CSCE Annual Conference
Growing with youth – Croître avec les jeunes

Laval (Greater Montreal)
June 12 - 15, 2019

OPTIMAL MAINTENANCE PLAN FOR A VIBRATING-GRATE BIOMASS BOILER: AVAILABILITY AND COST SAVING APPROACH

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Abstract: In recent years, political and economic issues motivated Canada government to make northern Canada more crowded. To hit this aim, it is vital to make these regions more energy secure since they are off-grid and consequently the long harsh winter worsens this situation. Currently, diesel generators mostly provide demanded energy through the remote areas in Canada while high capital and operational cost of system burden government and people. By brainstorming through available energy technologies, Biomass boilers can be pondered as a promising technology for such these areas particularly through areas far from source of diesel fuel. However, having the system available during the long winter plays a key role to ensure us about energy security. A mathematical optimization of the maintenance plan regarding a vibrating-grate biomass boiler, which is the case study in this paper, is carried out based on the system availability so that the maintenance cost is minimized while the system availability remains higher than initial availability. A modified failure density function is utilized to bring the maintenance effect to component reliability following the maintenance. A regression analysis is performed on the constant hazard rate to turn them into Weibull distribution parameters (α, β) to form a time-dependent hazard functions. To examine the system availability mathematically, Fault Tree (FT) method is employed and since only series and parallel arrangement exist through the system, this method is most proper one in this case study. A flowchart of maintenance optimization is designed to optimize the system availability function with 33 unique components and results shows 32% decay in the number of maintenance tasks over 10 years of operation. The flowchart performs fast and efficient somehow that it promises to stay efficient even for more complex system.

1. INTRODUCTION

In recent decades, climate change has been profoundly considered the most challenge ahead of human societies, political assemblies and economic systems. Massive efforts have been globally made to overcome the increasing rate of climate change and meanwhile in power and heat generation industries, there is a political-technical trend to take advantages of renewable energies rather than fossil fuels in order to lessen released carbon emission into the atmosphere. One of the most promising facilities deliberated to yield this aim is biomass boiler particularly where the biomass wastes are enormously available such as Europe, North and South America, Asia (Mcilveen-wright et al. 2013) although climate-caused disorders such as variations in precipitation line, pest invasion and raised periodicity of extreme weather incidents threaten the biomass resources (Aviso et al. 2015) . The reasons come from the CO2 neutral nature of biomass which releases the amount of CO2 equal to much it has been absorbed during its lifetime (Mandø 2013) as well as instead of to bury underground or burn unproductively, a valuable source of heat and power generation must not be neglected (Hendricks et al. 2016). On the other hand, considering remote areas where cannot access the electricity grid together with enough agricultural or forestry waste in vicinity, this type of boiler could be a beneficial alternative (Mazzola, Astolfi, and Macchi 2016; Stephen et al. 2016; Hendricks et al. 2016). With respect to remote area situation, the availability of the system is a critical factor which must be put in circle of attention, and having a reliable preservation and maintenance program appears to be crucial.

Despite plenty of research which investigate risks associated with biomass resources supply in recent years (Anselmo Filho and Badr 2004; Mirkouei et al. 2017; Bowd et al. 2018; Serra, Colauzzi, and Amaducci 2017), digging into literature in context of maintenance plan discloses lack of adequate research in field of biomass boiler. the communities who rely on this system as the only source of heating and electric power in particular through harsh winter such as local tribes in Northern Canada, availability of the energy providing system plays an important role to preserve the normal life. Eti et al. (Eti, Ogaji, and Probert 2006) carried out a comprehensive survey on the development and implementation of preventive-maintenance methods in industrial section, and the results suggested that focus should shift to inherent design of the system in addition to operational conditions. In another research (Eti, Ogaji, and Probert 2005), the authors conducted a maintenance audit at a thermal-power station and compared results with the best standard values. A reliability-availability investigation on a seabed storage tank was carried out by Choi and Chang (Choi and Chang 2016) using the fault tree analysis (FTA). Bourouni (Bourouni 2013) evaluated availability of a reverse osmosis plant by means of reliability block diagram (RBD) and FTA methods. Results showed that RBD method gave a lower availability than FTA coming from this fact that FTA neglects r-of-n and standby arrangement. Therefore, the RBD would be more precise for the complex system consists of these two configurations. Arjunwadkar et al. (Arjunwadkar, Basu, and Acharya 2016) reviewed operation and maintenance issues of a circulation fluidize bed boiler (CFBB), and they realized "loopseal" as heart of system from availability viewpoint. Moreover, tube erosion and to what extend corrosion made main contribution to boiler failure. A multi-objective model (Piasson et al. 2016) was developed to minimize the preventive maintenance costs while maximize the reliability of an electric power distribution system (EPDS). The model was able to operate on system with several feeders as well as one feeder separately with the same model. Vatn et al. (Vatn, Hokstad, and Bodsberg 1996) combined reliability-availability-maintenance-safety (RAMS) methods into one unique approach to build optimal maintenance method. They used expert judgement method to make credible input data. Also, a comprehensive review on the applications of maintenance optimization models was made and concluded inevitable future needs of mathematical maintenance optimization models (Dekker 1996).

In spite of all these great efforts, preventive maintenance models must still be proceeded toward being more feasible, easy-to-use and cost effective as well. This article presents a novel simplified maintenance model which is based on availability of the vibrating-grate biomass boiler to schedule the maintenance tasks period of each subsystem so that minimizes the number of maintenance tasks while the system availability stays over the initial availability.

2. MATERIALS AND METHODS

The preventive programs idea is generally based on the elapsed time and operating hours of the system and are known as time driven. The preventive schedule programs focus on system components repair or rebuild on the foundation of the MTTF and MTTR of each component. The same idea among all types of preventive maintenance programs is that the system's parts will degrade over a typical time frame depend on the classification and efforts would fulfil to control degradation to an acceptable level. A centrifugal pump, for instance, normally works 18 months in advance it must be rebuilt, so in a preventive plan it can be repaired after 17 months as an option. The US Navy pioneered preventive management as a means to increase the reliability of their vessels.

Carrying out the preventive maintenance suggested via system designer will make the equipment's life longer closer to design. It must be noticed that the preventive maintenance will not prevent components catastrophic failures, despite this, it will decline the number of failures and consequently we come up with maintenance and capital cost savings. This paper would focus on this method and more detailed explanations would be given later on.

2.1 System Description

The given system is a biomass boiler burning wood chips or pellet to produce heat for district heating, and have several subsystems consists of feeding, combustion, boiler unit, ash gathering, flue gas and finally controlling part. Fig. 1 shows a schematic of the system illustrating the main components. In the feeding part a fuel tank contains woody fuel and the fuel level is controlled by two low and high level switches. The biomass bin is vibrated from beneath to drive the fuel toward the metering screw to progress the fuel to the feed screw along with a rotary valve in between to control the feed flow. The feed screw conveys the feed to the fuel bed in the combustion chamber while a water tank is equipped to cool down the feeding screw casing periodically. The water tank is activated by signal originated from a temperature transmitter on the casing, and if it would not properly operate, a thermal sensor directly connected to pilot valve of the water tank replace it concurrently. A grate vibrator pushes the solid fuel through the length of the bed while the primary fan provides the combustion air in the bed and two other fans are employed to burn the released gaseous species from biomass in the over-bed zone. To monitor pressure and temperature inside the combustion chamber as well as supplied air lines, temperature and pressure transmitters installed in different places integrated with the sensors and the data are transferred to a central PLC to handle the operating condition of the system. In the following path of combustion chamber, a tube bundle receives the heat of combustion to boil the inlet cold water. The ashes associated with wood chips combustion are extracted from the combustion chamber in two stages and gathered into ashes bins. A centrifugal pump circulates the water through the tube bundle while a safety relief valve is mounted to regulate the pressure rise in the return line. The flue gas is drawn out by an induced draft fan through the stack duct. The emergency cooling system operates when temperature of combustion chamber succeeds the allowable limit, and circulates water around the casing. As it was referred above, a PLC procures data from all subsystems of the biomass boiler to manipulate the working condition of components in the normal design range. In the next section, methodology of maintenance scheduling of the portrayed system would be introduced.

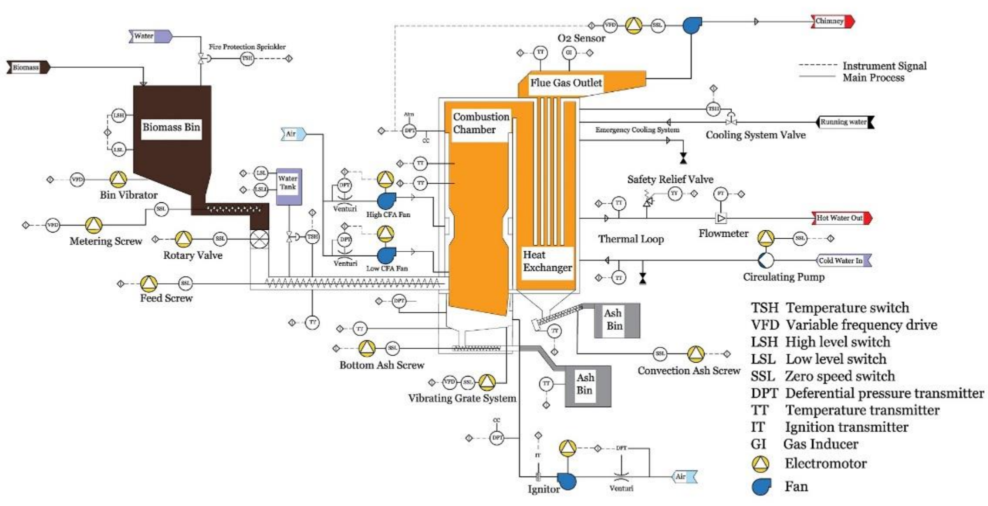

Figure 1: Schematic of vibrating grate biomass boiler

2.2 Fault Tree

In this paper, FTA method is chosen to analyze the reliability/availability of the system. In engineering applications, the FTA is realized very powerful and non-complicated method performing accurate outcomes particularly if the system only includes series and parallel arrangement, and is vastly applied in industrial practices. The FTA deducts systems from bottom to top to find the potential of incidents or even more for the estimation of system failures probabilities. The FTA structure begins with top events or underlying parts of the system and proceeds downward to single parts in each subsystem. Indeed, the failure among these single parts results in the malfunctioning or breaks in top systems. The FTA of the current system has been sketched in Fig. 2 including only "AND" and "OR" gates. The AND means all events must happen to top event happens, whereas OR denotes if each of which events occurs, it will lead to top event occurs respectively. Following the system was being broken down, 33 unique critical components were recognized in consultation with experts. Failure incidents are defined what physically occurs to equipment where a repair task is issued. The failure rate and MTTR of whole parts was derived from relative sources (Exida 2016a; IAEA 1988; Exida 2016b, 2015; *Offshore Reliability-Data Handbook (OREDA)* 2015; Denson et al. 1991). The principal portion of the failure events in the given references originates from the useful lifetime which occasionally known as critical failure, where the rate of failure is approximately constant. In the next section, it would be discussed that the time-independent failure rate does not fit in the modified failure density function and a process of regression would be imperative to turn the equipment failure density function to the Weibull distribution function which can reflect the effect of the maintenance.

2.3 Modified Failure Density Function

The obtained failure rates brought up in the later section are constant over operating time. Therefore, a regression task would be carried out to determine the Weibull density function parameters (α and β) which provide the possibility of indication of maintenance impact mathematically respecting inconstant hazard function over the time. Firstly, the failure data over the lifetime of each component were generated by virtue of the corresponding failure rate then, the regression regarding the Weibull distribution was performed to fit a Weibull distribution function to the data (Smith 1991).

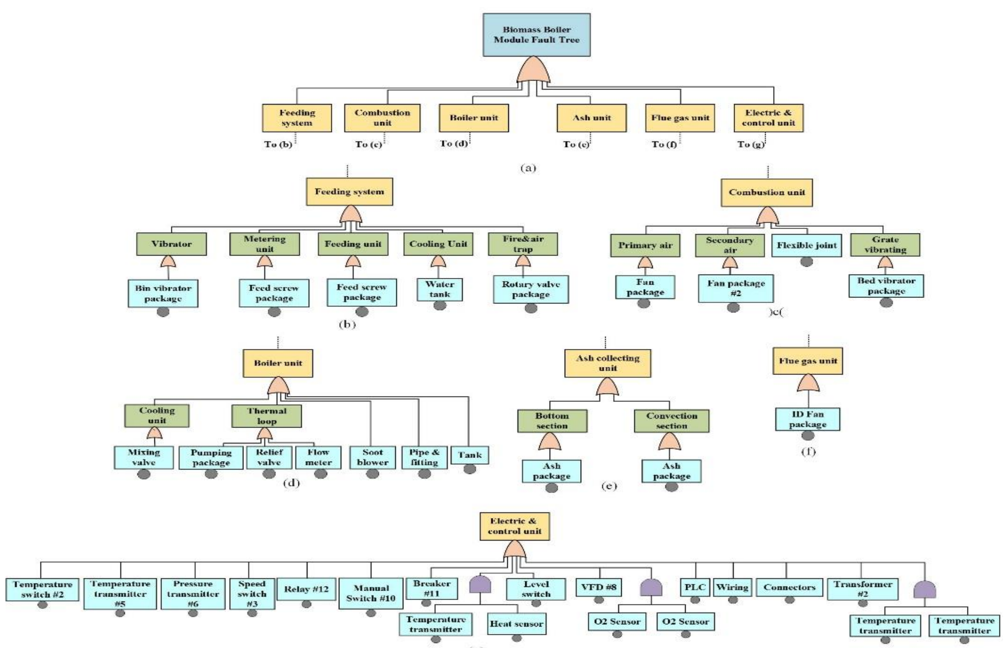

Figure 2: Fault tree of biomass boiler system

The α and β accompanying this fitted function were chosen as the new failure parameters for each component separately. To prove the validity of the regression, Kolmogorov Smirnov and Anderson Darling tests, which are commonly used to inspect the regression analysis results, were employed and fulfilled for each equipment. Deviation of the fitted function came out in a good agreement with reference data so that the goodness of fit wrapped up in range of 0.022-0.035 for Kolmogorov Smirnov test and 372-395 for Anderson Darling.

The failure rate and Weibull distribution parameters for whole components were listed in Table 1. Failure density function of repairable components after maintenance needs to be modified in regard to maintenance interval time (T), which seizes the frequency of preventive maintenance. Thereby, if f(t) would be the current failure density function of a component, the modified failure density function of the component after maintenance would be represented as follow (Ramakumar 1992):

[1] $$f_T^*(t) = \sum_{k=0}^{\infty} f(t - kT) R^k T$$

Where k is operation period and is equal to 0 at first operational period, 1 at second operational period and so on. T is maintenance interval time and RkT is scaling factor which means lower effect of maintenance over the life of the component. Likewise, the modified reliability function of Weibull distribution would be:

[2] $$R_T^*(t) = \sum_{k=0}^{\infty} \exp\left[-\left(\frac{t - kT}{\alpha}\right)^{\beta}\right] R^k T$$

2.4 Optimal Maintenance Plan

The intended method in this paper has been based on the component availability influence on the system availability which is called maintenance impact to cut the number of maintenance task down which denotes lowering the maintenance cost. The fixed-interval preventive maintenance is often adopted to ensure high system availability coming up with the over-maintenance in the most cases. The advantageous of optimal maintenance method to the traditional one is not only to suggest more proper and reliable scheduling, but also to diminish the maintenance cost. The reliability is generally referred to represent a specific degree of assurance that the components of a system will stay successfully in working condition over a certain time period.

For a system with repairable components, the term of reliability is quantitatively stated by the availability. Maintenance impact plays a key role in the optimal maintenance scheduling, which is quantitatively described as the change in the system availability caused by the change in components availability through the vicinity of average maintenance-interval types, and can be expressed as follow:

[3] $$\Delta A_{j,k_j} = A\left(a_{j,k_j}\right) - A\left(a_{j,k_j+1}\right)$$

Where $A(aj,kj)$ and $A(aj,kj$+1) are system availability influenced by component j with kjth average maintenance-interval type and (kj+1)th average maintenance-interval type respectively. It has been assumed that kjth is shorter maintenance period than (kj+1)th. To achieve a precise optimal maintenance scheduling, the accurate element availability calculation is vitally needed. The availability of component j with kjth average maintenance-interval type can be obtained as following:

[4] $$a_{j,k_j} = \frac{M_{j,k_j}}{M_{j,k_j+M_{r,j}}}$$

Where Mj,kj is the mean time to failure (MTTF) of component j with the kjth average maintenance-interval type, and Mr,j means mean time to repair (MTTR) of the component j in the system. From the FTA of the system shown in Fig. 2, it could be observed that there are two types of series and parallel configuration collaborating to meet the system operation properly.

Table 1: Failure density function characteristics

Components	Failure rate (per 106 hr)	Weibull distribution		MTTR (hr)	Components	Failure rate (per 106 hr)	Weibull distribution		MTTR (hr)
		α	β				α	β	
O2 Sensor	10	85305	1.1239	171	Pres Sensor	5.8	96546	1.5722	26
Coupling	1.907	93212	1.5181	74	VFD	1.2	145140	1.5186	75
Belt	23.719	42075	1.0134	49	Manual Switch	0.46	150960	1.5799	25
Level Switch	0.273	2E+05	1.5962	74	Flex joint	14.2	57917	1.1455	174
Water Storage Tank	0.074	2E+05	1.6142	348	Relay	0.3	152210	1.5939	24.25
Temp Switch	0.228	2E+05	1.6002	78	Bearing	7.99	96638	1.1746	78
Speed Switch	0.48	2E+05	1.5781	25	Piping	0.03	154340	1.618	76
Rotary Valve	9.26	89291	1.1407	342	Transformer	2.5	91290	1.4889	76
Relief Valve	3.84	1E+05	1.3443	76	Circuit Breaker	0.2	152990	1.6027	25
Temp Transmitter	0.437	2E+05	1.5819	26	Pipe Fitting	3.26	129190	1.3774	52
Pulley	12.609	72931	1.0787	74	Gearbox	5	83312	1.3815	339
Flowmeter	3.26	1E+05	1.3774	76	PLC	5	116370	1.286	88
Fan	2.5	91290	1.4889	339	Pump	20.52	45370	1.0728	78
ID Fan	2.5	91290	1.4889	726	Soot Blower	42	34060	1.1722	171
Pres Transmitter	0.414	2E+05	1.5839	26	Wiring	0.627	149650	1.5656	50
Mixing Valve	10.06	84995	1.1227	76	Motor	28.44	34559	1.0315	340
Temp Sensor	4.57	1E+05	1.3065	26	Electric connection	0.145	153420	1.6075	25

To recap, system with series elements normally works only when all elements work, whereas a system established with parallel components arrangement only needs to one of parallel parts to normally operate. The system availability computation for both arrangements are expressed below:

[5] $$A_s = \prod_{j=1}^{N_s} a_{j,k_j}$$

[6] $$A_p = 1 - \prod_{j=1}^{N_p} (1 - a_{j,k_j})$$

Where Ns and Np are number of series and parallel components respectively. From Eq. (4) it is evident that in order to reckon components availability, MTTF and MTTR of each element must be counted in advance.

The optimization problem has one objective (Ω) implying the total number of maintenance effort over life of the system which must be minimized given that the updated system availability would not drop down the initial system availability.

Optimization problem

Minimize Ω (overall number of maintenance task)

Subject to

$$A_s^* > A_s$$

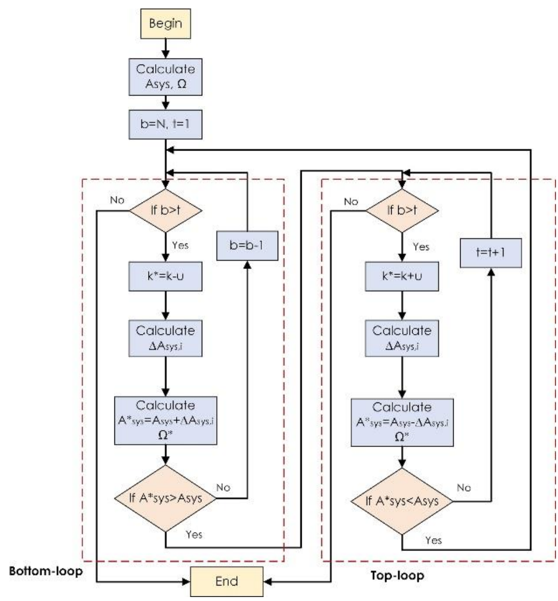

Figure 3: Optimization flowchart of maintenance scheduling

The optimal maintenance plan schedules the periodic maintenance with respect to maintenance impact of each component. In other words, components having higher effect on the system availability should be served higher consideration than others when periodical service is intended. Accordingly, it is indispensable to establish sorted list of parts showing how they pertain to availability of the system if the maintenance interval of them shift for few months.

3. RESULTS AND DISCUSSION

The availability effect of components is reckoned and a sorted list was achieved which is shown in Fig. 4. The figure determines which parts include top-list and which ones in bottom-list as well. The process of optimization begins with shortening maintenance impact of fan packages including one primary air fan and two secondary air fans to 9 months (one unit) in order that system availability raises from 71.85% to 71.9%. Then, the process is switched to top-loop from the component with lowest maintenance impact and the process iterates over the loop gradually to the mostly effective components in terms of maintenance impact amongst top-loop and the maintenance impact of them would be extended one unit individually until the system availability meets the primary system availability. The optimal maintenance process goes over bottom-loop and selects the feed screw package and decreases its maintenance impact one unit, new system availability is calculated afterwards switches to top-loop and the similar approach would be carried on from the element next to the last one chosen in previous step, and this trend continues up to maintenance impact of wiring from bottom-loop would be lowered one unit and eventually expansion of maintenance impact of top-loop elements up to reach the threshold. The results of maintenance scheduling optimization are presented in Fig. 5. In accordance with this optimal maintenance scheduling for the biomass boiler, a significant reduction through the number of maintenance task has been achieved so that the conventional maintenance plan stipulates 310 service tasks during 10 years while in optimal version of repair plan 210 tasks would be accomplished as the system availability remains over the initial availability.

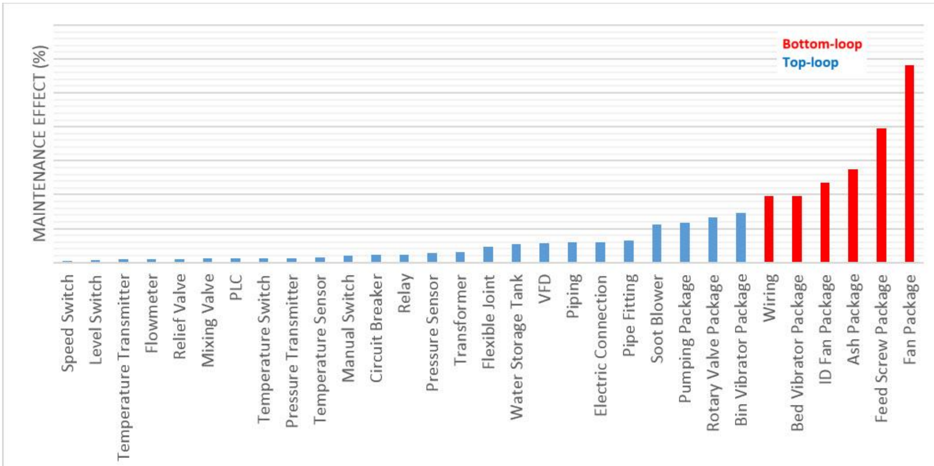

Figure 4: Sorted list on maintenance effect basis

The results notify that if the maintenance of the subsystems/components in bottom-loop would be performed each 9 months instead of 12 months, despite the growth of maintenance actions from 60 to 80 in bottom-loop, nevertheless, the maintenance efforts in top-loop would fall off from 250 to 130 over 10 years. The optimal scheduling in comparison with the conventional one, can reduce the number of maintenance tasks by 32.26% over 10 years. From industrial aspect, this value is realized a significant amount of cost saving.

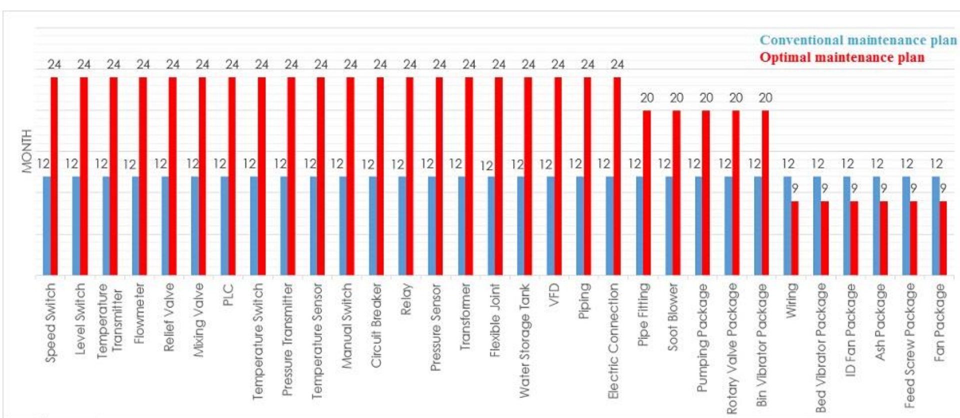

Figure 5: Optimal preventive maintenance scheduling

4. CONCLUSION

In present article, a successful practice has been implemented to optimize the maintenance scheduling of an industrial biomass boiler. The preventive maintenance program which functions based on MTTF and MTTR of the components, has been employed to achieve the optimal plan. The MTTF and MTTR were determined by historical failure data from the reliable references and these two factor are requirements of each component availability calculation. The fault tree of the system has been built to facilitate calculation of the system availability. To be able to use the modified failure density function, the components failure must comply with Weibull distribution function. For that purpose, the regression has been carried out on the collected failure rate and Weibull distribution parameters gained. the fault tree could be notably effective method for engineering applications and also is precise particularly when the system consists only series and parallel arrangements of components. The designed flowchart could be quickly and easily applied to code the optimization problem and the bottom-loop and the top-loop are flexible for different problem to be modified. The designed flowchart for optimal maintenance is highly sensitive to component with high maintenance effect into the system than other components and in such a case, the results would come across with unsatisfactory scheduling. Thus, the efforts need to be performed to remove that single component as in this paper the motor has been integrated with driven components. The results have demonstrated 32% decline in number of maintenance tasks than conventional one if the optimal maintenance task would be put into practice which is significant amount from cost saving view. Generally, preventive maintenance program could provide the effective maintenance plan with not as much costly as predictive method, although does not fully guarantee the system availability. The preventive scheduling algorithm may also be enriched by incorporating maintenance cost function to represent the multi-objective optimal maintenance problem.

ACKNOWLEDGEMENTS

The authors would like to thank Brais Malouin and Associates (BMA) corporation for the financial and information support.

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