RISK BASED DECISION MAKING APPLIED TO MAINTENANCE POLICY SELECTION

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Abstract.
The maintenance activity is related to actions aiming to keep the equipment operational capability level greater than a minimum value defined according to the production planning requirements. Those requirements usually are based on manufacturing volume and product quality goals.
The conceptual analysis of the recently developed maintenance selection techniques reveals that they do not strongly considers the costs associated with maintenance activities. Their main concern is the equipment reliability and how it degrades through the operational life. There is a great effort to define the equipment failure modes, how those modes affect its operational performance and what are the maintenance actions that can be taken to minimize a given failure mode occurrence probability. However the relation between the maintenance costs and failure mode occurrence probability are not considered in the decision making process once it is mainly based on technical aspects regarding equipment reliability.
Aiming to define a relation between the cost and technical aspects of the maintenance activities, this paper presents a method to evaluate the costs associated with a maintenance action, including those related to the failure and also those related to the consequences of failure for the manufacturing plant and for the product. Using the concepts of the decision-making theory a logical decision structure is proposed to select the best maintenance policy. The decision is based on the relation between the failure costs and the failure probability. The method is used to select the maintenance policy for an equipment installed in a food processing plant.
Keywords*. maintenance policies, risk analysis, decision making, risk assessment.*

1. Introduction

The concept of risk is used to assess and evaluate uncertainties associated with an event. Risk can be defined as the potential of losses as a result of a system failure, and can be measured as a pair of the probability of occurrence of an event, and the outcomes or consequences associated with the event's occurrence. This pairing can be represented by the following equation:

$$Risk = [(p_1, c_1), (p_2, c_2), \ldots\ldots\ldots\ldots, (p_n, c_n)] \tag{1}$$

In this equation p_i is the occurrence probability of event i, and c_i is the occurrence consequences or outcomes of the event. Risk is commonly evaluated as the product of likelihood of occurrence and the impact of an accident:

$$Risk\left(\frac{Consequence}{Time}\right) = Likelihood\left(\frac{Event}{Time}\right) x\ Im\ pact\left(\frac{Consequence}{Time}\right) \tag{2}$$

In the above equation, the likelihood can also be expressed as a probability. A plot of occurrence probabilities and consequences is called the Farmer curve. The risk for a system results from the interaction of natural hazards with a system, aging and degradation of the systems, and human factors. Consequently, risk can be classified into voluntary and involuntary depending whether the events leading to the risk are under the control of the persons or not, respectively. Society, in general, accepts a higher level of voluntary than involuntary risk. The losses associated with events can be classified into reversible and irreversible such as property and human losses, respectively. The population-size effect should be considered in risk studies since society responds differently for hazards associate with a large population in comparison to a small population. Risk methods can be classified into risk management that includes assessment and control, and risk communication. The risk assessment includes analysis and evaluation. The analysis consists of hazard identification, event-probability assessment, and consequence assessment. Risk evaluation requires the definition of acceptable risk, and comparative evaluation of options and/or alternatives. The risk control can be achieved through monitoring and decision analysis. Risk communication depends on the targeted audience, hence, classified into communication to the media and the public and to the engineering community.

The selection of a maintenance policy for an equipment or even a production line can be considered a risk-based decision analysis once the maintenance actions aims to reduce the failure probability. However, the maintenance costs can increase as a function of the maintenance policy, and the risk analysis provides a qualitative approach to evaluate the effects of a maintenance policy in terms of failure probability and costs. Aiming to define a relation between the cost and technical aspects of the maintenance activities, this paper presents a method to evaluated the costs associated with a maintenance action, including those related to the failure and also those related to the consequences of failure for the manufacturing plant and for the product. The method is used to select the maintenance policy for equipment installed in a food processing plant.

2. Scenario Understanding

The way and the quality of information are essential for a correct scenario definition. APELAND e AVEN (2000) affirm that technical features are reliable and generate good information, but risk perception – always considered as subjective – is poor, due to either wrong communication or fail in determine exactly the extent of failure consequences.

Many kinds of activities have generated risk analysis concepts, such as medical, military and financial, so bringing such concepts to the engineering context may generate some loss of objectivity and problems in understand information Sometimes, risk research appointments are quite generic, so the AIHC (American Industrial Health Council) established the kind of information to be presented, such as: risk situations establishment must be as wide as possible and understandable; utility and applicability of risk analysis for decision making must be clearly explained; presentation of obtained information must be clear and reliable enough, in order to avoid unexpected events occurrence; risk analysis report must contain a brief abstract that includes a balance between those features analyzed, hypothesis formulation basis must be a scientific approach, and any conclusion must come from risk management frame, APELAND e AVEN (2000).

Once technical and tangible information about initial failure of equipment is available, engineers can deal with risk situations in a confortable way; problems arise when one must deal with consequences. Often, a qualitative analysis is performed to determine the failure scenarios. But, when it's necessary to make some decision, a quantitative approach takes place, at least some probability must be known, and it will be associated with a consequence index. The main problem in risk situation identification is exactly to determine how significant those consequences are. Technical features are met by using many approaches, according to CROWE, DANA and FEINGERC (2001), but in terms of management and decision making, technical issues are not enough. It's needed to determine consequences of an event. Such consequences can be present in several types and nature, for instance, loss of human life, recall needs, replacement, loss of market share, anyway, every kind of consequence involves costs and this is the basis to be adopted to evaluate failure effects, since it's possible to determine or at least to estimate costs of failure itself, costs of failure extensions, warranty costs and so on, according to CARDOSO (2004). It must be reminded that some level of risk is always acceptable and the decision about accepting or not that risk is based on consequence extension and priority, BEVINGTON e GOSAIN (2005).

A decision model must be fed with probabilities and consequences extension. Many models have been developed, such as AHP (Analytic Hierarchy Process), Game Theory, and others. All of them are based on reliable information. In maintenance, AHP has been used with success, but this method requires well-specified scenario, corrects prioritization of events and, mainly, well stated criteria for decision making, according to SHIMIZU (2001) and CARDOSO et al. (2002). AHP model is used for maintenance decision-making purposes, however, is a complex method and determining priorities between each scenario is not easy and charges the method with uncertainties.

This work adopts a model based on SOUZA and AYYUB (2000) suggestion, using the cause-consequence diagram to determine failure consequences and building a decision tree to combine probabilities and failure consequences, to choose and apply the best maintenance policy.

2.1. Failure Effects in Operational Context

This work is based on a research in a food processing plant, whose lay out is shown below on Figure 1.

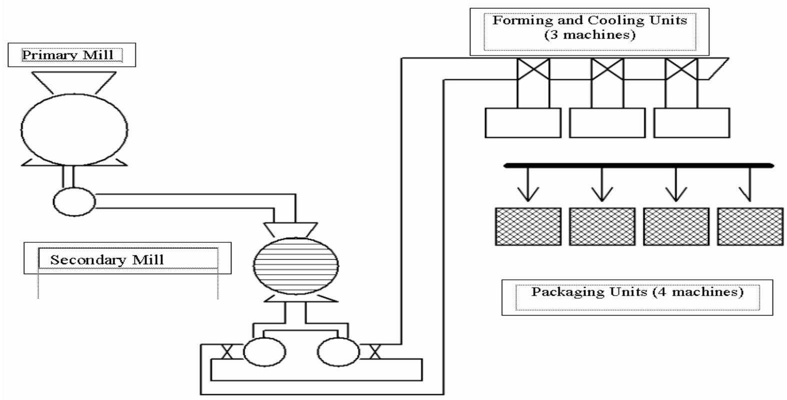

Figure 1. Food Processing Plant Lay Out

There are redundant components in this system, such as packaging units and molding units, but critical equipments and the overall aspect is a series type system, O'CONNOR (2002). Many failures can potentially stop the production.

The primary mill prepares sugar to be added to fat and powdered cocoa on the secondary mill. The primary mill is driven by a belt transmission at a 15000 rpm speed, such temperature forces the roller bearing to reach up to 170 ^{o}C, the problems become worse due to the impossibility of using forced lubrication, so bearings must be sealed, so the cooling is affected. The secondary mill is used to mix sugar, vegetal fat and cocoa (plus chemical additives) and often is operated over 4 hour a batch (depending on the type of product), handling 3600 kg of compound. Sometimes, nuts are added to the formula. Nuts may harm stirrers and if a small piece of metal is found, consequences are potentially heavy, especially regarding exported products, subjected to lawsuit. No lubrication is allowed in this machine, since temperature reaches over 80 ^{o}C, bearings can be severely damaged. Debris can damage the set of pumps that push the liquid chocolate to the upper floor in order to distribute the product to cooling lines. Cooling and forming machines are not too complex, they consist of belts moving inside a cooled chamber to crystallize the chocolate and give it the desired shape, always using molds (egg shaped, ball shaped and bars). There are 4 sets of cooling and forming machines. They don't operate in full time since it's needed to wait for the compound, but it's possible to use them as back up for other lines if they are inoperative. Packing machines are complex and mechanically driven, however, there are many units and a failure can be admitted. The most critical equipments are primary and secondary mills because most of the failures on their components can stop them or induce failures over other equipments, such as pumps and nozzles. So it's quite simple to determine the extension of a failure over the production line and over the product.

So, after collecting failure data and verify which maintenance practices are suitable, some items were submitted to a new maintenance practice and new data were collected. So, probabilities could be obtained for pure corrective situation and for other maintenance approach, whose scope is appropriate for the situation, according McCOLLIN (1999).

2.2 Field Failures Data Collected

For the primary and secondary mill, data were collected for approximately 1 year. This period corresponds to approximately 5600 service hours. During this time belt rupture and roller bearing failure were the most frequent failures. Since the failure in roller bearings were numerous and the rotor is directly driven by the pulley, belt rupture is suspiciously related to roller bearing failures, there's a coincidence, belt failures occurs almost at same time than roller bearing failure, note that this failure (bearing) is catastrophic. For the secondary mill, stirrer bearings and stirrer wear out were the most common failures. Stirrer bearing failure is progressive and symptoms are clear. Stirrer wear out is a hazardous failure since pieces of metal are detached from the component and can damage pump rotors or reach pipes and harm nozzles. Other consequences is the presence of metallic pieces can in the productthat cause contamination (Pb, Cu, Fe, Cr are main contaminants) or injuries to the consumer. Lawsuit costs are unpredictable, but if such consequence takes place, export contracts are cancelled, so losses are known in this case. Table 1 shows failure data collected for the primary mill during a year period. Table 2 shows failure data for the secondary mill. In the Table 3, failure time for the roller bearings and time to failure for each new part in service is shown.

Table 1. Failure Data Collected for Primary Mill Failures

Component	*Roller Bearing*	*Belt*	*Engine Fuse*	*Knives*
Number of Failures	10	14	6	4

Table 2. Failure Data Collected for Secondary Mill Failures

Component	Quantity of Failures
Stirrer Bearings	2
Stirrer Blades Wearout	3

Table 3. Failure Time and Time to Failure for Roller Bearings

Time (h)	157	672	1535	2126	2702	3506	3991	4581	5039	5597
Time to Failure (h)	157	515	863	591	576	804	485	590	458	558

For the primary mill, there are some points to be checked. Firstly, roller bearings failure is the most significant one, being the highest potentially hazard to the machine and having serious consequences to the production line. Such failure induces problems over engine fuse, which overheats due to excess of electrical current. Belt rupture is typically roller bearing failure induced, because a failing bearing requires more energy to be driven and forces on belts are increased, leading to the rupture. Although bearing failure immobilizes the machine, belts can be damaged even during bearings failure development. If the primary mill operates under bearings failure, possibly the sugar won't reach the size grain desired and the next phase can be affected. Not only the product quality is affected, but also sugar pellets can accelerate the stirrer blades wear out and damage pump rotors. A very bad situation was observed 2 times, when metallic parts were bounced from roller bearings and after the second roller bearing crash the mill was out of service during 21 days.

For the secondary mill, the stirrer bearings failure has a long development and noise produced is easily identified, so it's relatively simple to detect and solve the failure, the worst consequence is to stop the machine (the product batch can still be handled after the failure is fixed). Stirrer blades wear out is a more hazardous failure, because metal particles can block pump folds, damage rotors or, in the worst case, small metallic pieces can be delivered with the product potentially causing injuries or suffocation. Lawsuit charges are unpredictable, but loss of export contracts can be estimated and set as a consequence. Once failures are defined, it's possible to proceed with the method application.

3. Method Application

3.1. Cause-Consequence Diagrams Drawing for The Selected Failures

Cause-consequence diagram is a tool used to determine the events that might occur if a primary event starts. Such tool provides a more comprehensive overview if compared to FMEA, since several paths can be investigated and consequences are taken in a wide scope, not only regarding equipment or production line.

Once the hazards are identified, they form a basis for defining the initiating events. The suggested methodology transforms these initiating events into risk measures or profiles. After identifying the initiating events, all possible outcomes for the system as a result of these initiating events must be evaluated. The outcomes are defined based on scenarios that consider a given hazard as a basic event, and describe the event propagation in the system, defining all the possible outcomes associated with that hazard.

The description of the hazard propagation in the system can be executed using cause-consequence diagrams, which is a marriage of event trees and fault trees, as shown in Figure 2. The cause part of the analysis uses the fault tree technique to define the likelihood of occurrence of the initiating event. In the cause analysis, possible causes to each initiating event are identified to the extent necessary to estimate the needed likelihood of occurrence. The consequence analysis results in a description of all relevant accident scenarios given the occurrence of the initiating event and is used to calculate both the likelihood and the consequences of each accident scenario. Scenario building requires answering the following questions:

1. Under what conditions does the event lead to further events?
2. What alternative plant conditions lead to different events?
3. What other components or sub-systems does the event affect?
4. What further events does this event cause?

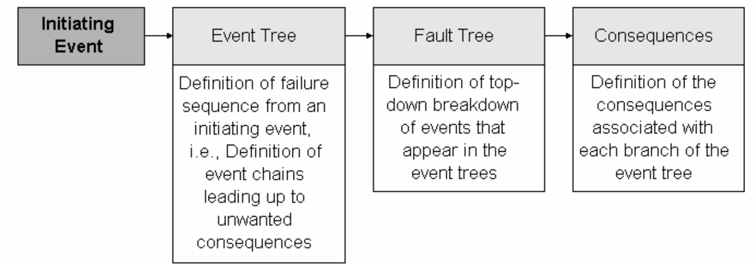

Figure 2. Basic Steps for Performing a Cause-Consequence Analysis

Figure 3 shows the cause-consequence logics. Figure 4 and 5 show the diagram related to the primary mill roller bearings failure and the cause-consequence diagram related to the secondary mill stirrer blades wear out, repectively.

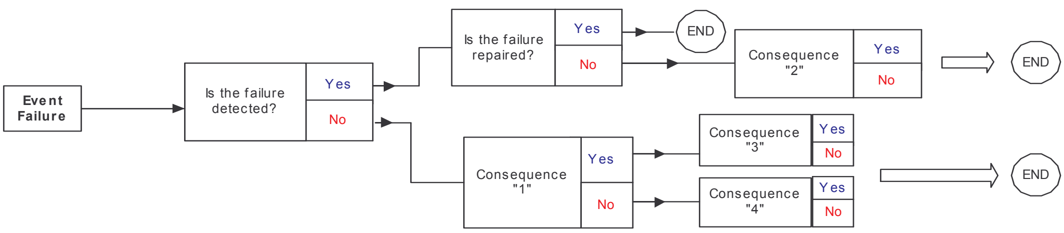

Figure 3. Cause-Consequence Diagram Logical Notation

Once extensions are determined, it's needed to establish probabilities associated with each scenario and costs related to this scenario, in order to build a decision procedure, which allows the decision making. A worth feature of such method is to support the elaboration of a complete maintenance decision making policy, comprising maintenance practices, time intervals, cost analysis, resource allocation and effects over the global operation scenario in a single method. This is an advantage if compared to Reliability Centered Maintenance (RCM) and reliability tools when used isolated, such as FMEA and FTA, according to CARDOSO (2004).

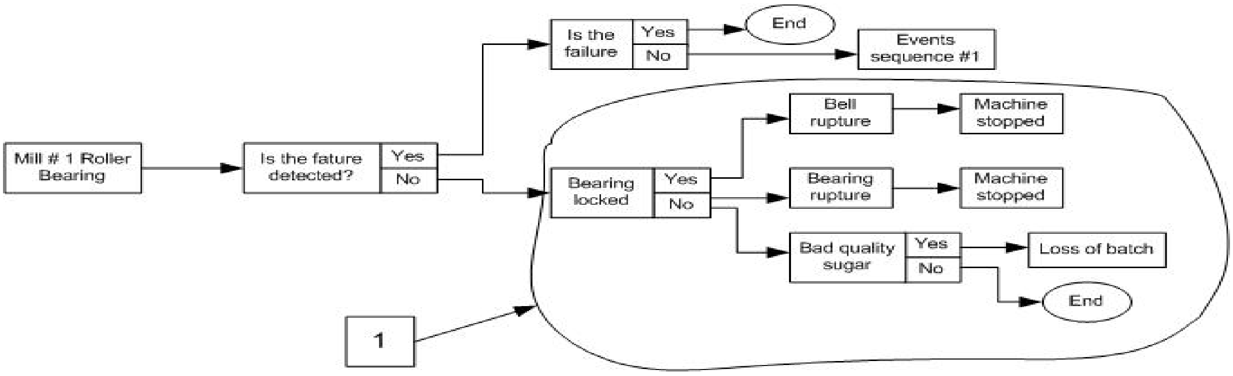

Figure 4. Cause-Consequence Diagram for the Primary Mill Roller Bearings Failure

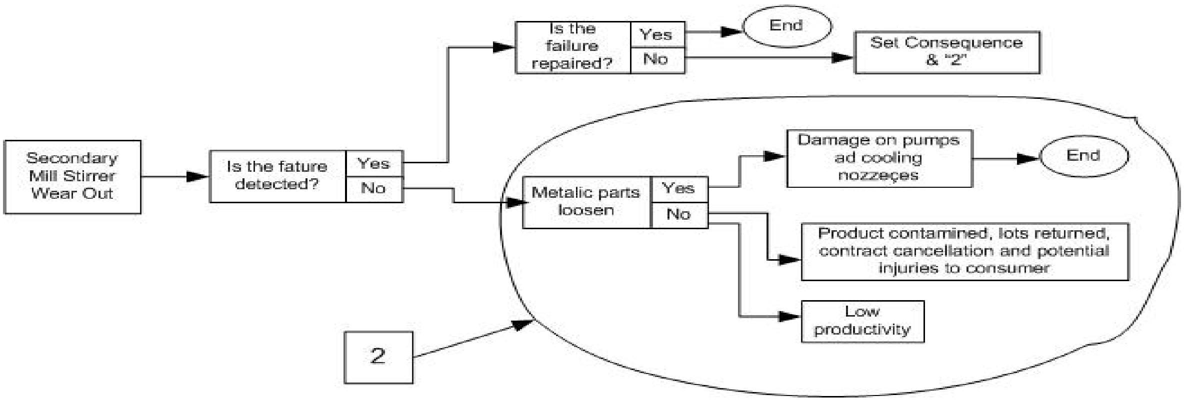

Figure 5. Cause-Consequence Diagram for Stirrer Bearings Wear Out Failure

3.2. Probabilities Calculation

To calculate probabilities related to selected failures, some points need to be explained. Firstly, equipments are mainly mechanical, but during the period of data collection only corrective interventions were done. There's no tendency whether such behavior denotes growth or reduction. With this hypothesis in mind, is possible to calculate the mean failure occurrence rate (λ), by using Eq. (3). If such rate is assumed to be constant, failure probability for a given failure mode can be calculated by using the Poison model, according to CARDOSO (2004), this distribution is expressed by means of Eq.(4).

$$\lambda = n/T \tag{3}$$

In Eq. (3), n is the quantity of failures given a specific failure mode during the period of time T.

$$p(X) = \frac{\lambda^X e^{-\lambda}}{x!} \tag{4}$$

When using Eq. (4), $X=1$, since when one failure occur, some maintenance action must be carried out and the production line will be out of service. In other words, the target value is the probability of one failure occurring at a period of time. Even if more than one failure occur at the same period, the subject is concerned to one event, since the maintenance action is required, once only corrective actions are carried out.

For the roller bearings primary mill failure, data were grouped into 600 hours intervals during a 6000 hours total time for observation, regarding only operational hours, as shown in the Table 4. Failures concerned to secondary mill were observed during the same period, but exact failure time was not recorded, since wear out is a cumulative failure mode, according to SHIGLEY et al (2004), and symptoms become evident earlier than pitting or metallic parts loosen are noticed. Just 2 failures were observed during such time.

For the roller bearings failure, by using Eq. (3), λ=1 was obtained, assumed as a constant value. In such case, probability of failure (p) is p=0.3679. From the Table 3, the mean time to failure is 559.7 hours. So, 500 hour seems like an appropriate time to replace roller bearings, just 2 failures occurred at times less than 500 hours. For sure, there's some loss, since there are items failed over 800 hours, but safety is accomplished when using 500 hours, even it's impossible to assure that the machine didn't fail due to overload or operational fault, especially regarding the first failure observed (the first roller bearing failure was monitored since the part was installed, i.e., since new). Choosing another class of roller bearings due to the high rotational speed contributed to reduce failure occurrences during the subsequent period (6 months), no failures of roller bearing were observed, however, some care must be taken in affirming that failure probability drop to zero, since the period was shorter than the former one and 500 hours seems like too far from the mean time to failure observed during 1 year.

Table 4. Grouped Data for the Primary Mill Roller Bearings Failure

Intervals (hours)	0 to 600	601 to 1200	1201 to 1800	1801 to 2400	2401 to 3000	3001 to 3600	3601 to 4200	4201 to 4800	4801 to 5400	5401 to 6000	Total
Quantity of Failures	1	1	1	1	1	1	1	1	1	1	10

For the stirrer blades wear out failure, two failures were reported during the same period considered for roller bearing failures, so λ=0.2 and p=0.1638. No data regarding failure times are available, but such failure has a long development time and symptoms are clear. In this case, a conditional inspection can be carried out periodically, since the preventive replacement is not worth, not only due to costs involved and data missing, but because preventive interventions can damage bearings and other parts of the equipment. After adopting conditional inspection and monitoring operation for 6 months, no failure was reported. Once inspection methods and non destructive tests are expensive and not effective for this case, a simple practice was adopted: a filter was installed in the outflow pipe, before pumps, and the grid is magnetically attractive to metallic parts. During the conditional inspection, this grid is examined, if metallic parts are found or grid is blocked, blades are replaced.

3.3. Costs Calculation

For the primary mill, costs are related to the replacement of bearings, repairs in the machine (if necessary) and, in some cases, the loss of production. Related to repairs in the machine, the representative of the manufacturer only requires the technical per hour work cost – a fixed value - plus spare parts. It's hard to determine the cost related to the loss of production. Data concerned to repair times are not available, but if the worst case is taken into account, the mill was twice out of service during 21 days. 18 of those days were working days. The plant works 18 hours a day, so, it's worth to affirm that 324 productive hours are lost. Since the mill stop also implies in the production line stop and regarding the production capability as 3600 kg each 4 hours, if time to setup and cleaning (about 2 hours a day) is rebated, total working time is 16 hours a day, around 260000 kg (260 tons) of product (chocolate) were not produced. Mean price to deliver the product is about R$ 12,00/kg, so, in the worst case, R$ 3120000,00 are lost. This results, considering 18 days at 16 hours a day, in an R$ 10833,33 cost per hour. For the worst case, total repair costs, including manpower was R$9500,00. Associated cost to this scenario is the sum, R$ 20333,33 (for 1 hour downtime). For two times, this associated cost reached R$3129500,00. If only roller bearings replacement is done, corresponding to adopt preventive maintenance to deal with this failure cost is R$ 1050,00 (spare parts plus manpower) and the job takes about 4 hours. Since it is scheduled, according to DRAPINSKI (1973), no loss of production must be expected.

For the secondary mill, costs are related to the repair on blades (it's a mean value since welding work cost is difficult to determine), settings, pump repair, loss of production and loss of contracts. Contract values are not available, so this work only regards loss of production costs, R$10833,33/hour. Settings takes, typically, 6 hours, then loss of production reaches R$64999.98. Repair on blades totalize R$3500,00 (manpower included), but if damage is severe, blades need to be replaced and costs are not available once this case was not observed. If pumps are affected, the most frequent problem is replacing rotors, regarding the worst case, i.e., it's needed to replace rotors for 2 pumps, cost is R$1500,00 (service to be done by an external supplier). In the worst case, total cost is R$69999.98 at a minimum, once loss of contracts or lawsuits are disregarded. If a conditional check is adopted (such conditional check consists in visually inspect stirrer blades and check a filter element - magnetic grid - replacing it if needed, such grid costs R$800,00) costs down to manpower only, regarding 2 hours a day. Every time a new batch finishes a conditional check is done, man power cost (including taxes, legal fares and other duties required) is about R$20,00/hour, so each inspection costs from R$40,00 to R$840,00 if grid needs to be replaced.

3.4. Decision Tree Building

The method presented in this work adopts the Decision Tree, which consists in a logical diagram that figures out alternatives for a decision relating them to possible consequences resulting from this choice, associated to uncertainties from scenarios configured when an alternative is selected. Figure 6 shows the logical notation for decision trees. By taking a branch, when multiplying probabilities associated to each decision node, the total branch probability is obtained, which means the probability of the event represented by such branch. When a consequence is associated to each branch and multiplied by the respective probability, the sum of such results is the mean consequence associated to the initial node. If probability is the probability of failure associated to a specific maintenance policy and consequence are costs associated to such policy, the result is the mean risk associated to a specific maintenance policy, and the decision can be made with the minimum risk in mind, that can be calculated, according SOUZA and AYYUB (2000) and CARDOSO (2004), by using Eq. (5).

$$Mean\ Risk = p_{no\ failure}.Maint.\ Cost + p_{failure}.\Sigma(p_{failure\ i}.Associated\ Cost_i) \tag{5}$$

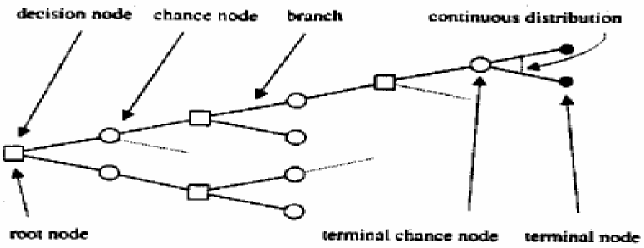

Figure 6. Logical Notation for Decision Trees

For the roller bearings failure, if only corrective maintenance is adopted, p=0.3679, so, if a failure occurs, this probability is multiplied by the total cost estimated in the section 3.3 (R$3129500,00) and the first part of equation 5 is equal to zero. If preventive maintenance is adopted there's a little bit more complicated situation. Although failure data is not available after adopting preventive maintenance, regular conditions can be applied. According SHIGLEY et al. (2004), when selecting a roller bearing, reliability can be set depending on usage conditions. For the case studied, where temperature and rotational speed are high, but no impact is present, reliability can be assumed as 95% (0.95). A simplified calculation gives a 5% probability of failure - of course, reliability is referred to a new element and decreases continuously with the time, CARDOSO (2000). So, the maintenance cost must be multiplied by 0.95 and the second term is obtained by multiplying the probability failure (5%) by associated cost and summing with the full preventive maintenance cost.

For the stirrer blade failure, if only corrective maintenance is adopted, the first terms equals to zero. If conditional check is adopted, however no failure was observed after implementing it, 95% reliability is adopted, so failure probability is 5% (a simplification is done). Procedures are the same as for roller bearings failure.

Figure 7 and 8 show the decision trees for roller bearings failure and for the stirrer blades failure, respectively.

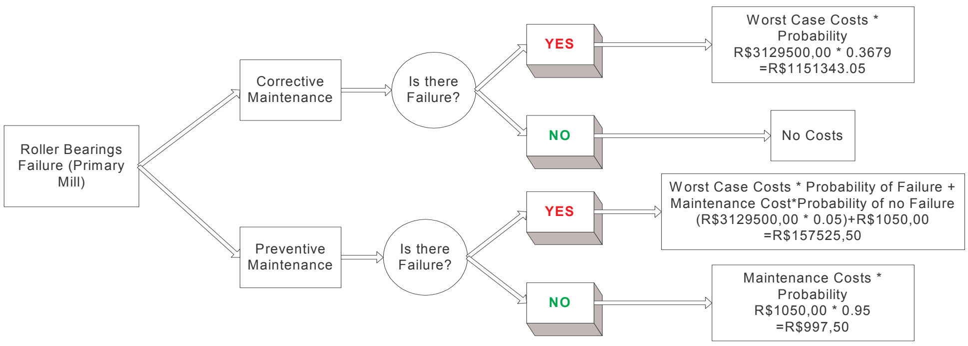

Figure 7. Decision Tree for Roller Bearings Failure in the Primary Mill

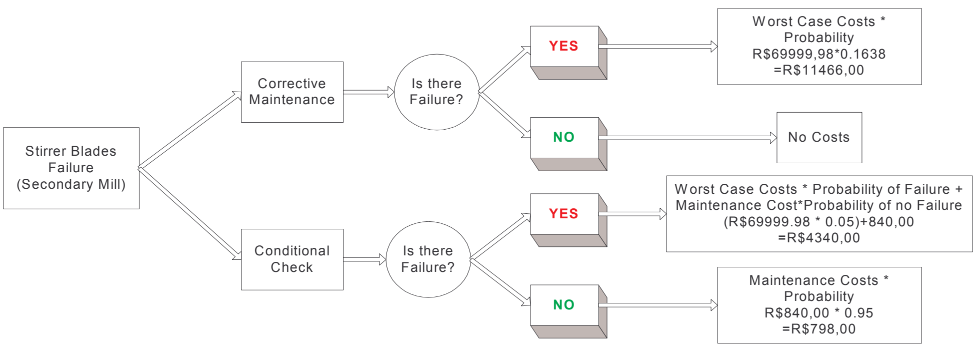

Figure 8. Decision Tree for Stirrer Blades Failure in the Secondary Mill

It must be noticed that failure associated costs in the Figure 8 can be much higher than the calculated due to lawsuits and loss of contracts, reposition of products in the market, etc. Anyway, this fact doesn't change the decision, since the adoption of the conditional inspection is favored.

3.5. Decision Making

Once decision trees are built, the decision making – in other words, the selection of the appropriate maintenance policy - is a matter of comparing mean risks for each branch. For both roller bearings failure and stirrer blades failure, data are shown in the Table 5. The decision is made with the minimum mean risk value.

Table 5. Mean Risks Associated with Maintenance Policies Alternatives to Decision Making

Failure Observed	Mean Risk associated to Corrective Maintenance	Mean Risk associated to alternate policy			Decision
		Fail	Not Fail	Total	
Roller Berings Failure (Primary Mill)	R$ 1,151,343.05	R$ 157,525.50	R$ 997.50	R$ 158,523.00	R$ 158,523.00
Stirrer Blades Failure (Secondary Mill)	R$ 11,466.00	R$ 4,340.00	R$ 798.00	R$ 5,138.00	R$ 5,936.00

From the Table 5, it's seen that alternative maintenance policies resulted in lower mean risks, these risks take into account technical issues and financial features. So, for the roller bearings failure, preventive maintenance as stated in the section 3.2 is the selected policy and for the stirrer blades failure the conditional inspection is the policy selected.

4. Conclusions

Risk based decision making appears to be a worth method when applied to maintenance policy selection, once specific criteria beyond technical features can be met. An important step when performing such risk analysis is to determine scenatios of failures because consequences must be clear and costs strongly depends on events and practices identified and how they affect the enterprise operation. Even if no preventive practice is appropriate, it's possible to reduce probability of failure and/or failure consequences, sometimes this is only possible by refurbishment or changes in the production, even if maintenance is not the responsible to carry out such matter, decision making is depending on maintenance issues. Better maintenance practices reduce mistakes possibility and may lead to less hazardous consequences, when preventive and predictive practices are appropriate, this feature becomes more and more important.

However, preventive practices can cost more than the corrective practices and their associated consequences, whether due to reduce in a small amount the probability of failure or replacement, manpower, downtimes and associated (including consequences) costs are high. These possibility figures out clearly in the decision tree and managers have been complaining for years regarding the conflict between technical features and financial decision making.

This work deals with all aspects that must be taken into account in the maintenance decision making process. By using reliability concepts and tools, according to CARDOSO (2004), it's possible to obtain refined policies, comprising details such as time to repair, availability, combined practices, and other maintenance policies can be used to enrich this method, for instance, TPM (Total Productive Maintenance) concepts help to define detailed procedures and RCM can be used to set requirements and indexes, optimizing the performance control.

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