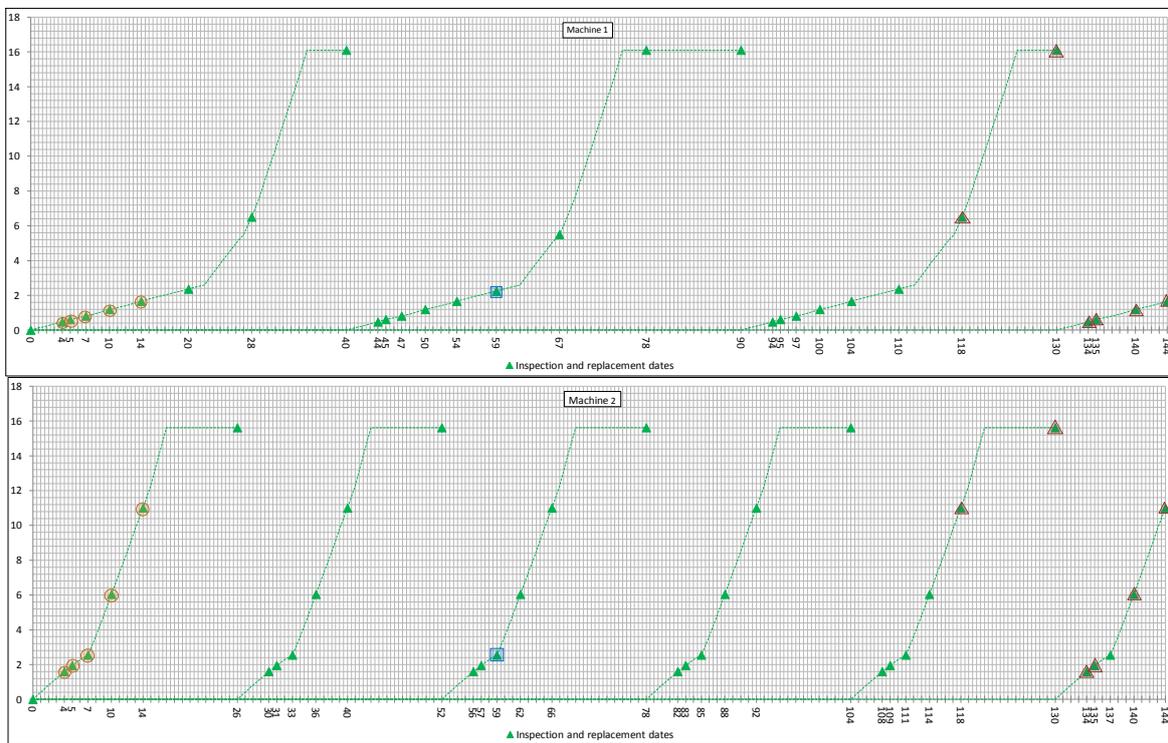


Figure 2b: Inspection and replacement dates with Heuristic-2 V1

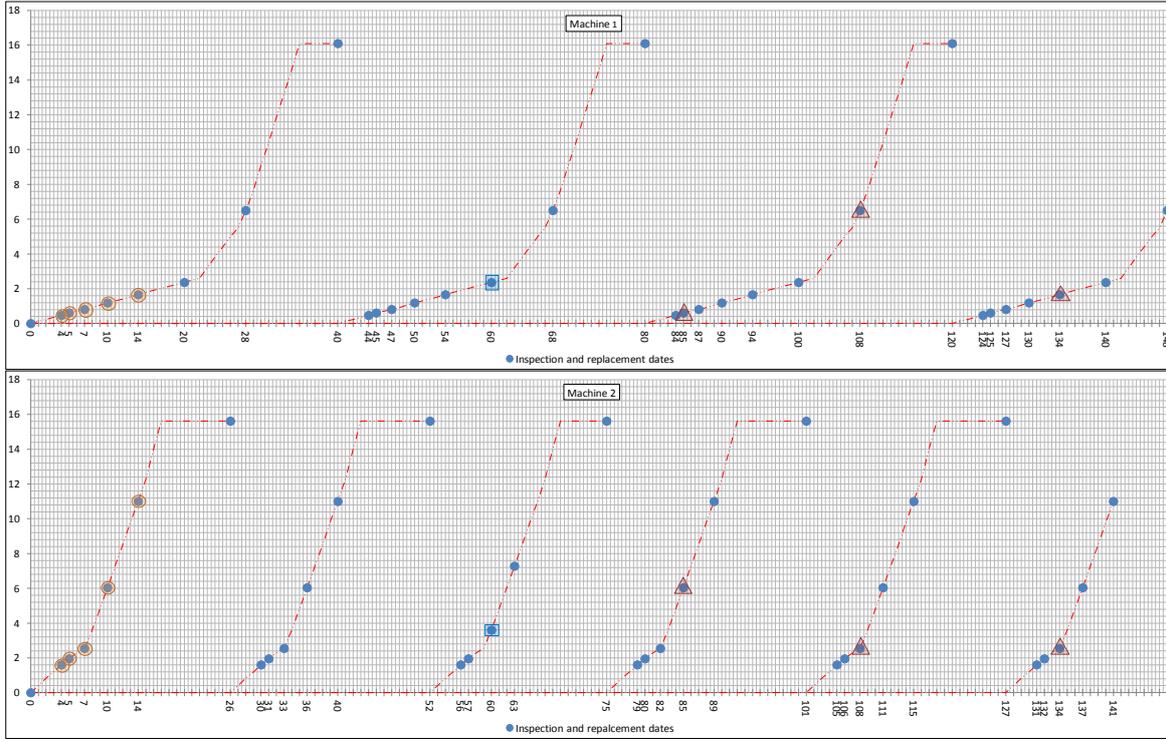
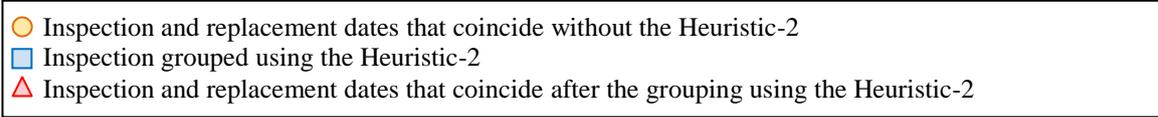


Figure 2c: Inspection and replacement dates with Heuristic-2 V2



The figure 2 represents a real degradation of both machines throughout the mission $T_{miss}=150$, and the inspection and replacement dates proposed by the three methods. In the figure 2a, the inspection dates that coincide are distinguished by circles. In the figures 2b and 2c the inspection dates that coincide are distinguished by circles. The dates obtained by the grouping using the Heuristic-2 are distinguished by squares. By comparing the three figures, we see that without the application of Heuristic-2, we have to intervene at $T=59$ on the machine 2, and at $T=60$ on the machine 1. By applying the Heuristic-2 V1, we intervene only at $T=59$ for both machines. By applying the Heuristic-2 V2, we intervene only at $T=60$ for both machines. The application of the Heuristic-2 has an impact on the next intervention date, which may have an impact on the total cost. The date that coincide after the grouping using the Heuristic-2, are distinguished by triangles in figures 2b and 2c. The impact of the Heuristic-2 on the total cost will be studied on the next section.

5 NUMERICAL EXAMPLE

In order to compare the three methods, we want to apply it on different sequence of the spare part installed in the machines. The qualities installed in the machine are the same, but the degradation scenario is different. We considered the different sources of the spare parts installed in the machine, for example, the spare part of

quality 1 can be the result of the remanufacturing of spare part of quality 2, 3 or quality 1 without remanufacturing. We consider (x,y) so that, the spare part of quality x is the result of remanufacturing of a spare part of quality y . For each quality able to be installed, we generate seven degradation scenarios. The scenarios are numbered from 1 to 7, where the scenario 1 represents the slower degradation scenario and scenario 7 the faster degradation scenario.

In order to better observe and analyze the results obtained for each method, we decided to treat the case of two machines that operates on a finite duration $T_{miss}=150$, the remaining data will be as follow:

The bounds of the random variables a_i are bounded by the values $a_0^{Min}=0.1$, $a_0^{Max}=1$, $a_1^{Min}=0.5$, $a_1^{Max}=5$, $a_2^{Min}=0.9$, $a_2^{Max}=9$, $a_3^{Min}=1.3$, $a_3^{Max}=13$. The spare part quality varies from $n=0..4$, where we have four usable qualities of spare parts. The implemented failure threshold is $d_{max}=15$. The initial degradation level of remanufactured spare parts are $L_1=2.5$ for quality 1, $L_2=5$ for quality 2 and $L_3=7.5$ for quality 3. We assume that the supplier may provide a new replacement part at any time, with a delivery time $t_{or}=12tu$ and an order cost $CU_{or}=200mu$. The remanufacturing times and the remanufacturing costs are given in the table 1. Using a recovered spare part involves a fixed cost $C_{usere} = 60mu$ (for quality 1), $30mu$ (for quality 2). The inspection cost $CU_{insp}=25mu$, Downtime cost per unit time $CU_p=20mu$, the storage unit cost $CU_s=3mu$, the preventive maintenance cost $CU_{pr}=50mu$ and the corrective

maintenance cost $CU_{cr}=500\text{mu}$. Disposal cost of spare part of quality 4 $CU_{disp}=20\text{mu}$. Intervention cost for a replacement $C_{Ireplace}=200\text{mu}$ and Intervention cost for an inspection $C_{Iinsp}=100\text{mu}$.

	3->2	3->1	2->1
Cost (mu)	8	10	7
Delivery time	2	7	3

Table 1: Cost and Delivery time of the remanufacturing action.

The decision thresholds d_s and d_r depend on the quality of spare part installed in the machine, and the quality as well as the original quality of the spare part that will be installed next. The table 2 and 3 represent the different used thresholds d_s and d_r , respectively.

		Next spare part quality						
		(0,0)	(1,1)	(1,2)	(1,3)	(2,2)	(2,3)	(3,3)
Installed spare part quality	0	6.33	2.34	6.53	6.73	2.43	7.35	2.47
	1	10.83	4.37	11.88	11.35	4.37	10.83	4.87
	2	10.08	7.35	10.58	11.61	8.21	11.35	7.77
	3	10.41	10.83	8.21	10.83	3.45	11.09	5.76

Table 2: Thresholds d_s .

		Next spare part quality						
		(0,0)	(1,1)	(1,2)	(1,3)	(2,2)	(2,3)	(3,3)
Installed spare part quality	0	9.75	7.8	9.9	10.05	8.1	10.5	8.25
	1	12.75	8.1	13.35	13.05	8.1	12.75	8.55
	2	12.3	10.5	12.6	13.2	11.1	13.05	10.8
	3	13.35	12.75	11.1	12.75	7.2	12.9	9.3

Table 3: Thresholds d_r .

Before comparing the three methods, we will start by seeking the best probability of grouping for each version of the Heuristic-2. We applied the two version of the Heuristic-2 with probability of grouping $P_{grouping}=1, 0.9, 0.5$ and 0.1 . The table 4 and 5 present a non-exhaustive list of the obtained results by applying the Heuristic-2 V1 and V2 respectively.

(x,y)		$P_{grouping}$	Total cost (10^3 mu)						
			(S1, S3)	(S1, S5)	(S2, S3)	(S2, S7)	(S3, S7)	(S4, S6)	(S5, S6)
(0,0)	1	15.40	23.17	15.64	26.54	26.89	25.63	20.30	29.42
	0.9	15.40	23.17	15.64	26.54	26.89	25.63	20.30	29.42
	0.5	15.40	23.17	15.64	26.54	26.89	25.63	20.30	29.42
	0.1	15.40	22.07	15.64	26.54	26.89	25.30	20.30	29.42
(1,1)	1	53.91	55.54	57.77	84.17	88.82	56.26	63.15	70.92
	0.9	53.91	55.54	57.77	84.17	88.82	56.26	63.15	70.92
	0.5	53.91	55.54	57.77	84.17	88.82	56.26	63.15	70.92
	0.1	53.91	55.54	57.77	84.17	88.82	56.31	63.15	70.92
(1,2)	1	57.42	61.99	57.44	63.96	57.92	62.48	62.45	50.78
	0.9	57.42	61.99	57.44	63.96	57.92	62.48	62.45	50.78
	0.5	57.42	61.99	57.44	63.96	57.92	62.48	62.45	50.78
	0.1	57.37	61.99	57.39	63.96	57.92	62.48	62.45	50.78
(1,3)	1	47.88	47.49	46.46	46.75	44.70	43.86	41.91	33.14
	0.9	47.88	47.49	46.46	46.75	44.70	43.86	41.91	33.14
	0.5	47.88	47.49	46.46	46.75	44.70	43.86	41.91	33.14
	0.1	47.83	47.49	46.41	46.75	44.70	42.76	41.86	33.14
(2,2)	1	51.81	57.60	58.97	69.86	67.87	77.86	67.86	90.16
	0.9	51.81	57.60	58.97	69.86	67.87	77.86	67.86	90.16
	0.5	51.81	57.60	58.97	69.86	67.87	77.86	67.86	90.16
	0.1	51.81	57.60	58.97	69.86	67.87	77.86	67.86	90.16
(2,3)	1	64.53	60.37	74.76	74.26	83.07	80.47	66.86	84.91
	0.9	64.53	60.37	74.76	74.26	83.07	80.47	66.86	84.91
	0.5	64.53	60.37	74.76	74.26	83.07	80.47	66.86	84.91
	0.1	64.53	60.37	74.76	74.26	83.07	80.52	66.86	84.91

Table 3: The variation of the total cost depending on the probability $P_{grouping}$, using Heuristic-2 V1.

(x,y)		$P_{grouping}$	Total cost (10^3 mu)						
			(S1, S3)	(S1, S5)	(S2, S3)	(S2, S7)	(S3, S7)	(S4, S6)	(S5, S6)
(0,0)	1	15.40	22.91	15.64	26.70	26.82	25.63	20.30	29.64
	0.9	15.40	22.91	15.64	26.70	26.82	25.63	20.30	29.64
	0.5	15.40	22.91	15.64	26.70	26.82	25.63	20.30	29.64
	0.1	15.40	23.54	15.64	26.70	26.82	25.30	20.30	29.64
(1,1)	1	53.66	55.29	57.72	84.17	88.57	56.26	62.90	70.92
	0.9	53.66	55.29	57.72	84.17	88.57	56.26	62.90	70.92
	0.5	53.66	55.29	57.72	84.17	88.57	56.26	62.90	70.92
	0.1	53.91	55.54	57.77	84.17	88.82	56.31	63.15	70.92
(1,2)	1	57.12	61.89	57.14	63.86	64.42	62.48	62.10	50.78
	0.9	57.12	61.89	57.14	63.86	64.42	62.48	62.10	50.78
	0.5	57.12	61.89	57.14	63.86	64.42	62.48	62.10	50.78
	0.1	57.32	61.89	57.34	63.86	64.42	62.48	62.10	50.78
(1,3)	1	47.58	47.44	46.16	46.05	44.40	43.86	41.36	33.14
	0.9	47.58	47.44	46.16	46.05	44.40	43.86	41.36	33.14
	0.5	47.58	47.44	46.16	46.05	44.40	43.86	41.36	33.14
	0.1	47.83	47.49	46.41	46.75	44.70	42.76	41.86	33.14
(2,2)	1	51.76	57.55	58.92	69.87	68.48	77.86	67.86	90.37
	0.9	51.76	57.55	58.92	69.87	68.48	77.86	67.86	90.37
	0.5	51.76	57.55	58.92	69.87	68.48	77.86	67.86	90.37
	0.1	51.81	57.60	58.97	69.86	67.87	77.86	67.86	90.16
(2,3)	1	64.48	60.32	74.71	84.66	83.07	80.47	66.86	84.31
	0.9	64.48	60.32	74.71	84.66	83.07	80.47	66.86	84.31
	0.5	64.48	60.32	74.71	84.66	83.07	80.47	66.86	84.31
	0.1	64.53	60.37	74.76	74.26	83.07	80.52	66.86	84.91

Table 4: The variation of the total cost depending on the probability $P_{grouping}$, using Heuristic-2 V2.

Where: S_i is the degradation scenario $i, i=1...7$.

From the tables 3 and 4, we can see that the influence of the grouping probability on the total cost does not follow a single trend, i.e. decreasing the probability may lead to an increase or a decrease of the total cost, as it may not have an influence. A thorough analysis of the obtained results, we were led to say that influence of the $P_{grouping}$ on depends, on the pair (x,y) (i.e. the quality of the spare part installed in the machine and its initial quality), the degradation scenario of each machine and the version of the Heuristic-2. For examples: For the pairs (1,1) and (2,2), the grouping probability don't have an influence on the total cost, using Heuristic-2 V1; whereas using the Heuristic-2 V2, the decreasing can increase the total cost (see Table 4: (S1,S3), (S1,S5), (S2,S3)). This implies that the spontaneous grouping is not beneficial every time.

We turn now to the comparison of the three methods, namely, Heuristic-2 V1, Heuristic-2 V2 and without the Heuristic-2. To make this comparison, we use the best grouping probability obtained for each version of the Heuristic-2. If $P_{grouping}$ don't have an influence on the total cost, we use the smallest probability, namely, $P_{grouping}=0.1$. The comparison is based on following rule: for each series of quality spare parts installed in both machines, we set the degradation scenario of the machine 1 and we vary the degradation scenarios of the machine 2. The obtained results are presented by the figure 3, 4, 5, 6 and 7 (The presented results are not exhaustive):

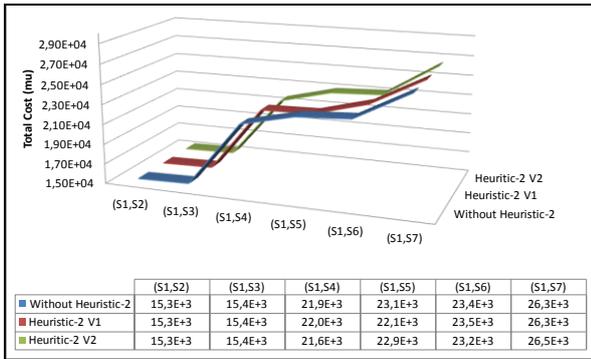


Figure 3: Total cost according to the degradation scenarios (Series of the spare part is of type (0,0))

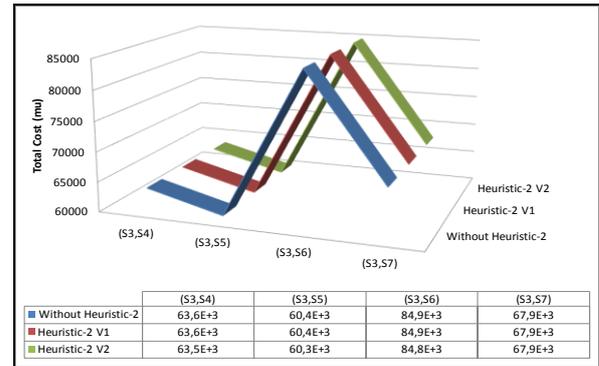


Figure 7: Total cost according to the degradation scenarios (Series of the spare part is of type (2,2))

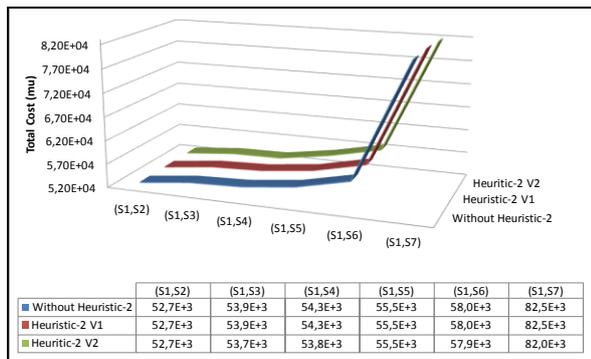


Figure 4: Total cost according to the degradation scenarios (Series of the spare part is of type (1,1))

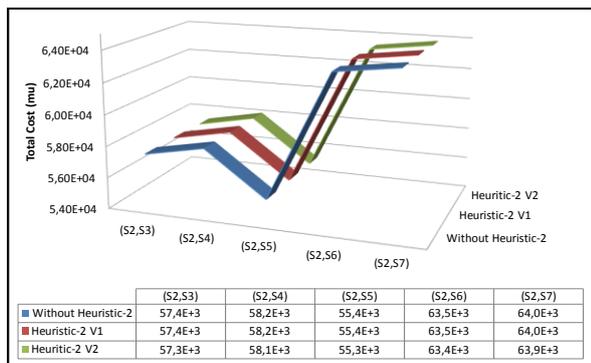


Figure 5: Total cost according to the degradation scenarios (Series of the spare part is of type (1,2))

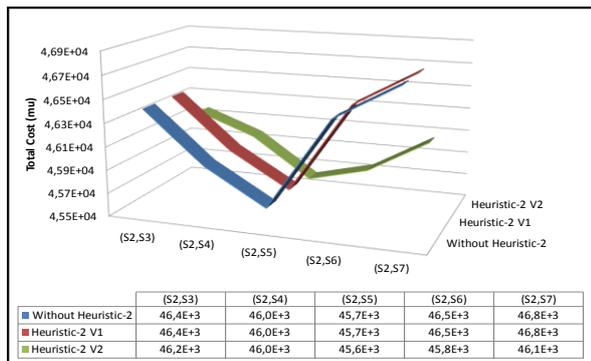


Figure 6: Total cost according to the degradation scenarios (Series of the spare part is of type (1,3))

From Figures 3-7, we can see that the Heuristic-2 V2 may provide improvement on the obtained total cost. The improvement may be significant (figure 5) and medium improvement (figure 3, 4, 6 and 7). Heuristic-2 V1 doesn't provide an improvement for the total cost, except for one case presented in figure 3, where the machine 1 degrades according to the degradation scenario S1 and the machine 2 degrades according to the degradation scenario S5. The remainders of the results demonstrate that the Heuristic-2 may provide a total cost that is higher the one which is provided without using the heuristic. Finally, we say that the heuristic is limited and requires further improvements, so that the grouping is not automatically performed, even if the rules were verified, i.e. add additional rules to the grouping procedure. A summary comparative of obtained results are presented in the Appendix.

6 CONCLUSION

In this paper, we have addressed the problem of planning the dates of intervention, for a production system consisting of m independent machines. The machines are subject to a monotone and stochastic deterioration, which lead to their failure. Condition based maintenance was adopted for the maintenance management. Spare parts of different qualities are used for maintenance. The parts are provided from two sources: Remanufacturing center (used parts) and supplier (new parts). Our contribution was to propose a heuristic to calculate the intervention dates on the machines. The results showed that the heuristic can bring improvement, with one of its versions. The heuristic still remains limited to the case of more than two machines, where it is necessary to introduce other grouping rules.

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APPENDIX

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Total cost\P _{grouping}																		
	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2
(0, 0)	15.3E+3	15.3E+3\0.1	15.3E+3\0.1	15.4E+3	15.4E+3\0.1	15.4E+3\0.1	21.9E+3	22.0E+3\0.1	21.6E+3\0.1	23.1E+3	22.1E+3\0.1	22.9E+3	23.4E+3	22.4E+3\0.1	23.2E+3\0.1	26.3E+3	26.3E+3\0.1	26.5E+3\0.1
(1, 1)	52.7E+3	52.7E+3\0.1	52.7E+3\0.1	53.9E+3	53.9E+3\0.1	53.7E+3\0.1	54.3E+3	54.3E+3\0.1	53.8E+3\0.1	55.5E+3	55.5E+3\0.1	55.5E+3\0.1	58.0E+3	58.0E+3\0.1	57.9E+3\0.1	82.5E+3	82.5E+3\0.1	82.5E+3\0.1
(1, 2)	57.4E+3	57.4E+3\0.1	57.2E+3\0.1	57.4E+3	57.4E+3\0.1	57.1E+3\0.1	59.1E+3	59.1E+3\0.1	59.1E+3\0.1	61.9E+3	62.0E+3\0.1	61.9E+3\0.1	63.8E+3	63.8E+3\0.1	63.1E+3\0.1	64.3E+3	64.3E+3\0.1	63.6E+3\0.1
(1, 3)	48.3E+3	48.3E+3\0.1	48.0E+3\0.1	47.8E+3	47.8E+3\0.1	47.6E+3\0.1	48.0E+3	48.0E+3\0.1	47.9E+3\0.1	47.5E+3	47.5E+3\0.1	47.4E+3\0.1	47.9E+3	47.9E+3\0.1	47.2E+3\0.1	48.2E+3	48.2E+3\0.1	47.5E+3\0.1
(2, 2)	54.4E+3	54.4E+3\0.1	54.4E+3\0.1	51.8E+3	51.8E+3\0.1	51.8E+3\0.1	60.8E+3	60.8E+3\0.1	60.8E+3\0.1	57.6E+3	57.6E+3\0.1	57.6E+3\0.1	82.1E+3	82.1E+3\0.1	82.1E+3\0.1	71.1E+3	71.1E+3\0.1	71.1E+3\0.1
(2, 3)	60.7E+3	60.7E+3\0.1	60.7E+3\0.1	64.5E+3	64.5E+3\0.1	64.5E+3\0.1	65.0E+3	65.0E+3\0.1	65.0E+3\0.1	60.4E+3	60.4E+3\0.1	60.3E+3\0.1	61.0E+3	61.0E+3\0.1	60.9E+3\0.1	72.6E+3	72.6E+3\0.1	72.0E+3\0.1
	(S1,S2)			(S1,S3)			(S1,S4)			(S1,S5)			(S1,S6)			(S1,S7)		

Total cost\P _{grouping}															
	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2
(0, 0)	15.6E+3	15.6E+3\0.1	15.6E+3\0.1	22.1E+3	22.2E+3\0.1	21.8E+3\0.1	23.4E+3	23.7E+3\0.1	23.2E+3\0.1	23.7E+3	23.7E+3\0.1	23.4E+3\0.1	26.5E+3	26.5E+3\0.1	26.7E+3\0.1
(1, 1)	57.8E+3	57.8E+3\0.1	57.7E+3\0.1	56.0E+3	56.0E+3\0.1	55.9E+3\0.1	53.6E+3	53.6E+3\0.1	53.6E+3\0.1	59.7E+3	59.7E+3\0.1	59.7E+3\0.1	84.2E+3	84.2E+3\0.1	84.2E+3\0.1
(1, 2)	57.4E+3	57.4E+3\0.1	57.3E+3\0.1	58.2E+3	58.2E+3\0.1	58.1E+3\0.1	55.4E+3	55.4E+3\0.1	55.3E+3\0.1	63.5E+3	63.5E+3\0.1	63.4E+3\0.1	64.0E+3	64.0E+3\0.1	63.9E+3\0.1
(1, 3)	46.4E+3	46.4E+3\0.1	46.2E+3\0.1	46.0E+3	46.0E+3\0.1	46.0E+3\0.1	45.7E+3	45.7E+3\0.1	45.6E+3\0.1	46.5E+3	46.5E+3\0.1	45.8E+3\0.1	46.8E+3	46.8E+3\0.1	46.1E+3\0.1
(2, 2)	59.0E+3	59.0E+3\0.1	58.9E+3\0.1	58.8E+3	58.8E+3\0.1	58.7E+3\0.1	53.8E+3	53.8E+3\0.1	53.7E+3\0.1	78.3E+3	78.3E+3\0.1	78.2E+3\0.1	69.9E+3	69.9E+3\0.1	69.9E+3\0.1
(2, 3)	74.8E+3	74.8E+3\0.1	74.7E+3\0.1	75.3E+3	75.3E+3\0.1	75.2E+3\0.1	75.6E+3	75.6E+3\0.1	75.6E+3\0.1	76.2E+3	76.2E+3\0.1	76.2E+3\0.1	74.3E+3	74.3E+3\0.1	74.3E+3\0.1
	(S2,S3)			(S2,S4)			(S2,S5)			(S2,S6)			(S2,S7)		

Total cost\P _{grouping}															
	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2
(0, 0)	22.3E+3	22.3E+3\0.1	22.0E+3\0.1	23.5E+3	23.5E+3\0.1	23.2E+3\0.1	23.8E+3	23.8E+3\0.1	23.5E+3\0.1	26.6E+3	26.9E+3\0.1	26.8E+3\0.1			
(1, 1)	59.4E+3	59.4E+3\0.1	59.4E+3\0.1	61.3E+3	61.3E+3\0.1	61.0E+3\0.1	64.3E+3	64.3E+3\0.1	64.1E+3\0.1	88.8E+3	88.8E+3\0.1	88.8E+3\0.1			
(1, 2)	58.9E+3	58.9E+3\0.1	58.7E+3\0.1	60.9E+3	60.9E+3\0.1	60.9E+3\0.1	57.4E+3	57.4E+3\0.1	63.9E+3\0.1	57.9E+3	57.9E+3\0.1	64.4E+3\0.1			
(1, 3)	46.3E+3	46.3E+3\0.1	46.1E+3\0.1	44.0E+3	44.0E+3\0.1	44.0E+3\0.1	44.4E+3	44.4E+3\0.1	44.1E+3\0.1	44.7E+3	44.7E+3\0.1	44.4E+3\0.1			
(2, 2)	63.6E+3	63.6E+3\0.1	63.5E+3\0.1	60.4E+3	60.4E+3\0.1	60.3E+3\0.1	84.9E+3	84.9E+3\0.1	84.8E+3\0.1	67.9E+3	67.9E+3\0.1	67.9E+3\0.1			
(2, 3)	63.3E+3	63.3E+3\0.1	63.3E+3\0.1	79.4E+3	79.4E+3\0.1	79.4E+3\0.1	80.0E+3	80.0E+3\0.1	80.0E+3\0.1	83.1E+3	83.1E+3\0.1	83.1E+3\0.1			
	(S3,S4)			(S3,S5)			(S3,S6)			(S3,S7)					

Total cost\P _{grouping}															
	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2
(0, 0)	25.6E+3	25.5E+3\0.1	25.0E+3\0.1	25.9E+3	25.3E+3\0.1	25.3E+3\0.1	28.3E+3	28.8E+3\0.1	27.9E+3\0.1						
(1, 1)	61.2E+3	61.2E+3\0.1	61.2E+3\0.1	56.3E+3	56.3E+3\0.1	56.3E+3\0.1	80.8E+3	80.8E+3\0.1	80.8E+3\0.1						
(1, 2)	60.5E+3	60.5E+3\0.1	60.4E+3\0.1	62.8E+3	62.8E+3\0.1	62.5E+3\0.1	63.3E+3	63.3E+3\0.1	63.0E+3\0.1						
(1, 3)	43.6E+3	43.6E+3\0.1	43.6E+3\0.1	42.8E+3	42.8E+3\0.1	42.8E+3\0.1	43.1E+3	43.1E+3\0.1	44.2E+3\0.1						
(2, 2)	53.4E+3	53.4E+3\0.1	53.4E+3\0.1	77.9E+3	77.9E+3\0.1	77.9E+3\0.1	68.1E+3	68.1E+3\0.1	68.1E+3\0.1						
(2, 3)	79.9E+3	79.9E+3\0.1	79.9E+3\0.1	80.5E+3	80.5E+3\0.1	80.5E+3\0.1	83.6E+3	83.6E+3\0.1	83.6E+3\0.1						
	(S4,S5)			(S4,S6)			(S4,S7)								

Total cost\P _{grouping}						
	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2
(0, 0)	20.3E+3	20.3E+3\0.1	20.3E+3\0.1	29.3E+3	29.2E+3\0.1	29.3E+3\0.1
(1, 1)	63.2E+3	63.2E+3	62.9E+3\0.1	87.7E+3	87.7E+3	87.4E+3\0.1
(1, 2)	62.4E+3	62.4E+3\0.1	62.1E+3\0.1	62.9E+3	62.9E+3\0.1	62.6E+3\0.1
(1, 3)	41.9E+3	41.9E+3\0.1	41.9E+3\0.1	42.2E+3	42.2E+3\0.1	41.7E+3\0.1
(2, 2)	67.9E+3	67.9E+3\0.1	67.9E+3\0.1	65.7E+3	65.7E+3\0.1	65.7E+3\0.1
(2, 3)	66.9E+3	66.9E+3\0.1	66.9E+3\0.1	84.3E+3	84.3E+3\0.1	83.7E+3\0.1
	(S5,S6)			(S5,S7)		

Total cost\P _{grouping}			
	Without Heuristic-2	Heuristic-2 V1	Heuristic-2 V2
(0, 0)	29.6E+3	29.4E+3\0.1	29.6E+3\0.1
(1, 1)	70.9E+3	70.9E+3\0.1	70.9E+3\0.1
(1, 2)	50.8E+3	50.8E+3\0.1	50.8E+3\0.1
(1, 3)	33.1E+3	33.1E+3\0.1	33.1E+3\0.1
(2, 2)	90.2E+3	90.2E+3\0.1	90.2E+3\0.1
(2, 3)	84.9E+3	84.9E+3\0.1	84.3E+3\0.1
	(S6,S7)		