‘ODDS ALGORITHM’-BASED OPPORTUNISTIC MAINTENANCE FOR PRESERVING COMPONENT PERFORMANCES

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Abstract: Today, a new role for maintenance exists to enhance the eco-efficiency of the product lifecycle. The concept of “lifecycle maintenance” has emerged to stress this role leading to push, at the manufacturing stage, an innovative culture wherein maintenance activities become of equal importance to actual production activities. This equivalence requires mainly to consider the integration of both the maintenance planning and the production strategy planning to develop opportunistic maintenance tasks guaranteeing conjointly the product – production – equipment performances. In this paper, a novel approach is proposed to synchronise the maintenance planning with the production planning. The approach uses the “odds algorithm” and is based upon the theory of optimal stopping. The objective is to select, among all the production stoppages already planned, those which will be optimal to develop maintenance tasks keeping the expected product conditions. It combines criteria such as product performance and component reliability. An approach evaluation is shown on a practical example.

Keywords: Maintenance; Decision-Making; Odds algorithm; Bruss algorithm; Production stoppage

1. INTRODUCTION

Even if maintenance is a necessity, maintenance has a negative image and suffers from a deficiency of understanding and respect. It is usually recognised as a cost, a necessary evil, not as a contributor. Moreover traditionally the scope of maintenance activities has been limited to the production vs. operation phase. But as the paradigm of manufacturing shifts towards conceiving a sustainable society, the role of maintenance has to change to take into account a ‘lifecycle management’-oriented approach (Takata, *et al.*, 2004). Indeed, limits on resources and energy consumption imply a sharp change in the objectives of manufacturing, shifting from the need to produce more efficiently to the need to produce new assets as late as possible while still ensuring the satisfaction of customers and profits. From a global perspective of lifecycle management, the role of (e)-maintenance is now to enhance the eco-efficiency (Desimone and Popoff, 1997) of the product lifecycle while preserving the product “characteristics” (Cunha and Caldeira Duarte, 2004). In that way, maintenance has to be considered not only in a production vs. operation phase but also in product design, product disassembly, and product recycling (Van Houten, *et al.*, 1998).
The concept of “lifecycle maintenance” (Takata, *et al.*, 2004) has emerged to stress this new role leading to push, at the operation stage where the product characteristics can have a huge influence on the performances of the manufacturing system, an innovative culture wherein maintenance activities become of equal importance to actual production activities.
However as a unified maintenance/production framework does not exist yet, this equivalence requires mainly to consider the synchronisation of the maintenance planning and of the production planning to develop opportunistic maintenance tasks (synchronised with production) in order to keep both the production and the equipment performances so as to preserve product conditions.
This notion of opportunistic maintenance, which is not defined inside a standard, has changed during the last decades. At first, an opportunistic inspection policy makes the inspection of a non-monitored part conditional on the state (good or failed) of a monitored part (McCall, 1963). Then an opportunistic maintenance is any action that combines a preventive maintenance action and a corrective maintenance action (Dekker, *et al.*, 1997), or the grouping of maintenance actions on different components for economical reasons (Berk and Moinzadeh, 2000). For (Jhang and Sheu, 1999), an opportunity appears as soon as an element is idle, thus allowing to perform simultaneous maintenance actions. This idleness can be due to failures of some other elements in the system. More generally, (Budai, *et al.*, 2006) define an opportunity as being a moment (1) at which the units to be maintained are less needed for their function than normally, (2) that occurs occasionally and (3) that is difficult to predict in advance. These opportunities appear not only in the case of failure of

other elements, but also at an interruption (or stoppage) of production. This view of an opportunity will be considered in the sequel.
Opportunistic maintenance is often criticised for not being 'plannable' long in advance and therefore no work preparation is possible. Then some models are purely economical ones, or purely stochastic ones, or too intricate to be of any use for a potential user (Scarf, 1997). Moreover the lengths of the finite horizons considered in those works are often much shorter than the lifespan of a component. But opportunistic maintenance can help save set-up costs and guarantee the expected performances for the system.
The challenge is now to move from conventional maintenance strategies towards new condition-based or predictive ones performed only when a certain level of equipment deterioration (impacting product conditions) occurs rather than after a specified period of time. It leads to have at one's disposal not only statistical and historical information about the system operation, but also just-in-time information processed by means of the prognosis model (Iung, *et al.*, 2005) in order to assess new product/system situations and to anticipate product deteriorations and system failures. More precisely, in relation to ISO13381, the prognosis process aims at foreseeing how a component will evolve, until it fails and then until the system breaks (this defines the residual lifetime of that component). From this result, an important opportunistic maintenance issue can be formulated as follows: Taking into account the residual lifetime of a component, is it possible to select one of the production stoppages already planned in order to carry out a maintenance action guaranteeing a compromise between costs, safety, impact on production conditions (i.e. functional performances) and on component availability…? If so, how is it possible to classify the selected production stoppages in decreasing order related to some relevance criteria?
In relation to this issue, some academic work has already been achieved by proposing (a) common maintenance-production scheduling (Kianfar, 2005), (b) production stoppage selection based on expert judgement (Rosqvist, 2002) or (c) decreasing of the maintenance operation time. The originality of the approach developed in this paper and based on the 'odds algorithm' is, first, to keep the initial production scheduling without modifying it to operate maintenance actions; second, to ensure an optimality of the maintenance decision compared to a given criterion (i.e. a functional performance), and finally, to use current system information delivered by a prognosis process.
In that way, section 2 aims at formalising the 'production stoppage problem' in terms of mathematical equations consistent with the 'odds algorithm', then section 3 shows the implementation of the 'odds algorithm' and section 4 its feasibility and interest for a specific application case. Finally conclusions and prospective are proposed in section 5.

2 FORMALISATION OF THE 'PRODUCTION STOPPAGE PROBLEM'

To solve the problem proposed in the introduction, a mathematical result, issued from Bruss' work (Bruss, 2000) and based on the theory of optimal stopping (Chow, *et al.*, 1991), is used. This method calculates the optimal behaviour in some situations where future is uncertain.

2.1 Problem statement

The product lifecycle phase concerned by this problem is the production phase. In this phase, an observation horizon being given, the production as well as the maintenance experts can access to the calendar of all the production stoppages already planned in order to carry out a maintenance action that takes into account the residual lifetime of the components of the manufacturing system.
Indeed let S be a system. The prognosis process provides a remaining lifetime of T time units for S, which defines a bounded uncertain observation horizon $[0;T]$. The expert has at his disposal, before time T, the 'production stoppages' which are defined by means of their respective 'beginning instants' and their respective 'durations'. A stoppage *stop* will thus be defined thanks to a beginning instant a and a duration d. This will be written *stop* = (a; d).
Among these production stoppages, some of them should be appropriated to develop 'just-in-time' maintenance actions which were not scheduled by the maintenance manager but required due to a short remaining lifetime. Thus an appropriated stoppage (a; d) means that (a) the system is survival at instant a and maintainable during d, (b) the deterioration of the product/production performances are acceptable at instant a but also (c) all the logistic resources (spare parts, qualified manpower…) are available to develop those maintenance actions. These selected stoppages will be called 'successes' in the following and the main issue can be formulated this way: Determine the last success at which a maintenance action can be performed in order to restore the system or one of its components into a nominal state to preserve the expected product/production performances.

2.2 Thomas Bruss' results

A way to solve the aforementioned problem is to use Bruss Theorem which can be described as follows.
Let $(I_i)_{1\le i\le n}$ be n indicators of random and independent events $(A_i)_{1\le i\le n}$ which are defined upon the same probability space $(\Omega;G;P)$. It is possible to observe $I_1, I_2, \cdots$ sequentially and to stop at any of these observations (say $I_k, 1\le k\le n$) but without recalling on the previous ones $(I_1 \ldots I_{k-1})$ and, of course, without knowing the future values of the indicators $(I_{k+1} \ldots I_n)$. A 'success' is defined as being an observation (an indicator) equals to 1. Let B_k

denote the sigma-field generated by $(I_i)_{1\le i\le k}$ and ξ the class of all rules τ such that the event $\{\tau = k\}$ is B_k –measurable, for $1\le k\le n$. The scope is to find a stopping rule $\tau_n \in \xi$ that will maximise $P\left(I_\tau = 1; I_j = 0; \tau+1\le j\le n\right)$ over every $\tau\in\xi$. This quantity is the probability to stop the observations precisely at the last success of the observed sequence. In the sequel, 'optimal' will hold in the sense of the maximisation of this probability. To develop the rule, the following quantities are used:

$$p_j := E(I_j) = P(A_j), \qquad (1)$$
$$q_j := 1 - p_j, \quad r_j := p_j / q_j, \quad 1\le j\le n$$

The quantities r_j are traditionally called the 'odds'. Then Bruss theorem can be stated (Bruss, 2000). An optimal rule τ_n for finding the last success exists and is to stop on the first index (if any) k with $I_k = 1$ and $k\ge s$, where:

$$s := \sup\left(1; \sup\left\{1\le k\le n \,\middle|\, \sum_{j=k}^{n} r_j \ge 1\right\}\right) \qquad (2)$$

with the convention $\sup(\varnothing) = -\infty$. The optimal reward is given by:

$$v_s = \left(\prod_{j=s}^{n} q_j\right).\left(\sum_{j=s}^{n} r_j\right) \qquad (3)$$

This theorem can also be stated that way: to find the very last success of the finite sequence $(I_i)_{1\le i\le n}$, the optimal stopping strategy consists in ignoring the first *s* – 1 observations, then in stopping right on the first success that occurs from the observation number *s* (included) onwards. This stopping index *s* is provided, and so is the probability that this strategy be optimal. The first success that occurs will be the observation (after the s^{th} one) with greatest odd.

2.3 *Thomas Bruss results adapted to the selection of a production stoppage*

Based on the previous formalisation, the odds algorithm is a decision-making tool that is relevant to answer the question of the 'best' choice, among the production stoppages, to perform an optimal just-in-time maintenance action.

In the following is made the assumption that the production stoppages are independent occurrences of a random variable, leading to consider the beginning of the stoppages and their respective duration as independent. The *n* independent occurrences $A_1,\ldots,A_n$ are the intervals materialising the production stoppages. To apply the theorem, it is necessary to assess the probability that these occurrences be successes. This probability is defined by the product (i) of the probability that the system be survival at instant *a* (reliability point of view) or the probability that the expected production performance be sufficient to guarantee the product quality at instant *a* (performance point of view) by (ii) the probability that the system be maintainable during the interval $[a;\, a+d]$.

The reliability (or performance) distribution and the maintainability distribution can be provided in practice by a prognosis process (Iung, *et al.*, 2005).

3 IMPLEMENTATION OF THE ALGORITHM

To be relevant for industrial applications, the objective is now to translate the previous mathematical formalisation into practice. To support this action, the quantities p_k, q_k, r_k can be successively written by beginning from the last index to the first one (for instance: $p_n, p_{n-1}, p_{n-2}, \cdots p_1$). Then it is necessary to add the numbers r_k from left to right, until the sum is equal to or greater than 1. It means to add, for decreasing values of *n*, $R_u := r_n + r_{n-1} + \cdots + r_u$, until the value of R_u exceeds 1. The value of *s*, for which this sum exceeds 1 at the first time, is the stopping index that is looked for. Then consider the next success after the stopping index *s* i.e. the stoppage (after index s) which has the greatest odds value. But if the value 1 is not reached once all the terms have been added $(R_1 < 1)$, let *s* be 1 (formula provided by the theorem). Finally the product $Q_s = q_n q_{n-1} \cdots q_s$ has to be computed to indicate the win probability of the optimal strategy, win probability which is equal to $v_s = Q_s R_s$.

The probability function that will be used to assess the probabilities that stoppages be successes is defined by the product of a function *X* (*X* can represent a reliability or a performance function) by a maintainability function. Every event A_i of the sequence is therefore characterised by a couple $(a_i; d_i)$ and:

$$p_i = X(a_i).M(d_i), \quad 1\le i\le n. \qquad (4)$$

The odds can thus be defined by:

$$r_i = X(a_i).M(d_i)/(1 - X(a_i).M(d_i)), \quad 1\le i\le n. \qquad (5)$$

The odds are calculated for every single production stoppage and summed up from the last one to the first one, until reaching (or going beyond) the value of 1 (at index *s*). The probability v_s that this particular production stoppage be optimal is given by:

$$v_s = \left(\prod_{j=s}^{n}(1 - X(a_i).M(d_i))\right).\left(\sum_{j=s}^{n}\frac{X(a_i).M(d_i)}{1 - X(a_i).M(d_i)}\right) \qquad (6)$$

4 APPLICATION OF THE ALGORITHM

The feasibility and the interest of the algorithm are shown on an application case taken from the e-maintenance platform TELMA; see (Iung, *et al.*, 2005).

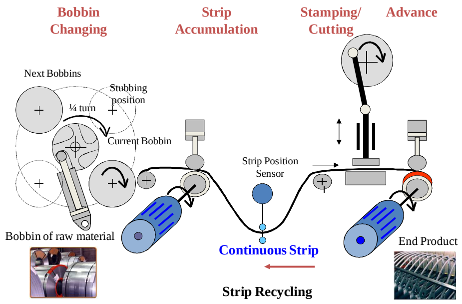

Fig. 1. Architecture of TELMA

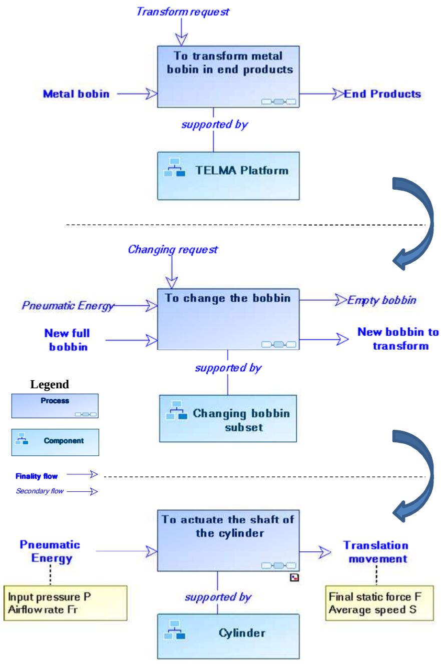

Fig. 2. Process analysis view of TELMA

TELMA allows to unwind metal bobbins and to stamp or cut the metal strip. One subset of TELMA is dedicated to lock/unlock the axis supporting the metal bobbin, in the changing bobbin part (Figure 1). This process is fulfilled by operating a mandrel unit action and is composed of four sub-processes in relation to four supports: a programmable logic controller (PLC), a distributor, a cylinder, and a mandrel (in contact with the axis).

The example only focuses on the sub-process named “To actuate the shaft of the cylinder” which is supported by the component “cylinder”. It enables to transform the “regulated pneumatic energy” flow (input flow) into a “translation movement” flow (i.e. Shaft movement). The input flow is characterised by two static variables: input pressure P and airflow rate Fr. The output flow is characterised by two static variables: a final static force F and an average speed S of translation. Figure 2 presents a TELMA process analysis, according to three functional levels from the TELMA level (‘To transform metal bobbin in end products’ process) to the component/cylinder level (‘To actuate the shaft of the cylinder’).

The causal relationships between (deviated) input-output flows and (degraded) components allow to define oriented arcs linking the potential cause variables (P, Fr and TL (k+1)) to effect variables (F and S), where TL (k+1) is the (nominal or degraded) state of the component supporting the process (Figure 3).

This functional vs. dysfunctional knowledge is used in (Iung, *et al.*, 2005) to formalise a prognosis model of this sub-process thanks to Dynamic Bayesian Network (DBN). The numerical values and results given by the prognosis model are reused here as main inputs of the maintenance decision making process. For example, after an operation period of 200h for the cylinder, vibrations are observed on the axis attesting that the gripping force F is decreasing. Thus it is necessary to carry out a just-in-time maintenance action which was not initially planned. This action aims at controlling the cylinder degradation and its impact directly on the process performance (shaft movement) and indirectly on the “product” quality (tightening in right position of the metal bobbin).

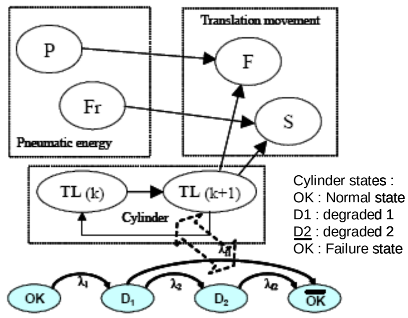

Fig.3. DBN of “To actuate the shaft of the cylinder”

This action has to be operated between the current instant (current time) and the next scheduled maintenance action (planned at T = 450h) but within a stoppage already planned by the production. These stoppages are known in advance, listed in Table 1 and materialise stoppages required for tool changes, series changes... on TELMA. The durations of the stoppages are assessed by maintenance experts in dialogue with a production expert. If some new stoppages occur (operator unavailability, lack of raw material…) it is possible to progressively integrate them into the stoppages list and to make new iterations to find the ‘best’ stoppage.

According to the selected values of the parameters (λ_1; λ_2; λ_3) in the Figure 3 (Iung, *et al.*, 2005), the process supported by the cylinder preserves the ‘product’ performances when the static Force (F) developed by the cylinder is higher or equal to 600 Newton. Thus this criterion will be used to assess, with the odds algorithm, the optimality of the stoppage required for a maintenance action and it represents a first step to take into account not only component conditions (i.e. reliability) but also some ‘finality’ conditions (global performance) in this optimality (Thomas, *et al.*, 2006). Therefore the approach and the proposed algorithm are enough generic to be implemented at higher abstraction levels, up to processes directly in charge with the transformed product (i.e. the metal bobbin). At the “cylinder” level, the finality performance is the probability that the static force be greater than 600N ($X(t)$=Prob($F(t)$ > 600N)) whereas the reliability is the probability that the cylinder be in state OK ($X(t) = R(t)$). By means of the prognosis model developed in (Iung, *et al.*, 2005), the evolution of $R(t)$ or Prob($F(t)$ > 600N) can be known at every instant. In that way, Figure 4 shows both the reliability and performance (Prob($F(t)$ > 600N)) curves between t = 0 and t = 1000h. The maintainability function of the system is supposed to be exponential with μ parameter equals to 0.3h^{-1} (mean time to repair: MTTR = 3.3h).

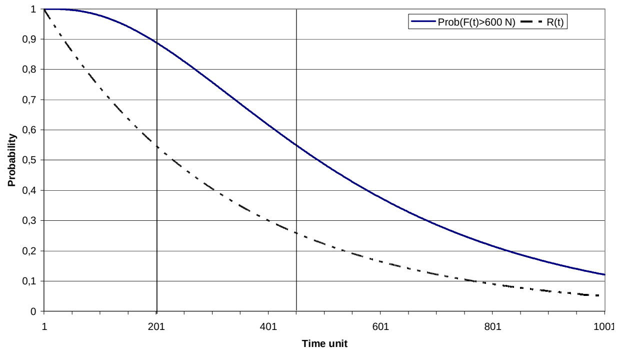

Fig. 4. Reliability *R* and *Prob(F(.) > 600N)* curves

During this horizon (1000h), 13 production stoppages are considered and distributed as indicated in Table 1. It is noticed that certain durations of production stoppages do not allow, in average time, to carry out the intervention (i.e. stoppages 2 and 4 have a duration lower than 3.3h). On the basis of the values given in Table 1, the odds algorithm is applied as formulated in section 3.

Table 1. Details of the 13 production stoppages

Index	Beginning (h)	Duration (h)
1	200	3
2	210	2
3	230	4
4	235	2
5	250	1
6	256	4
7	310	4
8	320	2
9	400	1
10	420	1
11	425	3
12	430	2
13	450	5

4.1 The decision-making

The results of the execution of the odds algorithm are given in Table 2. The case *A* corresponds to the reliability point of view whereas the case *B* corresponds to the finality performance point of view (Prob($F(.)$ > 600N). In relation to the case *A*, the optimal solution is obtained (7th stoppage) with a win probability equals to 40.2%. This percentage may seem low, but in fact it is excellent, as far as a general decision making algorithm is concerned (Bruss, 2003). In relation to the case *B*, the optimal solution is obtained (13th stoppage) with a win probability equals to 46.5%.

Moreover to improve the decision making process, the expert can have at his disposal the classification of the production stoppages as shown in Table 2 by decreasing order of relevance. The other solutions are found by deleting, in the list, the previous solution (coming from the higher row) and by applying the algorithm recursively.

Table 2. Complete results for both approaches

	Stoppage number		Win Probability		Decision
	A	*B*	*A*	*B*	
1	**7**	**13**	**0.4020**	**0.4650**	**Optimal**
2	6	11	0,4028	0.4349	Degraded
3	13	8	0,3997	0,4285	Degraded
4	4	7	0,4012	0,4564	Degraded
5	3	6	0,4098	0,4640	Degraded
6	2	4	0,4024	0,4124	Degraded
7	1	3	0,4081	0,4129	Degraded

Only the first solution (s = 7 in the case *A*; s = 13 in the case *B*) can be defined as 'optimal' because calculated by the odds algorithm according to the statement of the initial problem. For the other stoppages, the decision is necessary a non optimal decision (degraded decision).

The results of Table 2 are commented hereafter. The indices s are not indicated. In relation to the case *A*, the 7th stoppage is the last stoppage long enough (duration = 4h) before the stoppage concerned by the scheduled maintenance action (13th stoppage). The 1st, 2nd, 3rd and 6th stoppages have a win probability higher than stoppage 7 in Table 2 but they cannot be chosen as optimal because the odds algorithm is looking for the stoppage which must be the last success, for the initial problem (with the 13 stoppages). The 2nd stoppage appears in the list (case *A*) even if its duration is lower than MTTR because its probability of surviving is high (see Figure 4). The 13th stoppage is not selected because the reliability will be very low at the beginning of that stoppage, but yet it appears on the list because its maintainability is high. Conversely the 11th stoppage leads to such a weak surviving probability that it cannot be selected (even if its duration is adapted).

In relation to the case *B*, a more global view is adopted by focusing on the success of the process in relation to its finality. On Figure 4, the quantity Prob($F(t)$ > 600N) is always greater than the reliability $R(t)$, leading to consider a more optimistic vision than in the case *A*. This fact is also materialised in Table 2 with the win probabilities which are higher in the case *B*. In both cases, the algorithm brings to a compromise between the two points of view. Therefore the role of the expert is to use all these proposals for decision making but by integrating the uncertainties and constraints related to the industrial context.

One extra advantage is that it is possible to dynamically take into account every new future production stoppage. Should any information occur, these are integrated and the 'odds algorithm' is applied afresh. For example, at time t = 249h an information from the production staff indicates that a new production stoppage (named 8b) will be planned at a = 380h for a duration of d = 4h. The question from a maintenance point of view is: is this stoppage a new opportunity for maintenance, or should the previous decisions be kept? It can be seen in Table 3 that if the reliability of the component cylinder is only considered, it is possible to postpone the maintenance action from $a_1 = 310$h to a_2 = 380h. The win probability is greater. If some economical or logistic criteria are in favour of a_2 then the new decision is kept. If a finality performance view is adopted, this opportunity does not replace the previous decision.

Table 3. Complete results for both approaches

	Stoppage Number		Win Probability		Decision
	A	*B*	*A*	*B*	
1	**8b**	**13**	**0.4041**	**0.4650**	**Optimal**

5 CONCLUSIONS

In this paper, an odds algorithm-based approach is proposed to select a production stoppage in order to perform a just-in-time maintenance action preserving some finality performances and not only the conditions of a component. This approach is proved to be optimal and takes into account the results of a prognosis process. An application on a specific process (one component) of TELMA platform has been carried out. Based on these results, further developments should be implemented. These would consist mainly in:

- Developing the approach to a global system (many components) at different abstraction levels highlighting the impact on the real product delivered by the system. For this a European project (IP DYNAMITE FP6-IST-NMP-2-017498) can provide an experimentation site, for example in FIAT or VOLVO plants;
- Integrating the logistic and costs aspects in the algorithm;
- Combining the local optimal decisions (for each component) to deliver a global optimal decision (for the system).

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