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Short Term Maintenance Tasks Scheduling with Pinch Methodology

Hon Huin Chin*, Petar Sabev Varbanov, Jiří Jaromír Klemeš

Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology – VUT Brno, Technická 2896/2, 616 69 Brno, Czech Republic
chin@fme.vutbr.cz

Careful assets maintenance planning is crucial in ensuring minimal process interruptions in a chemical plant while fulfilling production demand. This paper aims to propose a systematic framework with easily comprehensible tools for effective and efficient maintenance optimisation. The first step is to identify the optimal maintenance time for the equipment depending on their failure time distributions, minimising the expected maintenance cost. A maintenance tasks clustering model is then formulated for grouping individual preventive maintenance actions, to save the production downtime and cost. The solutions from long-term planning are transferred to the short-term planning model for detailed manpower scheduling. In this work, Pinch Analysis is selected as the targeting tool to maximise the available manpower utilisation and target the extra working hours needed. The daily maintenance tasks are formulated as the 'Demand/Sink', while the workers' shifts are the 'Supply/Source'. This method not only provides excellent visualisation of the problem/results, it also enables tuneable workers' daily schedules, tasks delay and the required earliest finished date of a task. A case study of a chemical plant, namely the Tennessee Eastman problem is used to elucidate the proposed approach. The results show that extra 22 h are needed for 8 h shift (5 d/week) for a single worker, but extra 13 h for 12 h shift (4 d/week).

1. Introduction

Equipment or assets are the core of a chemical plant that houses several processes to produce valuable products. The efficacy of the maintenance policy for complex and expensive chemical processes is critical for reliable operations. A significant amount of published literature references is mainly focused on identifying the optimal maintenance time and intervals for the process (long-term planning). The short-term maintenance scheduling, considering resources availability (e.g. time or manpower) is generally ignored in previous studies. Megow et al. (2010) consider turnaround scheduling in the chemical industry, specifically in continuous plants. The task is to minimise the cost of maintenance for resources usages, which are manpower and maintenance equipment. This minimisation is subject to pre-set precedence rules for maintenance tasks and resource scheduling constraints that involve shift calendars for maintenance workers. The assignment constraint, which assigns maintenance resources to jobs in each time period, gives the detailed maintenance schedule. The time-cost trade-off allows more expensive external resources to be utilised in order to perform a certain task in reduced time. The availability of only a single maintenance team causes a critical bottleneck to the process. Aguirre and Papageorgiou (2017) formulated a continuous-time mixed-integer linear programming (MILP) model to determine the optimum production and maintenance schedule for a multiproduct batch process. The tasks are scheduled by using the travelling salesman problem (TSP)/precedence-based concepts, incorporated production resources constraint and unit performance decay that reflect the reality of a chemical process. The performance decay is modelled as a statistical distribution. It provides some numerical guidelines to engineers to determine the optimal maintenance actions considering the deterioration model.
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 'black box' models. A strong programming background is required for users to decipher the model. As such, this study proposes a graphical approach, named as Pinch Analysis to identify the short-term maintenance tasks allocation, where

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the optimal tasks are created through long-term planning. This method has been widely applied in a different field and is famous for its easily understandable methodology. Linnhoff et al. (1982) developed the Pinch Analysis for solving the Heat Integration problem. Foo et al. (2007) first applied the concept to scheduling problem that deals with batch reactors operation. Foo et al. (2010) then further demonstrated the operators shift scheduling to fulfil the pre-determined tasks. Later works on scheduling using 'Pinch Analysis' can be found in Ooi et al. (2013) for carbon storage planning, Lim et al. (2013) for production planning in manufacturing industries. Lim et al. (2014) also utilised the same concepts in inventory planning for small and medium manufacturing industries. 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 tasks allocation for a chemical system, propagating the benefits of Pinch Analysis to this area. A case study of a chemical plant, namely the Tennessee Eastman problem is used to elucidate the application. The full description of the process can be found in Nguyen and Bagajewicz (2010) The main novelties of this work include:

(i) Identify the optimal long-term maintenance periods and intervals, as well as a cluster the maintenance activities to minimise the system downtime.
(ii) The utilisation of the available manpower ('Supply/Sources') to perform pre-determined maintenance tasks ('Demands/Sinks'). The utilisation of maintenance crew has been maximised, and the expected extra working hours needed and wasted working hours are minimised, analogous to maximising recycling rates and minimising resources or wastages.
(iii) Identification of maintenance jobs scheduling using a graphical approach and allow for tuneable workers' daily shift hours.

2. Methodology

The methodology consists of three sections. Section 2.1 presents the rolling horizon approach in determining the optimal maintenance time for individual equipment and the maintenance grouping for each equipment. The proposed Pinch Methodology for short-term maintenance workers scheduling is then explained in section 2.2.

2.1 Equipment long-term maintenance optimisation

The failure behaviour of the equipment is modelled using a Weibull distribution model. The failure probability of the equipment is modelled using a Weibull distribution model. 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. 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. In this study, the individual failure rates of equipment are modelled using the Weibull model, as shown in Eq(1).

$$\lambda_i(t) = \left(\frac{b_i}{\theta_i}\right)\left(\frac{t}{\theta_i}\right)^{b_i-1} \quad (1)$$

Where $\lambda_i(t)$ is the failure rate of equipment i (i=1,2..I) (no.of failure/weeks), b_i is the shape parameters, t is time (weeks) and θ_i is the Mean-Time-Before-Failure (MTBF) (weeks).

The objective in this stage is to minimise the infinite-horizon expected maintenance cost, as shown in Eq(2). In this work, a minimal repair policy is assumed, i.e. once a failure of equipment happens, the production is not stopped but it is immediately repaired to the state where it just failed ('as bad as an old state). Using renewal theory (Do et al., 2015) to model the long-run average cost, see Eq(3), the execution of maintenance for each equipment can be computed.

$$E\left(\frac{C}{T}\right) = E\left(\frac{C_{PM}}{T_{PM}}\right)P_{PM} + E\left(\frac{C_{cm}}{T_{cm}}\right)P_{cm} \quad (2)$$

$$Min\ \ E\left(\frac{C}{x}\right) = \frac{\left(Cp_i + Cc_i\int_0^{x_i}\lambda_i(t)\ dt\right)}{x_i} = \frac{\left(Cp_i + Cc_i\left(\frac{x_i}{\theta_i}\right)^{b_i}\right)}{x_i} \quad (3)$$

Where E(C/T) is the expected maintenance cost per unit time for an equipment, $E(C_{PM}/T_{PM})$ stands for the expected cost per unit time for preventive maintenance (PM), P_{PM} is the probability it is preventively maintained (not failed before T_{PM}), $E(C_{CM}/T_{CM})$ is the expected cost per unit time for corrective maintenance (P_{CM}) and P_{CM} is the probability that it is correctively maintained (failed before T_{CM}). Under the minimal repair policy in Eq (3), since the process is not stopped, the equipment is definitely to undergo preventive maintenance at T_{PM}. The cost is made up by the PM cost ($C_{p,i}$) and CM cost ($C_{c,i}$) times the expected number of failure $(x_i/\theta_i)^{bi}$. The decision variable is the optimal preventive maintenance execution time, x_i, in weeks. Eq(4) and Eq(5) below presents the calculations for the PM cost and CM cost for each equipment i.

$$Cp_i = S + Cl_i durr_{PM} \quad (4)$$

$$Cc_i = S + Cl_i durr_{CM} \quad (5)$$

Where S is the set-up cost (USD)for each production stoppage (repair crew mobilisation, safety provision, disassembling and transportation), Cl_i is the cost of production loss for each equipment i (USD/d) and $durr_{PM}$/$durr_{CM}$ is the maintenance tasks duration (h). In this study, a constant value of set-up cost, S is assigned to a value of 1,000 USD. The tentative maintenance cycle in the time window [t_{begin}, t_{end}] is determined with Eq(6) and Eq(7) below.

$$t_{i,j} = \begin{cases} t_{begin} - d_i + x_i + durr_i, & j = 1 \\ t_{i,j-1} + x_i + durr_i, & j > 1 \end{cases} \quad (6)$$

$$t_{i,j} \leq t_{end} \quad (7)$$

Where $t_{i,j}$ is the maintenance execution time for equipment i and j-th maintenance activities (weeks), d_i is the operational time since the last maintenance before $t_{begin,}$ and $durr_i$ is the total maintenance duration for equipment i (CM and PM). After the individual maintenance time ($t_{i,j}$) are found, the maintenance grouping model is then solved to determine the optimal maintenance tasks clusters. The model is presented in Eqs(8-13).

$$h_{i,j} = Cc_i * \left(\frac{x_i + dt_{i,j}}{\theta_i}\right)^{b_i} - \left(\frac{x_i}{\theta_i}\right)^{b_i} - dt_{i,j} E\left(\frac{C}{x}\right) \quad (8)$$

$$dt_{i,j} > -x_i \quad (9)$$

$$t_{i,j}^* = t_{i,j} + dt_{i,j} = \sum_{k \epsilon K} z_{i,j,k} T_k \quad (10)$$

$$\sum_{i \in I, j \in J} z_{i,j,k} \leq 1 \quad (11)$$

$$Setr_k = \left(\sum_{i \in I, j \in J} (z_{i,j,k} - 1) S\right)\left(\sum_{i \in I, j \in J} z_{i,j,k}\right) \quad (12)$$

$$Max \;\; EP = -\sum_{i \in I, j \in J} h_{i,j} + \sum_{k \epsilon K} Setr_k \quad (13)$$

Where $h_{i,j}$ is the penalty cost for shifting maintenance activities for equipment i and j-th maintenance, $dt_{i,j}$ is the amount of time shift, T_k is the maintenance execution time for group k, $z_{i,j,k}$ is the binary variables to specify that whether the j-th maintenance task for equipment i is in group k, $Setr_k$ is the set-up cost reduction for group k and EP is the economic profit for grouping maintenance tasks. The main objective of this model is to identify the shifting time ($dt_{i,j}$) that maximises the economic profit gain (EP) from grouping maintenance activities together. More information on such models can be found in Do et al. (2015).

2.2 Pinch Analysis for short-term maintenance scheduling

The step-by-step framework for applying Pinch Analysis in maintenance scheduling is presented as follow:

(a) Identify the optimal maintenance cycles and clusters for each equipment using models presented in section 2.1.

(b) In each cluster k, arrange the daily maintenance tasks based on the priority level and determine the latest finish date of the tasks. The work is limited to at least 8 h works per day. Plot the curve with cumulative duration (h) in x-axis and time (d) in the y-axis. This is the Tasks Composite Curve ('Demand/Sinks').

(c) Determine the available manhour and their daily work schedule in the plant. Plot similar curve in the same figure, with the duration represented by the daily shift hours. This is the Manhour Composite Curve ('Supply/Sources').

(d) Shift the Manhour Composite Curve horizontally until it is on the right side of the Tasks Composite Curve. The reason is that on a specific day, cumulative available manhour should be larger or equals to the cumulative tasks duration. This is also to ensure the tasks are finished before the deadlines. Please refer to Figure 2.

3. Case study

The proposed methodology is applied to a small scale chemical process, which is the Tennessee Eastman Problem. The full description of the process can be found in Nguyen and Bagajewicz (2010). Table 1 shows the list of equipment with their corresponding failure and maintenance data. In this study, the set-up cost is assigned to a value of $ 1,000. The starting time, t_{begin} and operational time before t_{begin}, d_i is assumed to be zero. The time length is fixed as all the equipment are maintained at least once, i.e. $t_{end} = \max(t_{i,j})$.

Table 1: Equipment failure and maintenance data (Nguyen and Bagajewicz, 2010)

Equipment	Quantity	MTBF, θ_i (d)	b_i	CM duration (h)	PM duration (h)	Priority	Production Loss (USD/d)
Valves	11	1,000	1.55	3.5	3	3	1,000
Compressors	1	381	1.7	15	6	1	60,000
Pumps	2	381	1.75	8	5	4	10
Heat Exchanger	2	1,193	1.8	13	7	2	60,000
Flash Drum	1	2,208	2	42	12	1	60,000
Stripper	1	2,582	2	72	12	1	60,000
Reactor	1	1,660	2	42	12	1	60,000

4. Results and discussion

Table 2 below shows the optimisation results using models presented in Section 2.1. It shows that the optimal maintenance grouping strategy is divided into four groups which yield the highest economic profit.

Table 2: Long-term maintenance planning results

Equipment	Quantity	Optimal maintenance time, $t^*(i,j)$ (Weeks)			
		k=1	k=2	k=3	k=4
Valves	11	63	134	134	124
Compressors	1	63	38	38	38
Pumps	2	63	134	134	124
Heat Exchanger	2	63	38	74	74
Flash Drum	1	63	134	134	146
Stripper	1	63	134	134	146
Reactor	1	63	134	134	124
EP/(T_{end}-T_{begin}) ($/week)	-	-134.79	13.63	17.92	18.22

To demonstrate the approach of Pinch Analysis, the schedule at k = 3 and at 134th week is chosen due to the longer task duration at that week. Figure 1a to b and Figure 2a and b show the plot of infeasible and feasible Composite Curves for a single worker. The shift hour for the worker is 8 h/d for 5 d/week. Notice that extra 22 h of working hours are needed at the beginning of the time and extra 8 h at the end is wasted. The worker is expected to take a weekend break, as shown in a longer vertical line at 6th and 7th d. The 'Pinch' Point is expected on the 8th day due to the cumulative working hours are just enough to complete the cumulated tasks before this day. It suggests that the worker can take a leave on 11th d as all the tasks are expected to finish.

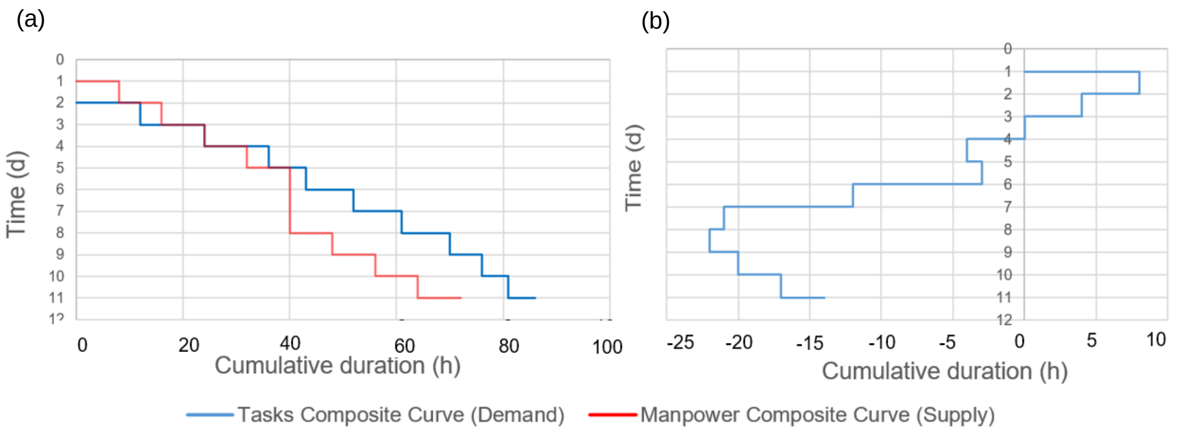

Figure 1: Pinch Analysis framework (8 h/d shift for 5 days shift) with (a) Infeasible Composite Curves matching (b) Infeasible Grand Composite Curve (GCC)

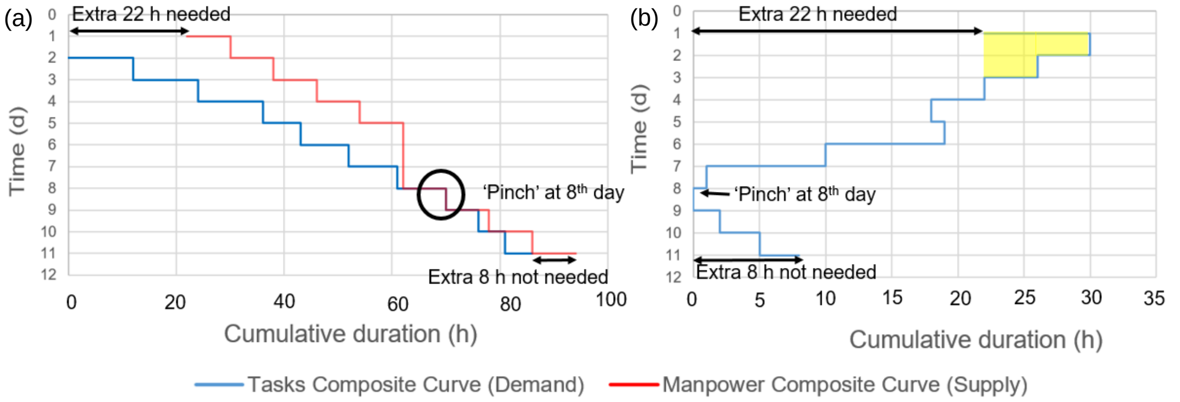

Figure 2: Pinch Analysis framework (8 h/d shift for 5 d shift) (a) Feasible Composite Curves matching after shifting (b) Feasible GCC after shifting

4.1 Shift hour changes

For this case, the workers' daily shift schedules are changed to 12 h/d for 4 d/week. Figure 3a and b shows the Composite Curves and the Grand Composite Curves. The extra working hour is reduced to 13 h, and the 'pinch' point is at 7th day. The 22 h at the end are not needed, and this suggests that the worker can take the leave as the tasks are expected to finish at 9th day.

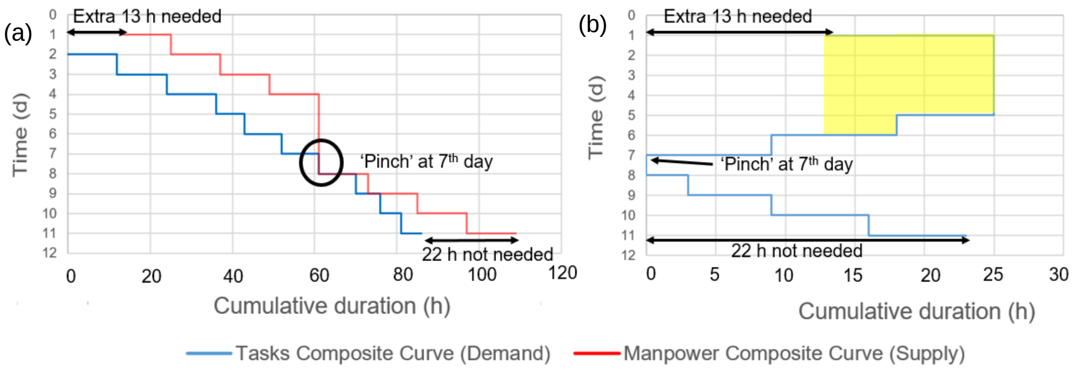

Figure 3: Pinch Analysis framework (12 h/d for 4 d shift) with (a) Composite Curves (b) GCC

4.2 Minimum finished date difference (ΔT)

Another analysis is conducted to demonstrate that the tasks are to be finished one day before the fixed end date (ΔT = 1 d). The worker's shift is fixed at 12 h/d (4 d) for the first week and 8 h/d (5 d) for the second week. Figure 4 (a) and (b) shows the plot of the Composite Curves.

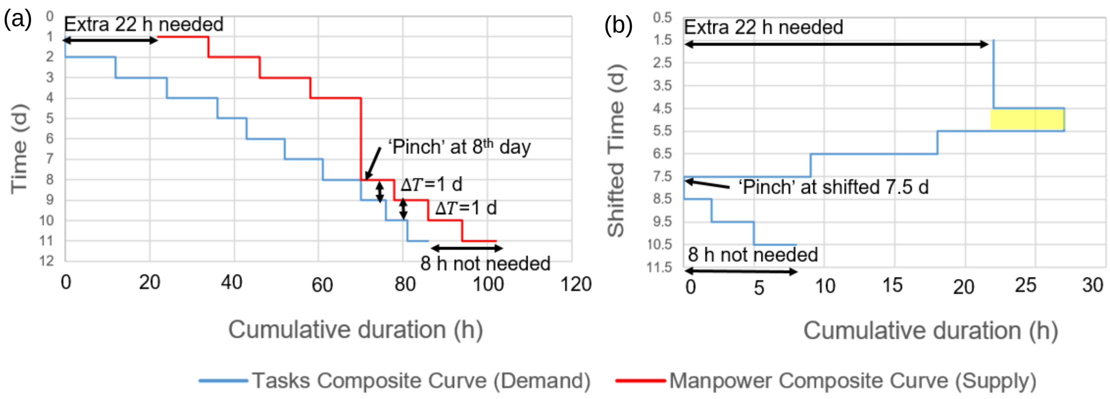

Figure 4: Pinch Analysis framework (ΔT=1 d) with (a) Composite Curves (b) GCC

Longer working hours are needed to finish the tasks before the deadline. It can be observed that the worker is entitled to take holidays in the early days as the maintenance tasks can be finished on time. The GCC can be computed using shifted days: (Worker's working day+ΔT/2 and tasks finished date-ΔT/2).

5. Conclusions

This paper proposed a combination of mathematical optimisation and graphical strategy to facilitate long-term and short-term maintenance planning. A case study of a small scale plant is used to demonstrate the methodology. For a single maintenance crew, extra 22 h is needed to complete the tasks with a 8 h/d for 5 d working hours, while extra 13 h is needed with a 12 h/d for 4 d shifts. Depending on the minimum finished date difference for the tasks, extra working hours are needed to account for uncertainties. Pinch Analysis provides excellent visualisation interface for the scheduler to plan for daily maintenance tasks. The limitation of this concept is that the problem is solved sequentially, which global optimality is not guaranteed. For future study, a scenario can be created where the maintenance tasks require specific skillsets from a worker, i.e. workers are either dealing with rotating equipment, heat exchangers or large equipment. The uncertainties of equipment failure can also be incorporated so that the engineers can tackle emergencies with sufficient resources.

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