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Application of Pinch Analysis to Opportunistic Maintenance Management

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The opportunistic maintenance (OM) approach allows exploiting the stoppage for performing additional maintenance actions alongside those planned, to save cost and time. This study aims to propose a graphical approach to identify the optimal maintenance grouping strategies in an operating process. The failure of a specific component is predicted by using the statistically-derived probability distribution function that reflects its time-variant failure behaviours. The periodic maintenance schedule is first derived, and the system failure likelihood is predicted within each time interval. The failure of one of the component creates an opportunity to reschedule maintenance activities, which can be carried out while replacing the failed components. The expected cost to mitigate the failures ('Sinks') can be reduced by the expected maintenance reschedule cost savings ('Sources') based on the derived schedule previously. In this work, Pinch Analysis is used as a targeting tool to determine the maximum cost savings and expected cost required to handle unexpected plant shutdown. The methodology is presented and demonstrated with a case study, featuring the component replacement for a hydrogen compressor in an oil refinery. The results show that about 35 % of the expected failure cost would need to be invested for opportunistic maintenance at the earlier time, minimising the risk of failure, while the remaining 65 % can be saved. The extra savings at the end of the period also suggest the maintenance grouping can be further reduced. The limitations and potential future development of the framework are discussed as well.

1. Introduction

Maintenance plays an essential role in a production process to ensure the equipment or assets are repaired, replaced or modified according to the production requirements. The efficacy of the maintenance policy for complex and expensive chemical processes is critical for reliable operations. Basri et al. (2017) highlighted that the opportunistic grouping of maintenance planning could be practical and effective in the process industries. For such maintenance policy, it relies on various opportunities such as production stoppages, economic considerations and environmental conditions. For example, a failure event in the separation system in oil refineries is likely to shut down the oil export system. The maintenance team may take the equipment failure opportunity to perform preventive maintenance for other components (Truong Ba et al., 2017).

Another example would be the sugarcane processing system. The supply of sugarcane is stopped during rainy seasons, which the production has to be stopped and creates an opportunity for maintenance (Jiao et al., 2005). Substantial cost and time can be saved using this policy when compared to awaiting the regular maintenance schedule.

Several researchers had proposed several opportunistic maintenance management techniques. Laggoune et al. (2009) proposed a decision rule to identify the relevant maintenance activities grouping for a hydrogen compressor in a petrochemical plant. They stated that the simultaneous maintenance of the non-failed components could be carried out, only if the expected cost to repair at the current time is lower than the expected cost in the future. Kamaruddin and Ab-Samat (2014) conducted an overview of the implementation of opportunistic maintenance. They concluded that most of the researchers utilised mathematical modelling, fuzzy

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logic and statistical analysis to perform opportunistic maintenance planning. Majority of the published works prior to 2013 use cost as a decision criterion. For the recent works, Cavalcante and Lopes (2015) suggested a multi-criteria model as decision support for developing opportunistic maintenance policy in a power cogeneration system. They investigated the behaviours of the cost and availability of the power plant and devised a maintenance plan to balance the two attributes. The failure-based maintenance grouping strategies that incorporate human factors: time pressure and fatigue level are also applied in the petrochemical plant (Sheikhalishahi et al. 2017). Their results suggested that the maintenance cost and the risks of maintenance delay can be reduced. Li et al. (2018) also proposed a maintenance strategy for automotive production line considering the reliability, operating rate and maintenance cost for the equipment. The machines are grouped into three main categories based on their individual failure rates, and the optimal maintenance plan is devised. Most of the methods mentioned are mainly mathematical optimisation models. It is often difficult to understand how the optimal solutions are obtained and determine the process bottlenecks from these models. A strong programming background is required for users to understand the model. As such, this study proposes a graphical approach, named as Pinch Analysis to identify the opportunistic maintenance activities grouping created by the failure events. This method has been widely applied in different field and is famous for its easily understandable methodology. Linnhoff et al. (1982) first developed the Heat Recovery Pinch Analysis in solving the Heat Integration problem. Tan et al. (2016) extended the method to select the optimal industrial risks and pollution reduction measures based on available budgets. Jia et al. (2018) also applied the method to determine the waste management strategies in China constrained by the GHG emissions threshold. Klemeš et al. (2018) had conducted a comprehensive overview of various extensions of Pinch Analysis, including water integration, regional resources planning, power system planning and hydrogen network synthesis. The capability of Pinch Analysis to target the resources and identify bottlenecks through visualisation provides added merits for its applicability. This study aims to propose a graphical approach in identifying the optimal maintenance grouping strategy for a chemical system, inspired by the benefits of Pinch Analysis. A case study of components replacement for a hydrogen compressor in an oil refinery is used to elucidate the application. The main novelties of this work include:

(i) The utilisation of the expected opportunistic maintenance cost savings ('Sources') to cover the expected failure cost ('Sinks'). The cost savings has been maximised, and the expected cost required is minimised, analogous to maximising recycling rates and minimising resources required. This strategy has not been applied before, and this is the first time that it is considered in this work.
(ii) Identification of optimal maintenance grouping strategy using a graphical approach.
(iii) Visualisation of the system bottlenecks in terms of time units where the cost savings have been maximised.

2. Methodology

The methodology consists of three sections. The simplified approach to determine the periodic maintenance schedule is explained in section 2.1. The mathematical formulation of expected cost calculations will be shown in Section 2.2. The hierarchical framework of the proposed Pinch Methodology will be explained in section 2.3.

2.1 Periodic maintenance scheduling

The failure probability of the equipment is modelled using a Weibull distribution model. Vilarinho et al. (2017) stated that the failure analysis has to be performed at the design stage to determine the reliability functions of the equipment. The primary approach for reliability functions estimation is based on the collected past failure data. The time-to-failure for the equipment is then fitted with the failure likelihood with appropriate theoretical distributions, such as Weibull, Exponential or Normal distributions (Faccio et al., 2014). The most popular distribution model for the reliability function is the Weibull model, due to its flexibility to study the lifetime of components with different hazard rate functions (Jóźwiak, 1997). In this study, the individual failure probabilities of the components are modelled using the Weibull model as shown in Eq(1).

$$f_i(t) = \frac{B_i}{n_i}\left(\frac{t}{n_i}\right)^{B_i-1} e^{-\left(\frac{t}{n_i}\right)^{B_i}} \quad \forall i \tag{1}$$

Where $f_i(t)$ is the failure probability of component i, B_i and n_i are the shape parameter and the scale parameter for component i, and t is the time of the operation.

For simplicity, the periodic maintenance interval is determined based on the Mean-Time-Between-Failure (MTBF) of each equipment, as shown in Eq(2). For example, each equipment or components in the process will undergo maintenance after a certain period of time (t = MTBF) from last maintenance. Each periodic time interval will be equal to the minimum of MTBF- see Eq(3). The frequency of the preventive maintenance activities for each equipment is determined using Eq(4). This is a simplified method to determine the maintenance intervals and frequencies. More advanced method, such as Risk-Based Maintenance using Bayesian Network can be used to determine the maintenance period more effectively (Abbassi et al., 2016). In this work, the purpose of the maintenance intervals is just to demonstrate the concept of Pinch Analysis framework.

$$MTBF_i = \int_0^{\infty} t f_i(t) dt \ \ \forall i \quad (2)$$

$$T = \alpha Min_i(MTBF_i) \quad (3)$$

$$F_i = Round\left(\frac{MTBF_i}{T}\right) \ \ \forall i \quad (4)$$

Where $MTBF_i$ is the Mean-time-to-Failure of each component i, T is the discretised time interval which is equal to some factor, α (0≤α≤1) times the minimum of MTBF among the components and F_i is the frequency of maintenance, which is rounded ratio of individual components' MTBF to the minimum MTBF. The periodic maintenance of the two components is illustrated in Figure 1. For example, the MTBF of component 2 is smaller than component 1. The component 2 is consequently maintained at each time interval, which equals to its MTBF (T = $MTBF_2$). Let us assume the MTBF of component 1 is about two times higher than the MTBF of component 2; the frequency of maintenance, F_1 will be equal to 2. That means that component 1 is to be maintained for every two periods.

2.2 Expected cost calculations

After determining the maintenance intervals and frequencies, the expected cost due to the failure of components i can be calculated using Eq(5).

$$C_{F,ik} = (C_o^c + C_i^c) \int_{T_{i,k}^*}^{(k+1)T} f_i\left(t - T_{i,k}^*\right) dt \ \ \forall i, k \quad (5)$$

Where $C_{F,ik}$ represents the expected failure cost of component i at time interval [$T^*_{i,k}$, (k+1)T], C_o^C is the typical set-up cost due to the failure, C_i^C is the corrective replacement cost for component i, and $T^*_{i,k}$ is the last periodic maintenance for component i (Eq(6)). The common set-up cost, C_o^C is the summation of the cost for mobilising repair crews, safety provision, disassembling, transportation and production loss. Each failure incurs emergency stoppage to the process, which requires a corrective common set-up cost. In this study, a constant value is assigned to the set-up cost of $ 30,000 (Laggoune et al., 2009). Notice that the calculation in Eq(5) only consider a single failure per component, which is also the assumption of this study. The system is also assumed to be a series process, in which the failure of one component induces the system failure. The term $T^*_{i,k}$ is required as each maintenance action improves the reliability of the component. This study assumes the maintenance is perfect, which means the maintenance action restores the reliability of the component back to its original state. $T^*_{i,k}$ can be computed using Eq(6) as follows:

$$T_{i,k}^* = \begin{cases} kT & , k \bmod F_i = 0 \\ T_{i,k-1}^* & , else \end{cases} \ \ \forall i, k \quad (6)$$

The condition statement from Eq(6) signifies that $T^*_{i,k}$ equals to kT, only if the k modulo the maintenance frequency of component i, F_i is zero (k divides F_i does not have remainders). Take an example from Figure 1, at time 2T, as the last maintenance of component 2 is at time T, the failure probability should be evaluated from T ($T^*_{i,1}$) to 2T. As for component 1 at time 2T, since it is not maintained at time T (k mod F_1 ≠0 as F_1=2 and k=1), the failure probability is evaluated from time 0 ($T^*_{i,0}$) to 2T.
The opportunistic cost saving for each component and each time periods can be computed using Eq(7).

$$C_{OS,ik} = \left(C_o^p + C_i^p\right)\left(1 - \int_{T_{i,k}^*}^{(k+1)T} f_i\left(t - T_{i,k}^*\right) dt\right) - C_i^p \left(1 - \prod_{j \neq i} \int_{T_{i,k}^*}^{(k+1)T} f_j\left(t - T_{i,k}^*\right) dt\right) \ \ \forall i, k \quad (7)$$

Where $C_{OS,ik}$ represents the expected cost saving due to opportunistic rescheduling of component i at time interval [$T^*_{i,k}$, (k+1)T], C_o^P is the typical set-up cost due to preventive maintenance (assumed $ 20,000), C_i^P is the preventive maintenance cost for component i and j is the failed components (j≠i). The common set-up cost (C_o^P) has similar physical meaning as the corrective set-up cost (C_o^C), and is assumed to be lower than the common corrective cost. The first term in Eq(7) represents the expected preventive maintenance cost between [$T^*_{i,k}$, (k+1)T]. In this study, the expected preventive maintenance cost for each component are still considered for each time period. That is because the maintenance schedule is still expected to be changed from the determined schedule. The second term represents the cost incurred for opportunity maintenance. It considers the probabilities of other failed component j and creating an opportunity to maintain non-failed component i. Notice that C_o^P is not considered in this term due to the corrective set-up cost has been incurred (C_o^C) as a failure happens.
Figure 1 is presented to allow the illustration of the concepts explained.

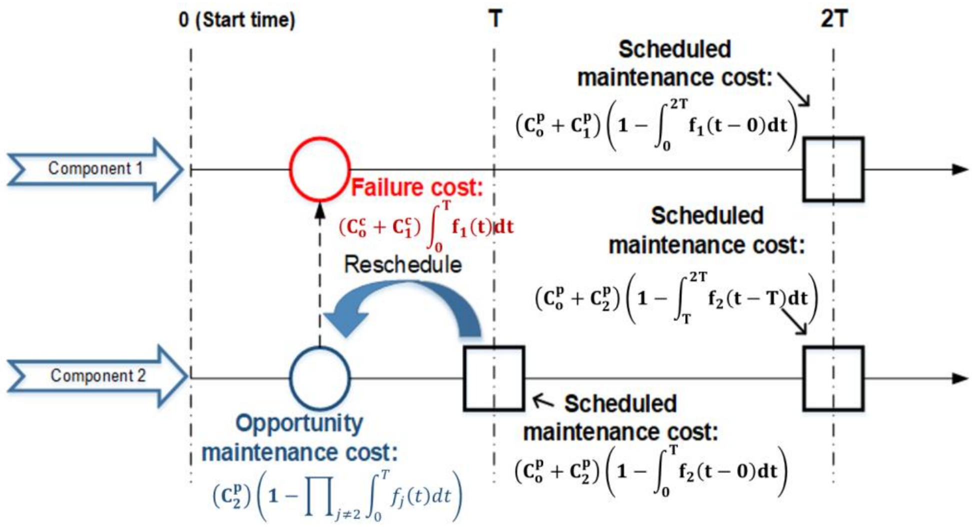

Figure 1: Demonstration of the maintenance cycle for a system of two components

2.3 Pinch Analysis Algorithm

The step-by-step framework for constructing the Composite Curves is presented as follow:

1. Identify the maintenance cycles for each components using Eq(1) - Eq(4). In this study, the time length is fixed when all the components have at least undergone maintenance once.
2. Determine the expected failure cost ('Sinks') using Eq(5) and expected opportunistic cost saving ('Sources') using Eq(7) for each time interval.
3. Plot the Failure Cost Composite Curve ('Sinks'), with cumulative cost as x-axis and time intervals as the y-axis. Please refer to Figure 2(a).
4. Plot the Opportunistic Cost Saving Composite Curve ('Sources') in the same figure.
5. Shift the Source Composite Curve horizontally until it is below the Sink Composite Curve. The reason is that at a given time, the expected cost saving has to be larger than the failure expected cost. That is to ensure sufficient cost to mitigate the expected failure at the given time. The point where both of the curves meet is called the time 'Pinch'. It is the time where the cost saved from opportunistic maintenance is just enough to cover the failure cost. Cost saved before this period (below the Pinch Region) cannot be transferred to cover the expected failure cost beyond this period (above the Pinch Region)- see Figure 3 (a).

3. Case study demonstration

The proposed methodology has been applied to a hydrogen gas centrifugal compressor of the catalytic reforming unit in Skikida refinery. It was determined as the leading cause of the catalytic reformer breakdowns (Laggoune et al., 2009). For a reformer, the role of the compressor to maintain the pressure of hydrogen gas helps in reducing coke formation and production losses. As such, the maintenance on compressor plays an important part in ensuring the process reliability to drive more considerable profit. The detailed process description can be found in Laggoune et al. (2009). The data required for this study are presented in Table 1.

Table 1: Cost data and the Weibull parameters of the system components (Laggoune et al., 2009)

Component i	C_i^C ($)	C_i^P ($)	B_i	n_i	$MTBF_i^a$ (d)
Sheathing (C1)	14,868	3,639	1.73	486	433
Sheathing (C2)	39,20	5,438	1.88	507	450
Tightness (C3)	44,880	7,398	2.43	286	254
Stub bearing (C4)	57,876	8,277	2.53	898	797
Tightness ring (C5)	73,860	13,554	2.14	905	801
Carrying bearing (C6)	46,752	14,130	3.55	736	663
Stub bearing (C7)	48,568	21,356	2.68	1,094	973
Labyrinth support (C8)	74,232	24,348	2.09	1,388	1,229

[a]The calculated values of MTBF slightly differ from the data in the literature. The calculated MTBF is used in this study as the data source from the literature is unknown.

Figure 2(a) shows the plot of the Composite Curves after completing steps 1-4 in the algorithm (Section 2.3). Note that the time interval has been fixed at slightly before the minimum MTBF (254 d) (Table 1), which is 244 d with α=0.96, see Eq(3). The values are set for demonstration purpose only and can be modified according to preferences. As can be seen that after time 488 d, the expected failure cost is higher than the expected opportunistic cost savings. Extra cost has to be invested in mitigating the expected failures after that time. Figure 2 (b) shows the Grand Composite Curve, which is the cumulative cost difference between sources and sinks.

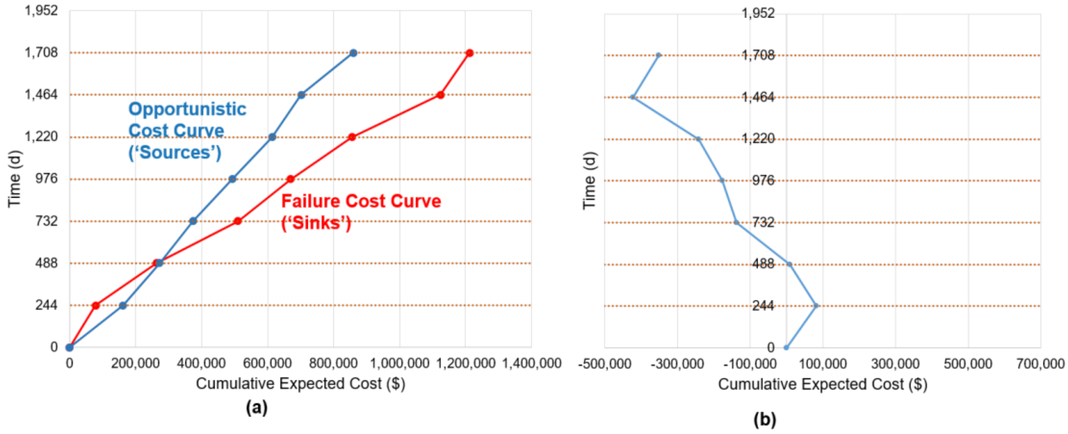

Figure 2: Graphical representation of the Pinch Analysis framework before shifting (a) Composite Curves (b) Grand Composite Curve

The Source Composite Curve in Figure 2 (a) is shifted to the right horizontally until it lies below the Sink Composite Curve. The reason is that at a specific time, the cumulative cost saved and the extra investment have to be enough to cover the expected failure cost. The interception of the two Composite Curves at 1,464 d, called time 'Pinch' signifies that the cost saved from opportunistic maintenance is just enough to cover the expected cost due to failures. Cost saved before this period (below Pinch Region) is not able to cover the expected failure after this period (above Pinch Region). The shifted amount is the extra cost needed to mitigate the expected failure of the system. According to Figure 3 (a) and (b), extra $ 422,183 has to be paid to cover the failures that are expected to happen at the earlier time. A total amount of $ 789,270 (about 65 % or total failure cost) can be saved from the opportunistic maintenance policy (overlapped regions). Extra $ 70,465 saved at the end of the period can be reserved for the next period or to handle emergencies. This amount can also be further reduced by removing unnecessary maintenance grouping. The discussions above are just demonstrations of the proposed methodology and strategy for maintenance management. Further development and solution benchmarking with the real case studies are required to confirm the framework's legitimacy.

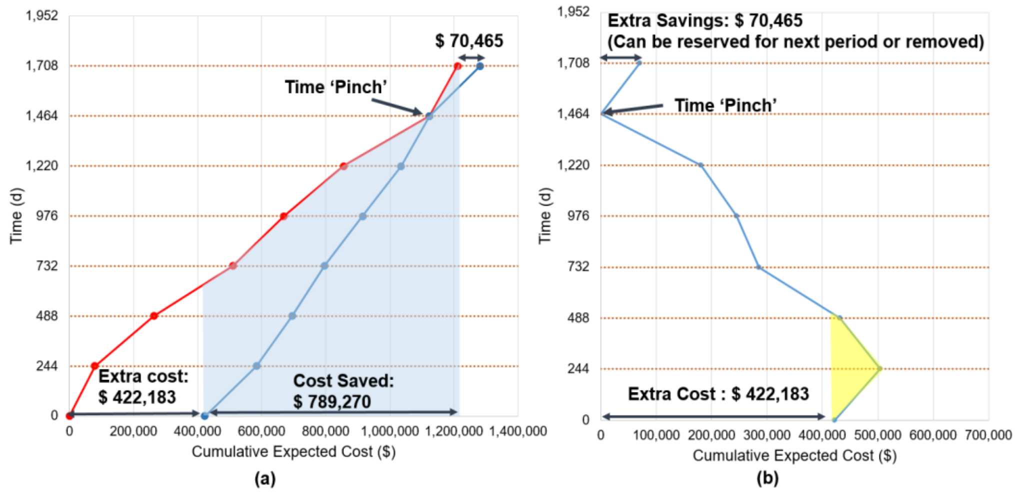

Figure 3: Graphical representation of the Pinch Analysis framework after shifting (a) Composite Curves (b) Grand Composite Curve

4. Conclusion

This work proposed a graphical strategy to facilitate opportunistic maintenance management. The cost saved from the maintenance policy is used to cover the expected failure cost. A case study of component replacement of a hydrogen gas compressor is used to demonstrate the methodology. The result shows that about 35 % of the failure cost from the start time has to be paid at extra cost. The remaining 65 % can be covered by applying maintenance policy. The extra cost savings at the end of the period also suggest that the maintenance grouping can be further reduced. The limitations of this concept are that it is highly dependent on maintenance schedules. The solution will change as the schedule has been modified. The updates on the reliability function after maintenance rescheduling are also ignored in this study. The potential future research would be the full maintenance scheduling using similar approach considering the resources availability (manpower, time and spare parts). Criticality analysis and the concept of the circular economy can also be incorporated to assess the maintenance policy. Solution benchmarking is also necessary to determine its accuracy and legitimation.

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