Optimising Paper Machine Felt Change Schedules

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Abstract

To make paper, machines spray wet pulp on a moving screen and extract the water from it by squeezing it between rollers, before drying it using heat and rolling it on reels as finished product. The water extracted in the squeezing process is removed by a continuous roll of fabric called a *felt*. There are typically three felts on a paper machine. Felts wear out over time, and therefore must be replaced, either at a planned machine shutdown or at some other time when the machine fails randomly. All machine stoppages incur a downtime cost. This paper presents a stochastic dynamic programming model for determining a felt replacement policy that minimises the expected felt cost and cost of downtime.

1   Introduction

This paper examines a problem that arises in running the paper machines at the Tasman pulp and paper mill in Kawerau, Bay of Plenty. The problem is that of scheduling the replacement of felts within the press section of the paper machine. This part of the machine is responsible for removing the bulk of the moisture from the pulp.

In considering the scheduling of the felt changes, we aim to improve the way in which decisions are made to replace these components of the paper machines. Both the replacement cost of a felt, and the cost of downtime necessary to change a felt are considerable expenses to the mill, therefore we wish to devise a strategy to keep this cost at a minimum.

1.1   Paper Making Process

In order to put the project into context, it is important to have an understanding of how paper is made. There are two types of pulp used, namely *kraft pulp* and *mechanical pulp*.

The two pulps are combined in various concentrations, dependent on the type of paper being produced, and pumped into a head box at the beginning of the paper machine. At this stage the pulp is approximately 99% water. From the head box, the pulp is 'jetted' onto a fast moving *mesh fabric*. The water is forced through the mesh, while the solid component of the pulp remains on the surface. This is the first stage of the process, taking place in the area of the paper machine referred to as the *former*.

The pulp then moves into the *press section*, where the water is squeezed out through the *felts*, which are large piece of continuous fabric similar in texture to carpet. The felts are supported by a series of rollers, which move the felts around at a very fast speed. It is the three felts in this section of the paper machine around which the felt change scheduling model has been based.

The run of paper leaves the *press section* to progress through the *dryer* section where it passes over approximately 50 steam-heated cylinders to further reduce the moisture content. The finished paper is then cut into manageable sizes on the winder and packaged for distribution.

1.2   Felt Changing

In the press section of the paper machine there are typically three felts that are used in the process of water removal from the pulp. The average lifetime of a felt varies, depending on the type of felt, but is around 35-45 days for an endless felt, or around 70-80 days for a seamed felt. The differences between the two styles are in both the durability of the fabric and the physical structure of the felts, where an endless felt is a continuous piece of fabric, and the two ends of a seamed felt are joined by a zip-like seam. In addition to the standard purchase cost of each felt, there is some expense involved in physically changing the felt due to a downtime cost of the machine being unproductive.

There are several issues to be considered in developing a model, which are outlined below.

Felt wear / Maximum Allowable Age
As a felt increases in age, the likelihood of the felt wearing out increases until reaching a point at which the felt begins to operate inefficiently, i.e. its maximum operating age. This indicates that information about the ages of the felts at any particular time is a critical factor in the decision making process.

Scheduled Shutdowns
The paper machine is shut at regular intervals during which time routine maintenance is performed. It is possible for felts to be changed at this time with little cost.

Machine stoppages
In some cases problems arise which cause the paper machine to stop. The model investigates the situations in which these stoppages are advantageous, and should be taken as an opportunity to change one or more of the press felts.

Damage
There are instances in which the felts are subject to factors that result in the felt being holed or damaged in some way. In some cases, if the hole is small and lies outside the edge of the run of paper, it is repairable, however in many cases, damage requires the felt to be replaced.

Felt costs
There are different brands and models of felts available for use on the paper machines, all of which have varying costs. It is important to be aware of which type of felt is intended for the next use in any of the three positions in the press section, for calculation of an expected cost.

Downtime / Shifts
Downtime is attributable to lost production time, therefore is encountered during any stoppage of the paper machine. The downtime due to felt changes varies with both the time of day, and the day of the week.

2 Stochastic Dynamic Programming Model Formulation

Taking the above issues into consideration, we develop a mathematical model to determine a felt changing policy that minimises the overall expected costs. Stochastic dynamic programming is used to develop a model primarily for a single felt, which is then extended to consider the interaction of a system of multiple felts.

There are a number of parameters that contribute to the felt change decision process, which require analysis for inclusion in the stochastic dynamic programming model. These parameters were evaluated from historical data related to felt ages, felt changes and their reasons, machine breakdowns / stoppages and their causes, and the timing of past scheduled shutdowns.

2.1 Events

At any given time, the paper machine can be either running, or stopped. While running, there are a number of events that could occur, affecting the state of the machine, for example, the machine may stop running, or a felt may wear out. These events give rise to circumstances that occur during the normal operation of the paper machine, in which opportunities exist to change a felt outside of the scheduled shutdowns. In predicting the likelihood of these events occurring, and knowing when planned shutdowns are to occur, an informed decision can be made as to whether to keep or change a felt at any point in time.

There are generally two instances in which a decision must be made whether to change a felt; either a scheduled shutdown, or a machine stoppage that has not caused damage to a felt. The required action for any of the other events is pre-determined as the felt has either suffered damage or has reached the end of its useful lifetime, and so must be changed. Figure 2.1 overleaf, distinguishes between the *decision* events and the *action* events.
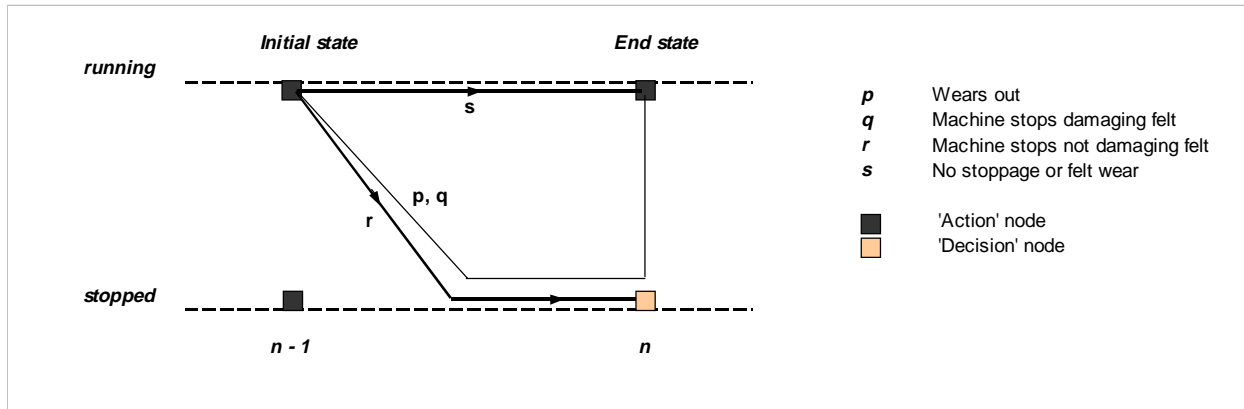
Figure 2.1 Events with pre-determined action or decision opportunity

2.2 Likelihood of Events

Given that at different points in time, the felts and paper machine can be in different states, it is expected that they move between the states with varying likelihood. The following probabilities of events have been determined, as those that change the state.

p = Probability there is no stoppage, but the felt wears out
q = Probability there is a stoppage damaging a felt
r = Probability there is a stoppage not damaging a felt
qp = Probability there is a stoppage damaging a felt, and the felt wears out
rp = Probability there is a stoppage not damaging felt, and the felt wears out
s = Probability there is no stoppage, and the felt does not wear out

Each of these probabilities stem from four basic events, represented in Figure 2.2 below.

P_init = Probability of a felt wearing out within the next day
Q_init = Probability of a stoppage damaging a felt
R_init = Probability of a stoppage not damaging a felt
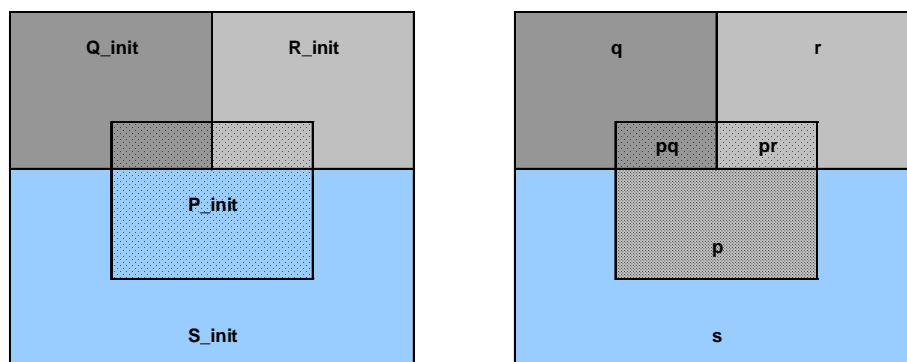S_init = Probability of no stoppage occurring

Figure 2.2 Venn diagrams representing the likelihood of events

The distribution of felt wear over time is modelled by estimated probabilities of felt wear supplied by Tasman Pulp and Paper. The probabilities were found to fit the following empirical distribution.

$$P\_init(x) \ = \ \frac{e^{-\lambda(MaxAge-x)}}{1 - e^{-\lambda(MaxAge-x)}} \qquad , \ x > MaxAge$$

$$= \ 1 \qquad\qquad\qquad , \ x \ otherwise$$

The scale parameter λ is estimated from empirical data provided by Tasman Pulp and Paper.

| In all cases, | $MaxAge$ | $=$ | Maximum age felt can reach |
| | x | $=$ | Current age of the felt |

The likelihood of stoppages, both those that cause damage to felts and those that do not, are calculated by evaluation of historical data of paper machine stoppages.

2.3 Downtime

The cost of downtime is based on a dollar value per minute, directly related to the non-productivity of the machine. The length of downtime can vary in different situations, and these situations have been taken into consideration in the model. There are three primary contributors to the downtime, which are as follows;

Shutdowns and Penalties

The paper machine is periodically stopped for time intervals of 8-12 hours, which occasionally extend up to 16 hours. These *scheduled shutdowns* currently take place at approximately 35-day intervals, and are predominantly for maintenance purposes. A felt change made during a scheduled shutdown is not considered to incur any downtime and the felt can therefore be changed at a lower cost.

Felt changes made during a scheduled shutdown tend to be more efficient, as the change is anticipated and prepared for. To reflect this improved efficiency, a penalty of 2 hours additional downtime is incurred in the event that a felt is changed outside of a scheduled shutdown. This 2 hours relates to extra organisation required in preparing for a felt change, and also allows for the likelihood that maintenance staff and felt change equipment are not immediately available at the time of a stoppage.

Type of stoppage

The type of stoppage has a significant impact on the cost of the downtime. The two general forms of stoppage have been defined as; *decision dependent* and *decision independent*.

Decision dependent stoppages are those which are within our control, as the choice we make to either change or keep a felt when an opportunity arises, influences the future likelihood of these stoppages occurring e.g. The event that a felt wears out. Decision independent stoppages are those which lie beyond our control, as the choice we make to change or keep a felt has no effect on the occurrence of these stoppages e.g. The event of a mechanical machine failure.

In the case that a stoppage is due to a felt either wearing out or suffering damage, there is no decision to be made as the felt must be changed. The associated downtime cost is the time taken to replace the felt and start the machine running again and the associated penalty cost for changing outside of a scheduled shutdown, as previously discussed.

In the case that a decision independent stoppage occurs not causing damage to a felt, a decision must be made whether or not to take the opportunity to change. Given that downtime is accounted for at the cause of the stoppage, any felt maintenance performed during a decision independent stoppage, which is out of our control, is not considered to incur any additional downtime, therefore, potential savings could be made.

The length of a stoppage is considered to be uncertain at the time of occurrence. An expected stoppage duration can be evaluated from historical data, and an estimation of the potential savings can be calculated.

Time taken to change a felt
The time to change a felt is dependent on both the type of felt, and the time of day. As previously discussed, there are two types of felt currently being used on the paper machines, seamed and endless. The seamed felts are designed with a zip-like seam, which makes the felt easier to change. The endless felts however, are continuous, and significantly more difficult to change. It also takes around 1 hour longer to change a felt on an evening shift, compared with a day shift.

3 Model for a single felt

The model for a single felt was initially developed with time stages of 24-hour days, which was then extended to time stages of 12-hour shifts to incorporate additional factors that arise due to the time of day.

Stochastic dynamic programming (see [1]) uses a *backward recursion*, which begins at a point in the future, at the end of a finite *planning horizon*. The model evaluates stage by stage, what the best decision would be to get to the next stage, for each of the possible states the system could be in at that time.

For our model, let $V_n(x,z)$ be the expected cost to go with n periods remaining and a felt of age x, given the machine is in state $z \in \{0,1\}$, where 0 denotes a stopped machine, and 1 a running machine. We then have the following recursion:

$V_n(x,0) = \min\{\text{Cost of a felt change} + \underset{z}{\text{E}}[V_{n-1}(0,z)], \; \underset{z}{\text{E}}[V_{n-1}(x+1,z)]\},$

$V_n(x,1) = \min\{\text{Cost of a felt change} + \text{Cost of a stoppage} + \underset{z}{\text{E}}[V_{n-1}(0,z)], \; \underset{z}{\text{E}}[V_{n-1}(x+1,z)]\}.$

The general recursion is modified for three different situations in the stochastic dynamic model.

Shift is a standard shift
If the time stage is a standard shift with no special considerations, the general recursion is implemented, without any modification.

Shift is a scheduled shutdown
If any time stage is a scheduled shutdown, the cost of changing a felt is considered to be zero. The change decision is evaluated by the actual felt cost and the expected *cost to go*.

Shift is prior to a scheduled shutdown
If any time stage is an immediate predecessor of a scheduled change, then regardless of the event that occurs, the system will result in a stopped state at the end of the time stage.

3.1 Assumptions of model

- Only one event can occur in any given time period. The model works on the assumption that the resulting state of an event occurring between two time steps, is the state at the end of the time stage

- Any felt change made on a scheduled shutdown incurs the cost of a new felt, but is free of a downtime expense

- A felt may not be kept after it reaches its maximum expected age. In reality, some felts may wear better than others, dependent on factors such as product type and variations in the concentration of the pulp.

- Felt damage is assumed to be non-repairable. In reality, some holes can be repaired.

- Felt damage is independent of the age of the felt. Stoppages due to damage are assumed to occur randomly, affecting any of the three felts with differing likelihood.

- Downtime due to machine stoppages outside of our control is accounted for in other areas of the mill. Any work or maintenance performed on the press section of the paper machine during these stoppages are assumed to be free of a downtime expense.

- Analysis of the stoppage duration considers any stops greater than 13 hours to be exceptional occurrences and are not accounted for in the estimation.

- It is assumed that at any time, it is known which felt is to be used next in any of the three press positions.

4 Model for a system of multiple felts

From the development of the stochastic dynamic programming model for a single felt, we extend the single felt model to consider a system of multiple felts, in particular the three felts in the press section. The same approach was taken as for the single felt model, however the increase in the number of felts multiplies both the number of state variables and the combinations of possible events.

The single felt model produced an optimal decision for a felt of a particular state, at a given time stage. Similarly, the triple felt model considers the state of each felt at any point in time, evaluating both the likelihood of possible events and the cost of their occurrence, to produce an optimal decision policy for any given state. The expansion to a model for three felts added both state variables and possible events to those already existing in the single felt model.

5 Comparison of Models

The main difference in the two felt change models is the increase in the number of opportunities for felt changes. The multiple felt model gives rise to situations in which more than one felt can be changed at one time. The triple felt model has eight decision options, resulting from all possible combinations of keeping and changing the three felts.

Increased computational time
The extension of the stochastic dynamic programming model for a single felt, to a model that allows for the interaction of multiple felts, greatly increased the number of possible states the system could be in at any time stage. This in turn significantly increased the time taken to run the model for a system of multiple felts.

Representation of solutions
At each time stage in the single felt model, there is an age at which it becomes the best decision to change the felt, as opposed to keeping it. These results are easily represented either in table form, or graphically. Representation of the decision policy for the multiple felt model is more difficult as there is no specific age at which it becomes best to change a felt as opposed to keeping it. The decisions are dependent not only on the age of a particular felt, but also on the ages of the other two felts in the system.

Trade-offs between models
The stochastic dynamic programming model for a multiple felt system gives consideration to the interaction of the three felts as a complete unit, providing a much more accurate estimation of the likelihood of an opportunity to change one or more felts than the single felt model.

To reduce the computational time of the model for a system of multiple felts, the decision policy can be determined at time stages of 24-hour days, as opposed to 12-hour shifts. This means cost differences between day and night shifts will not be taken into consideration in the policy, a factor that can be retained in the decision policy for a single felt.

The single felt model is also more easily implemented than the model for a multiple felt system, by means of visual tables and charts. A disadvantage of the model for a single felt, is that proper consideration is not given to the influences of the other two felts in the system.

6 Results

In order to test the results of the felt change model, the policy was put into practice in a simulation using past data. The stochastic dynamic programming model for a single felt was used.

The parameters for the likelihood of occurrence of certain events, as defined in Section 2.2, were evaluated from data outside of the time frame considered for the simulation. This precaution removes the possibility of the model being biased towards data from the period used in the simulation. The types of felt used, damage to felts and timing of scheduled shutdowns were kept consistent in the simulation with those made by Tasman Pulp and Paper during the same time period.

6.1 Simulation Results

ACTUAL represents the changes that were made by Tasman Pulp and Paper
MAXIMUM represents the simulation run with maximum felt ages of 45 and 80
    - Considered to be maximum felt ages following discussion with Tasman staff
RESTRICTED represents the simulation run with maximum felt ages of 40 and 70
    - Considered to be maximum felt ages during the simulated time period

SCENARIO	Pos. 1 changes	Pos. 2 changes	Pos. 3 changes	% On shutdowns
Actual	8	10	12	80%
Maximum	8	10	12	90%
Restricted	8	10	11	24.14%

Table 4.2 Results of model simulation

In the 'Restricted' case, the shutdowns are more closely in synchronisation with the expected maximum operating ages of the felts, ie. Scheduled shutdowns at intervals of 35 days when the felts are expected to reach either 35 or 70 days before wearing out, the model is likely to make a saving on the felt cost. In contrast, if the maximum felt age exceeds the time between scheduled shutdowns, the likelihood that a felt will last until the

next scheduled shutdown increases, therefore a higher proportion of changes are made on the scheduled shutdown dates.

There are a number of factors to be taken into consideration in evaluating the results of the simulation. The simulation was done using the stochastic decision model for a single felt, as opposed to the stochastic decision model for a system of multiple felts. There would be times in the real life situation that opportunities arose to change a felt due to wear of the other felts, which were not considered in the simulation.

6.2   Multiple felt model results

The stochastic dynamic model for a system of multiple felts was trialed also. The results clearly show a relationship between the ages of the three felts and the optimal decision for each time stage. There is clear interaction between the likelihood of one felt failing and the decision to change or keep another felt.

6.3   Applications of the model

There are two main areas in which the stochastic dynamic programming models are applicable; as a generic analytical tool and for producing a felt change policy.

Analytical tool
The results of the simulation show that the timing of the scheduled shutdowns has a direct effect on the ability to make long term savings on felt costs. The stochastic dynamic programming model is therefore applicable for use as an analytical tool to investigate the effects of rescheduling the maintenance shutdowns at different intervals.

Felt Change Policy
The results from the simulation show the model to be as good as or better than Tasman Pulp and Paper's current decision making methods. This suggests that implementing the model as a reference in the instance that an opportunity arises to change a felt, could provide savings in the long term planning horizon.

Acknowledgements

References

[1] Wagner, H. M. (1969) *Principles of Operations Research with Applications to Managerial Decisions.* Prentice-Hall, Inc., New Jersey.