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INTEGRATING SIMULATION MODELING AND EQUIPMENT CONDITION DIAGNOSTICS FOR PREDICTIVE MAINTENANCE STRATEGIES –A CASE STUDY

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ABSTRACT

This paper presents results from a case study in predictive maintenance at a distribution warehouse. A simulation model was built with ARENA™ 5.0 for integrating predictive maintenance strategies with production planning strategies, for a conveyor system. Equipment health was monitored using condition-based parameters such as temperature and vibration for mechanical and electrical components such as rollers, electrical motors, and gearboxes. This diagnostic information was then integrated with a simulation model to simulate various equipment breakdown and failure conditions. Integration of condition-based monitoring of conveying equipment with a simulation model of the distribution system has provided a useful analytical tool for management to reduce production downtime due to unplanned maintenance activities – in this instance, downtime was reduced by more than 50% and work in process inventory was reduced by more than 65%.

1 INTRODUCTION

Maintenance is an important determinant of industrial productivity. A predictive rather than a reactive maintenance policy is desired as the most effective way of reducing costs due to unexpected failure and stoppage of equipment.

Predictive maintenance is based on continuous monitoring of equipment through sensor-based data collection equipment, and specialized technologies to measure specific system variables. In small industries with limited maintenance resources, however, reactive maintenance is the dominant practice. Implementing an effective predictive maintenance plan represents a considerable change in policies and resources assigned to maintenance tasks.

Condition-based predictive maintenance can be implemented by manufacturing industries to detect faults, and for troubleshooting and anticipating equipment failure (Murty and Naikan 1996). Companies can optimize maintenance resources when predictive information is available.

The present case study was developed and implemented in a garment distribution center with a production plan determined by a variable daily demand, based on monthly expected production goals. Simulation was used as a tool to compare the preventive and predictive maintenance policies.

2 PROBLEM SETTINGS

2.1 Company Background and Equipment

The industry in this case study is a garment distribution center and warehouse, located in Santa Teresa, New Mexico. At the distribution center, garments are packaged in boxes filled with different types of garments such as skirts, trousers, blazers, shorts and shipped to small and large department stores and clothing retailers in the United States such as J.C. Penny, Sears, etc. Garments are filled into boxes based on customer orders received (dubbed *wave*) in a day. Each *wave* is unique to a particular customer's needs, and is dependent on the market demand for the product, and inventory levels of a specific type of product at the customer's warehouse, season of the year, etc.

Two hundred and eight AC induction motors drive the roller and belt conveyors in the entire warehouse; gearboxes coupled to the motors control speeds of rollers and belts. Motors in the warehouse vary in horsepower depending upon the number of rollers driven by the motor. Motor ratings in the plant are 0.75, 1, 1.5, and 2 HP. Gearboxes in the system have speed ratios in the ranges 15:1, 20:1, and 30:1. Gearboxes with lower speed ratios are used in work zones where boxes move in a straight line, and hence move faster. Gearboxes with higher speed ratios are used in work zones with curved cross-sectional areas. Motors and gearboxes being used are from several different manufacturers.

Four optical scanners located at sections of the conveyor system, where the conveyor branches into different work zones and direct boxes to appropriate routes in the system; the routes are determined by the *wave* on a particular day. Pneumatic clutches are coupled to certain motors to stop these motors from driving the system in the event of blockage in any part of the conveyor. Numerous photovoltaic cells placed at strategic locations on the entire conveyor system detect and prevent clogging of the boxes in case of a stoppage in any part of the system (Chopra 2001).

2.2 Technical Background

The maintenance practice being used currently at the distribution center for the AC motors was based on routine and scheduled maintenance inspection, and reactive maintenance. Two maintenance personnel work in each of the two shifts sometimes performing routine preventive maintenance activities, and also reacting to breakdowns in the conveyor system. Maintenance personnel perform only simple visual checks, and react by replacing any items that have failed (Chopra 2001).

To develop an effective maintenance management function, the warehouse's goal is optimizing resources to prevent downtimes and associated economic losses.

3 SOLUTION METHODOLOGY

The stages in the development and implementation of the condition-based maintenance plan were: a) identification of system elements highly likely to fail; b) selection of variables to be monitored, selection of equipment to monitor the variables, and characterization of the present state of the system; and c) simulation of the system to model production characteristics of the system. This case study presents results from the third stage of the project; for details on the other stages of the project refer to Lopez, Contreras and Pennathur (2000).

3.1 Pilot Area

To study the problem and develop a Reliability Centered Maintenance Plan for the conveyor system, a pilot experimental area was chosen after discussion with plant manager. It was chosen on the basis of being most representative of the conveyor. Six locations in the pilot area were chosen to monitor motor performance variables. The components in the pilot area were:

1. Six Motors
2. Six Gearboxes
3. Rollers
4. One Pneumatic Clutch
5. One Scanner
6. Chains
7. Bands

Figure 1 below shows the locations corresponding to the pilot area as it was selected for study.

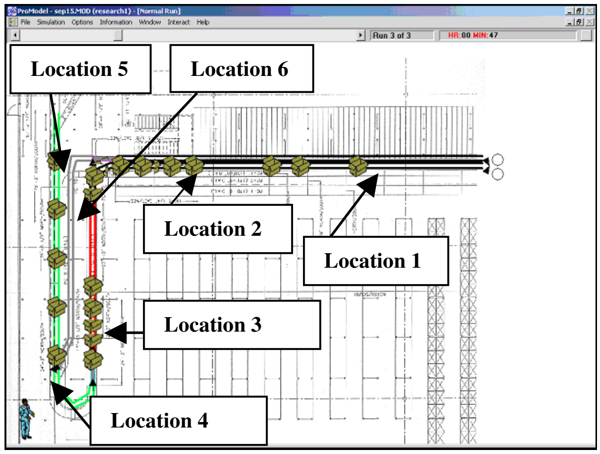

Figure 1: Pilot Area for Experiment and Failure Generation

To identify components most likely to fail, and to develop failure modes and effects, a brainstorming session was conducted with company engineers and the research team. Components most likely to fail in the pilot area were identified as:

1. Motors
2. Gearboxes
3. Rollers
4. Bands

In the monitoring process, to identify the most common failure modes in all each of the 4 components, the above 4 components of the conveyor system were further broken down into their sub-components and all failure modes were analyzed (Paul 1998). Table 1 below shows the Failure Modes and Effect Analysis for pilot area.

To detect failures in the system, we need to monitor parameters that can provide an indication of the degree of damage to the components (NIST 1998). From failure modes for separate components discussed in Table 1 above, it was observed that motors and gearboxes had the maximum number of failure modes and the maximum number of components that were likely to fail if not maintained properly. Parameters that have been shown to be related to component failure in equipment such as motors and gearboxes include temperature, vibration, noise, current, load, and instantaneous power (Rao 1996).

Table 1: Failure Modes and Effect Analysis of Motor, Gearbox and Rollers

Hierarchy	**Failure Mode / Failure Cause**	**Operational Phase**	**Local Effects**	**Next Higher Level**	**End Effects**	**Fault Detection**	**Compensating Provisions**
A	***Motor Failure***						
1	Bearing failure						
a	Improper lubrication	When layer of lubrication between bearing and casing is improper	Slipping of bearings due to excess lubrication and contact of bearings with casing due to inadequate lubrication resulting in wear and tear of bearings	Bearing failure	Bearing and motor failure	Sound and visual indication	Proper lubrication
b	Wear and tear of bearings	Deflection of bearing from axis	Deflection of bearing from axis	Bearing failure	Bearing and motor failure	Sound and visual indication	Check for misaligned bearings and mounting misalignment in motor during maintenance hours
2	Burning out of stator and rotor windings	Improper loading on windings	Residual magnetism in windings	Residual magnetism and magnetic field summation might become greater than resistivity of the windings	Burning of windings and motor failure	Sound, smell and visual indication. Improper performance of gearbox	Check for indications of overheated / burnt coils and current input of motor during maintenance hours
3	Loosening of rotor and stator windings in their slots	Motor not cleaned properly during maintenance hours and due to age of windings	Loosening of windings does not allow windings to come in contact with iron core	Improper loading on windings	Motor failure	Sound, smell and visual indication. Improper performance of gearbox	Check for broken rotors and clean up dust and maintain general cleanliness of motor during maintenance hours
B	***Gearbox Failure***						
1	Bearing failure	Misalignment in bearing while installation	Clearance between meshing gear teeth increases	Increase in temperature within gearbox	Bearing failure	Sound, smell and visual indication. Improper performance of gearbox	Check for misaligned bearings and mounting misalignment in motor during maintenance hours
2	Wear and tear of gears	More metal-to-metal contact between gears. Increase in clearance between meshing gears	Increase in temperature within gearbox	Increase in temperature within the gearbox with more metal-to-metal contact over a period of time	Gearbox failure	Sound, smell and visual indication. Improper performance of gearbox	Proper lubrication of meshing gears
3	Failure of seals	Improper lubrication	Inadequate lubrication leads to added temperature on seals. Too much lubrication causes excess fluid pressure and this provides an escape route to lubricating material in system	If temperature exceeds absorption capability of seals, then seals tend to wear off. Seals start leaking due to excess lubrication	Seal and gearbox failure	Sound, smell and visual indication. Improper performance of gearbox	Proper lubrication and change the seals regularly based on maintenance schedule
4	Improper lubrication	When the layer of lubrication between bearing and casing is improper	Inadequate lubrication leads to added temperature on seals. Too much lubrication causes ex-	If temperature exceeds the absorption capability of the	Seal and gearbox failure	Sound, smell and visual indication. Im-	Proper lubrication

			cess fluid pressure and this provides an escape route to the lubricating material in the system	seals, then seals tend to wear off. Seals start leaking due to excess lubrication		proper performance of gearbox	
C	***Rollers***						
1	Shaft failure	Contact with metal frame	Metal-to-metal contact between shaft and frame and the relative motion to each other wears out the shaft	Constant contact between shaft and frame wears out the shaft faster	Wearing of shaft and frame	Sound and inefficient transmission of conveyor	Proper lubrication

Temperature and Vibration compared to other parameters offer the following benefits:

- Temperature and Vibration are economically desirable alternatives as compared to current testing or surge testing;
- Temperature and Vibration can be measured on the equipment surface but other parameters such as current may require testing of the current carrying wires, which can often be hazardous for a non-skilled user;
- Temperature as a parameter for measurement provides a more physical (heat at surface equipment) and visual (with the use of temperature strips) alarm than any other parameter;
- Portable characteristics of both the temperature and vibration sensors allow ease in measurement and also reduce user economic burden;
- Any failure in the equipment is characterized by temperature and vibration as they indicate abnormality based on internal characteristics of the equipment;
- Temperature and Vibration sensors selected are non-intrusive and non-destructive modes of monitoring, as opposed to some other methods such as torque monitoring which requires components to be opened or probes inserted into components to obtain accurate indication of the condition of the component being measured.

To monitor these parameters an analysis of sensor technologies that can be used revealed the following commercial technologies for temperature and vibration monitoring:

1. Vibration
   a. Accelerometer
   b. Band Filters
   c. Fast Fourier Transform
   d. Portable Vibration Meters
   e. Ultrasound Techniques
2. Temperature
   a. Temperature Indicating Strips
   b. Thermocouples
   c. Resistance Thermometer Detectors
   d. Thermistors
   e. Bimetallic Thermometer
   f. Infrared Temperature Measurement and Laser Sensing

3.2 Data Collection Scheme

As discussed earlier, based on discussion with plant managers, a pilot area (critical area) was selected for the initial study. A laser gun was selected for monitoring temperature based on its cost effectiveness and sensitivity to measure temperature (Chopra 2001). All six motors in the pilot area were monitored at fifteen-minute time intervals and under various loads (different sizes of boxes with different number of garments).

The fifteen minute time interval was scheduled based on historical temperature behavior of the motors, which indicated that for the type of load being exerted by the system on the motors, temperature changes took approximately that much time. Surface temperatures on motors were analyzed at three sections of the motor casing: at the section where the blower fan is located; at the center of the motor casing; and at the end of the motor farthest from the fan. It is important to note that the maximum temperature at the surface will help uncover worst case scenarios, and also help correlate inside temperature of the motor with surface temperature.

3.3 Data Analysis

Following were the findings from the experimentation:

- Increase in load showed a corresponding increase in temperature of all motors;
- Maximum temperature was observed at the center of the motor for all classes of motors;
- Motors in the conveyor system, which have fins on their surface, have much higher heat dissipation and therefore, surface temperature of these motors is much less than for motors without fins;
- The rise in temperature from a cold start (at ambient temperature of 25 degree centigrade) for the

three classes of motors (0.75 HP, 1.5 HP, and 2 HP) was following:

  - For 0.75 HP motor: 30 degree C
  - For 1.5 HP motor (with fins): 10.5 degree C
  - For 2 HP motor (with fins): 14.8 degree C

- A wide range of difference in temperature between the inside and surface temperature of a motor was observed (between 12-25 degree centigrade), which illustrated the fact that no standard Condition Based Monitoring (CBM) technique could be applied to induction motors due to the large variations in induction motors.
- Vibration velocity measurement of motors and gearboxes resulted in the conclusion that only one motor was working in the FAIR operational region, corresponding to a minor fault (Vibration Monitoring Systems Catalogue 2000).

3.4 Simulation

Two models were constructed in ARENA™ 5.0. The first model represented current preventive maintenance policies and the second model represented predictive maintenance policies recommended to the company.

In both models, entities (garment boxes) were programmed to arrive in the system based on their inter-arrival distribution. They are captured by a transport resource to enter the conveyor system. Conveyor system is spread through three different work zones: picking, packaging and shipping. Two hundred and eight resources (AC induction motors) drive the conveyor system. Entities leave the system after passing through these working zones. Different processes are performed on entities with the help of resources, programmed to fail.

Failures in resources (motors) are caused predominantly due to electrical insulation breakdown. Maximum temperature for failure of insulation (based on insulation operational conditions and the Arrhenius plots (Rizzoni 1993)), was used in the simulation model to generate failure. All motors in the pilot area have a class B insulation type, which has a maximum designed temperature of 130 degree C. Based on the temperature increase observed during experimental data collection, and the maximum design temperature, a failure distribution was generated for insulation failure for different motors in the pilot area. Following are the Mean Time Between Failures (MTBF) used in the simulation model for motors under consideration.

- Location 1, Motor 1: 29.54 hours
- Location 2, Motor 2: 8.45 hours
- Location 3, Motor 3: 9.78 hours
- Location 4, Motor 4: 10.34 hours
- Location 5, Motor 5: 20.67 hours
- Location 6, Motor 6: 8.45 hours

Another cause of failure modeled in the system is aging of insulation and hence failure of the motor. In the absence of historical data, an estimate of the remaining useful life was used to generate failure of motor due to insulation aging. For motors at locations described in Figure 1, the following estimated remaining useful life was used in the simulation model (Brancacto 1992):

- Location 1, Motor 1: 9384 hours
- Location 2, Motor 2: 6558 hours
- Location 3, Motor 3: 6510 hours
- Location 4, Motor 4: 6153 hours
- Location 5, Motor 5: 9864 hours
- Location 6, Motor 6: 6221 hours

The simulation considers current failures for motors and its corresponding gearboxes; the rest of the elements of the system can be repaired without stopping the system; also, the failure detectability rate is higher for these elements than insulation failures in the motor.

We simulated our model for 365 days, 15.5 hours a day (930 minutes) with 10 replications, which is again a realistic representation of the actual production period in the warehouse. Our model is a terminating simulation model, in which the model begins with arrival of the first box in the conveyor system, and terminates after the process of packaging into boxes is complete.

The following performance measures (output parameters) were programmed in the model, to enable a comparative analysis between the current preventive maintenance policies and the proposed predictive maintenance recommendations:

1. Boxes In (Production Programmed): The programmed quantity of boxes for the day. Production trends were obtained from triangular distributions based on production information obtained from the plant.
2. Blocked Production (Loss in Production due to failure): This variable records the quantity of boxes that could have being produced during the failure and repair time.
3. Boxes Out (Output): Production of the warehouse with preventive maintenance, and predictive maintenance.
4. Total time for the boxes: This variable represents the time required for a box to travel through the entire conveyor system.

5. Waiting time for the boxes: This variable represents amount of time the entity (box), spends in the system waiting to be processed.
6. Transfer time for the boxes: It represents the total time spent by the box, in transit (excluding idle time and processing time).
7. Work in Process Inventory: This variable indicates the work in process inventory, i.e., the number of boxes in process in the system.

3.4.1 Preventive Maintenance

Based on increase in temperature for a particular class of motor, electrical insulation failures were generated in the system. The Mean Time To Repair (MTTR) for these failures is modeled as a triangular distribution with mean of 30 minutes, maximum of 35 minutes, and minimum of 25 minutes. The MTTR distribution is based on prior experience of maintenance technicians in the warehouse, and was obtained from the maintenance department at the distribution center. If a major failure occurs, or the value of temperature above design limit is reached, the preferred maintenance policy is to replace the motor to minimize the idle time.

3.4.2 Predictive Maintenance

A predictive maintenance policy based on failure prediction using temperature and vibration was proposed to the company. In the simulation model, it is assumed that the distribution for Mean Time Between Failure (MTBF), since it is a component-based measure, is constant for insulation failures, while the Mean Time To Repair (MTTR) for insulation failures is reduced (compared to the preventive maintenance plan) with a predictive maintenance plan – the technician has prior indication and knowledge of the failure modes and effects *before* actual failure. The MTTR is assumed to be a triangular distribution with mean of 12 minutes, maximum of 15 minutes, and minimum of 10 minutes. A detailed RCM is enclosed in appendix A. The failure due to aging of motor insulation is assumed to be the same as under the preventive maintenance policy.

The posterior probability of failure is not included in our simulation model. Manivannan and Banks (1990) suggested a real time knowledge based simulation in which the simulation tool will take the next failure data from the data recorded from the previous failure. This will simulate a real time situation.

3.5 Results

Simulation results are presented in Table 2. The total time considered was 930 minutes (15.5 hours). Simulation was run for one year (365 days).

Ten replications were run to obtain averages and 95% Confidence Intervals (indicated by UCL and LCL) for the parameters presented in the Table 2. All time units are in minutes.

4 ANALYSIS OF OUTPUT

Statistical analysis was carried out on important parameters namely Boxes Out, Total Time for Boxes, Waiting Time for Boxes, Transfer Time for Boxes, and work in Process Inventory of Boxes. Since the p-value of the F test is less than 0.05 for all the parameters above, there is no evidence at the 95% level of significance to conclude that the mean performance measures between preventive and predictive maintenance policies as implemented in the simulation models are the same. Values in the column UCL and LCL in Table 2 indicate 95% confidence limits in repeated trials.

It can also be seen from Table 2 that considerable amount of time saving is achieved with the help of predictive maintenance using condition based monitoring. This difference is because maintenance personnel can now predict failure of the motor based on reliability-centered maintenance plan provided to them. Increase in production and system efficiency, reduction in total downtime, waiting time for entities (boxes), and work-in- process inventory in addition to smoothening of maintenance operations is achieved through CBM.

Several factors affect repair time. An important factor to consider in a maintenance program is equipment history. It is recommended to have an updated database containing information about the failure date, type of failure, and corrective action implemented.

5 CONCLUSIONS

A simulation model was developed and implemented in a distribution warehouse to determine the effectiveness of predictive maintenance vis-à-vis preventive maintenance. A model was built based on failure data available for motors and gearboxes. Failures were generated in the system and model was simulated for 365 days. Results show that predictive maintenance results in better performance than preventive maintenance due to the enhanced ability of maintenance personnel to determine failure modes and effects before failures occur in the system. The case also indicates the importance of integrating condition based monitoring in predictive maintenance and integrating production requirements and maintenance requirements through simulation. Although maintenance may still be a necessary evil, it is possible to reduce the effects of reactive maintenance through use of tools and methods discussed in this paper.

Table 2: Summary of Results for Preventive and Predictive Maintenance Policies

Sr. No.	**Parameters**	**Preventive Maintenance**			**Predictive Maintenance**			**p-value**	**Result**
		UCL	**Mean**	**LCL**	**UCL**	**Mean**	**LCL**		***p < 0.05?***
1	Boxes In (units)		102490			102490			
2	Boxes Out (units)		102480			102490		0	Yes
3	Loss in Production (units)		10			0		0	Yes
4	Total Downtime		88290.58			36290.9			
5	Total Time for Boxes	44.79	44.67	44.54	15.31	15.26	15.21	0	Yes
6	Waiting Time for Boxes	34.94	34.82	34.69	5.51	5.47	5.43	0	Yes
7	Transfer Time for Boxes	5.35	5.35	5.35	5.29	5.29	5.29	0	Yes
8	Work In Process Inventory (units)	137.1	134.003	130.9	45.92	45.80	45.69	0	Yes

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APPENDIX A

Reliability Centered Maintenance (RCM) Plan for Class B Motors

Measured Temperature Value	**Reference Values**	**Corrective Actions**	**When?**
	Upto 65 deg C	Clean up dust and maintain general cleanliness	Every 2 weeks
	65-77 deg C	Visual Check for Stuck Rollers on Conveyor	During normal operation
		Check for misaligned bearings	During maintenance hours
		Check for cleanliness of fans	During maintenance hours
		Check mounting misalignment in motor	During maintenance hours
		Check current input into Motor	During normal operation
	77-87 deg C	Check for broken rotors	During maintenance hours
		Check for indications of overheated / burnt coils	During maintenance hours
	> 87 deg C	REPLACE MOTOR	Immediately