Dynamic Maintenance Scheduling based on Cost Analysis and Genetic Algorithm for Offshore Facilities

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Abstract This paper introduces a dynamic Maintenance Work Order (MWO) schedule model for offshore facilities' daily maintenance management. The objective of the MWO schedule model is to improve maintenance performance by reducing MWO overall delay and suspension time and the related costs. More facilities now are equipped with predictive maintenance systems to generate MWOs in short time periods, which means periodical maintenance forecasting and planning strategies are now challenged by a more dynamic context. We examine these challenges and design a model to generate an optimal MWO schedule instantly based on cost analysis and real-time data processed by customized heuristic algorithms.

1 Introduction

Offshore facilities' maintenance activities are often constrained by operation time windows and weather conditions, resources' allocation and spare parts' logistics etc. To obtain efficient maintenance schedules, one should take all constraints into consideration even they are dynamic and interrelated. For offshore facilities equipped with predictive maintenance systems, more MWOs will be generated in shorter time periods based on condition monitoring data, which means periodical maintenance forecasting and planning strategies are now challenged by an even more dynamic context. MWOs thus are subjected to possible delays and suspensions due to service capacity and environmental constraints. These delays and suspensions will increase costs due to extended equipment downtime, higher labor cost, longer time logistics etc. To improve maintenance performance, one should reduce overall delay and suspension of MWO execution by proper prioritizing of MWOs under such scenarios, and it is a typical multistage discrete optimization

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problem which can only be practically solved by a heuristic algorithm in combination with industry domain knowledge. The rest of the paper will be organized as follows: Section 2 will analyze offshore facilities' MWO delays and suspensions and their cost impact as domain knowledge input, then present them mathematically for modeling. Section 3 will introduce the customized heuristic algorithm and the way in which MWO delays and suspensions can be modeled based on it. Section 4 will test the model's performance with a specifically designed dataset.

2 MWO delay and suspension analysis

Regarding maintenance services for critical equipment on offshore facilities, the following two constraints are often the norm:

- MWO execution sequential constraint: A rigid working process has to be followed to achieve a high level of service integrity.
- Work center occupation constraint: Often, onsite maintenance services for critical equipment are executed one at a time, and the service will not be suspended by technicians working on shifts until the service is done. The MWO is suspendable between different work centers, but the work center's ongoing job is unlikely to be suspendable. This is mostly because technical complexity requires operation continuality, moreover, logistic will be easier if services are completed in a single offshore trip.

The above two constraints fit well into the manufacturing industry's well-studied Flow Shop Schedule (FSS) problem, where n jobs have to be processed by j machines in identical order; each machine can only process one job at a time and will not be stopped until it is done (Werner, 2011). In the following section, we will apply these two constraints, together with FSS methodology, to model the MWO delays and suspensions.

2.1 MWO delay and suspension calculation

To start with a simple example: At the time of scheduling, we assume that we have 3 MWOs (ID: 1, 2, 3) for 3 equipment within the foreseeable future. All 3 MWOs have due dates as of now and need to be processed by 3 work centers in identical order as: (1) MWOs' planning and registration (planning), (2) resources' allocation and spare parts' logistic (logistic), (3) MWO execution and verification (execution). Given that the available man-hours at each work center are one man-hour at a time, the standard man-hours required by each MWO at each work center are given below:

Table 1 Required man-hours for each work order at each work center

MWO ID	Standard man-hours needed for each MWO at each work center (hr)			
	Work center 1	Work center 2	Work center 3	Total
1	3	5	6	14
2	4	8	6	18
3	1	2	3	6

According to the MWO execution sequential constraints and work center occupation constraints, we only need to decide the maintenance schedule at work center 1, then the schedule for the following work center will be auto-formulated by following the two constraints. For example, if we decide that the execution sequence at work center 1 is MWO ID 3-1-2, the entire maintenance schedule is shown below:

Table 2 MWO execution timespan at each work center

<table>
<tr><td>Work Center</td><td colspan="23">MWO execution at each work center (MWO ID is the number in the block)</td></tr>
<tr><td>1</td><td>3</td><td colspan="3">1</td><td colspan="4">2</td><td colspan="15"></td></tr>
<tr><td>2</td><td></td><td colspan="2">3</td><td></td><td colspan="5">1</td><td colspan="8">2</td><td colspan="6"></td></tr>
<tr><td>3</td><td colspan="3"></td><td colspan="3">3</td><td colspan="3"></td><td colspan="6">1</td><td colspan="2"></td><td colspan="6">2</td></tr>
<tr><td>Man-hr</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td></tr>
</table>

The total timespan for the execution of all MWOs is 23 hours: MWO 3 has no delay or suspension; MWO 1 is delayed for 1 hour at work center 1 but there is no suspension until it is complete; MWO 2 is delayed for 4 hours at work center 1 and suspended for 1 hour at work center 2, respectively work center 2 has 1 hour idle time and work center 3 has 5 hours idle time. If we decide that the execution sequence should be MWO ID 1, 2, 3 instead of 3, 1, 2, all the delays and suspensions will change accordingly.

Moreover, the operational efficiency at each work center is not constant due to seasonal environmental changes and geological impact on equipment maintainability, labor availability, resources' allocation and logistics etc. For example at remote facility during wintertime, more time and resources may be needed to prepare for the repair following sudden equipment breakdown. The actual required man-hours at each work center may then be higher and may cause lower levels of operational efficiency(Faccio *et al.*, 2014).

To generalize the calculation, given a maintenance schedule consisting of N MWOs to be executed on J work centers with identical order, we use the denotation shown in Table 3 and give the following calculation, according to the two constraints:

Table 3 Mathematic denotation

Work center ID	j	Operational efficiency	E
MWO ID	i	Standard required man-hrs	MTTR
MWO expected execution start time	R	MWO suspension time	Sus
MWO execution actual start time	S	MWO delay / advance time	D
MWO execution actual complete time	C	Work center idle time	Idle
MWO Schedule adjacent MWO ID: k (k precedes i, k = i-1)			

Note:

1. MWO delay / advance time D_i is the difference between MWO expected start time and the actual start time
2. MWO suspension time Sus_i is time gap between execution of one MWO on different work centers after execution start, for example, MWO has completed planning on work center 1, but cannot perform logistic immediately on work center 2 due to occupation by other MWO.

MWO delay/ advance time, and MWO suspension time represent different scheduling emphasis. For instance, for one MWO, scheduler want it start as soon as possible, then the delay time should be minimized; in other case, scheduler want a MWO to be complete as soon as possible after it start, then the suspension time should be minimized.

- S_i^j (MWO_i's start time at $Work\ Center_j$) is the later (bigger in man-hour sense) one between C_k^j(precedent MWO_k's completion time at $Work\ Center_j$) and C_i^{j-1}(MWO_i's precedent $Work\ Center_{j-1}$'s completion time) :

$$S_i^j = max(C_i^{j-1}, C_k^j) \qquad \textit{Equation 1}$$

- Complete time C_i^j is the actual start time S_i^j added the actual execution time:

$$C_i^j = S_i^j + E_i^j * MTTR_i^j \qquad \textit{Equation 2}$$

- Delay / advanced time at work center 1 is the difference between C_k^1 and R_i:

$$Df_i^1 = C_k^1 - R_i \qquad \textit{Equation 3}$$

- Suspension time after work center 1 is the difference between C_k^j and C_i^{j-1} when C_k^j is later than C_i^{j-1}:

$$Sus_i^j = C_k^j - C_i^{j-1}, j > 1 \qquad \textit{Equation 4}$$

- Total time span T_i (from expected start to actual complete) of MWO i is the sum of Df_i^1 , C_i^j and Sus_i^j for all work center j:

$$T_i = Df_i^1 + \sum_{j \in J}(C_i^j + Sus_i^j) \qquad \text{Equation 5}$$

- Idle time at work center j is the sum of the difference between C_k^j and C_i^{j-1} when C_k^j is earlier than C_i^{j-1} for all MWOs:

$$Idle_j = \sum_{i \in N}(C_i^{j-1} - C_k^j), j > 1 \qquad \textit{Equation 6}$$

We are able to calculate all the parameters of each MWO listed above easily by recursive calculation given a defined MWO schedule at work center 1.

2.2 Cost analysis for MWO with delays and suspension

As defined by Lyonnet (2013), maintenance costs are grouped into two categories: (1) Maintenance operation costs, which include labor costs, maintenance equipment costs, spare parts' costs and total intervention costs, and (2) Loss due to a stoppage, which includes production losses, failed equipment amortization, energy consumption, etc. We will alter the second category from "production loss" to "function loss" to cover a wider range of maintenance activities. Moreover, since our goal here is to reduce delays and suspensions and the related cost, the static costs, regardless of delay and suspension, such as material and spare parts' costs, will be excluded from our calculation. For cost category (2), we only take function lost cost into consideration:

1. Maintenance operation cost: different MWOs have different operation cost rates at different work centers, and the cost rate fluctuates with time and other influencing factors. We denote $O(t)_i^j$ as the maintenance operation cost rate function of time for MWO_i at work center j; the remaining denotation following Table 3 in Section 2.1, the total operation cost of MWO_i will be:

$$MWO_{\,operation\ cost,i} = \sum_{j \in J} \int_{S_i^j}^{C_i^j} O(t)_i^j \; dt \qquad \textit{Equation 7}$$

   Note: refere to Equation 1 and 2, the acutal execution duration of MWO i from S_i^j to C_i^j on work center j do not include suspension time Sus_i^j.

2. Function lost cost due to maintenance delay, suspension and execution: each MWO has a different level of impact on function lost, and the impact fluctuates with time and other influencing factors. Longer delay and suspension of MWO with higher function lost impact at a period with even higher impact rate will cause a higher level of function lost. If we convert the function lost (whether the function is production or safety and environmental protection) to money terms, and we denote $F(t)_i$ as MWO_i's function lost cost rate as a function of time, then we have:

$$MWO_{\,function\ lost,i} = \int_{R_i}^{T_i} F(t)_i dt \qquad \textit{Equation 8}$$

Note: we assume the function lost start at the point when the MWO execution is expected to start, which is R_i; and recover to normal at the point when the MWO is complete , which is T_i.

Using Equations 1 to 8, we can calculate all and each MWO's delay, suspension and related cost; with the data given, we are able to fulfill the following typical MWO schedule objectives:

- Obtain the shortest total work span to complete all MWOs in the backlog.
- Obtain the lowest function loss cost during intense production seasons.
- Obtain the shortest idle time for a particular work center if that work center is a costly outsourcing contractor.
- Obtain the shortest delay and suspension time for a MWO if it critically impacts production and safety functions.
- Obtain the lowest maintenance backlog to complete all MWOs in time.

The MWO scheduling can be executed based on the above calculations and objectives by real-time data processing iteratively, the real-time data includes, but not limit to MWO list, maintenance operation cost rate, function lost cost rate, operation efficiency rate etc. The scheduling process is illustrated in Figure 1 below:

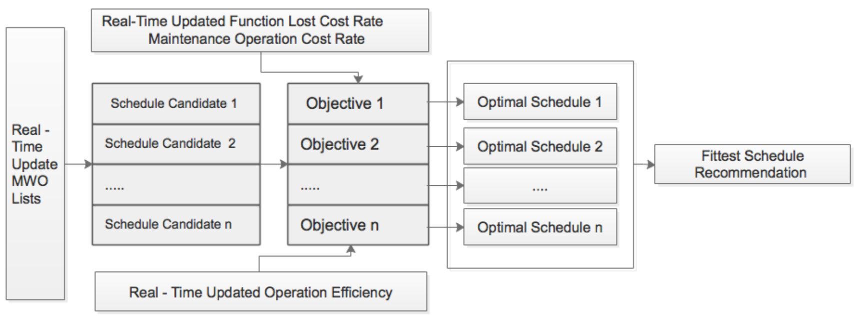

Figure 1 MWO scheduling based on real-time data

The process can be executed daily or even hourly automatically, and will be used as a framework for modeling in the next section.

3 Maintenance work order schedule modeling

MWO schedule optimizations are multistage discrete optimization problems, which can be practically solved only by heuristic algorithms with industry domain knowledge. For example, Muise (2016) used a neighborhood search with a hill-climbing algorithm to find the optimal schedule for a typical flow shop schedule problem. Wang and Handschin (2000) used a genetic algorithm to find the optimal schedule for a preventive maintenance problem. In our case, we use a genetic algorithm, together with an enhanced local search, to model a MWO schedule for both preventive and corrective maintenance scenarios.

3.1 Genetic algorithm and MWO schedule modeling

The genetic algorithm (GA) was originally developed by Holland (Goldberg and Holland, 1988). In short, the idea is to mimic the efficient selection process of natural evolution, where the environmentally fittest chromosomes will survive from the massive chromosome populations, in which individual chromosome randomly cross over with each other and mutate to generate new chromosomes to update the population for iterative fitness selection, until convergence criteria are achieved; the process is illustrated in Figure 2.

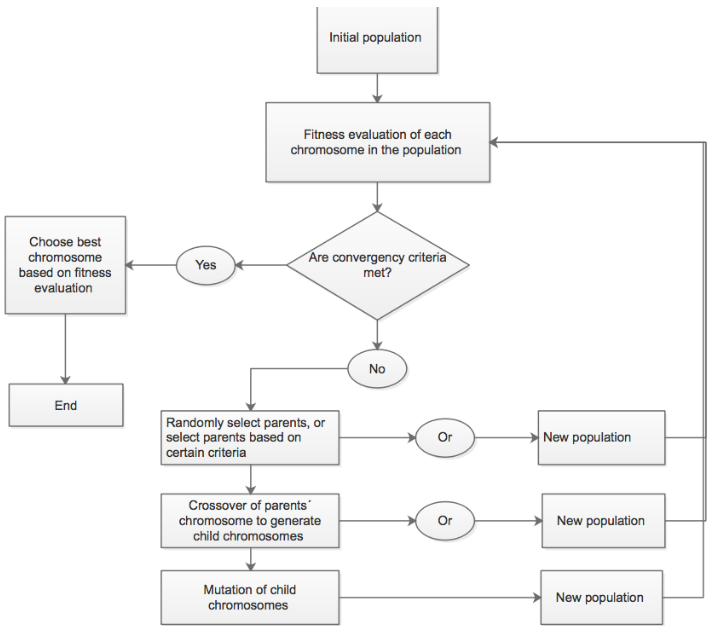

Figure 2 Genetic algorithm procedure

By analogy, a maintenance schedule can be seen as a chromosome, and each MWO within the maintenance schedule as a gene of the chromosome. The gene (MWO) can be sequentially altered or replaced by another gene (MWO). By applying a genetic algorithm iteratively to our schedule problem, we aim to select the fittest maintenance schedule, according to our objectives, as listed in Section 2.2.

We use MWO ID as the gene and a MWO ID permutation as a chromosome for fitness calculation against the predefined schedule objectives. Once the fittest chromosome is selected, the maintenance schedule (execution sequence at work center 1) can be decoded immediately, as shown in Table 4.

Table 4 Maintenance scheduling problem representation

Chromosome population	Genes (MWO ID)							
Chromosome 1	1	2	3	5	4	6	...	n
Chromosome 2	2	5	1	3	6	4	...	n
Chromosome 3	n	2	3	4	5	6	...	1
.....	.....							
Chromosome x	1	2	3	5	6	4	...	n
MWO schedule population								

4 MWO model test and demonstration

We programmed the model by Python script, based on the GA and the MWO schedule process illustrated in Figure 1. Note that we will not elaborate on the programming and algorithm setting details, since this paper is concerned with maintenance scheduling conceptual modeling rather than computer programming. We used Microsoft Azure Machine Learning Workbench (Microsoft, 2018) as the computation environment to deploy and run our model. Model input and output data were stored in the cloud. The results were demonstrated through Microsoft Power BI online visualization. The purpose of running the model and demonstrating the results on the cloud is to test the model's ability for real-time information processing and presenting. For conceptual testing, we created a test data set of 10 MWOs executed through 3 work centers. The available man-hours at each work center are 1 man-hour at a time. The data set includes the following segments:

Table 5 Model test data set properties

Name	Property	Used in Equation
MWO registration list	Given expected start date R_i and $MTTR_i$ for each MWO at each work center	Used in equation 2 and 3
Operation efficiency factor $E(t)_i^j$	A given number range between 0 to 4 for each MWO at each work center which varied from month to month through the year	Used in equation 2
Maintenance operation cost rate $O(t)_i^j$	A given number range between 10 to 100 for each MWO at each work center which varied from month to month through the year.	Used in equation 7

Function lost cost rate $F(t)_i$	A given number range between 1 to 700 for each MWO which varied from month to month through the year.	Used in equation 8

We ran the model according to the objectives listed in Section 2.2. Through 1000 iterations within eight minutes, we obtained the results as shown in Figure 4:

- Each circle is a MWO schedule, generated by the model after one iteration; the center location of the circle represents the schedule's total maintenance operational cost and functional lost cost, as indicated on the X and Y axes, respectively.
- The radius of the circle is positively correlated to the total work span of the maintenance schedule.
- The darkness of the circle is positively correlated to the total maintenance backlog of the maintenance schedule.

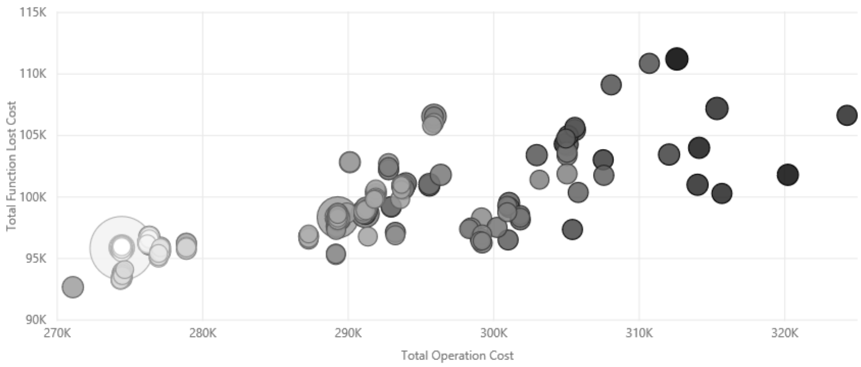

Figure 4 Genetic algorithm procedure

According to our objectives, the circle at the left most, lowest part of the chart with the smallest radius and lowest level of darkness is the favorable maintenance schedule we are looking for, since it has the lowest function lost cost and maintenance operation cost, with the smallest work span and backlog of man-hours. We can also easily choose the schedule by ranging the selection criteria from Figure 4.

5 Conclusion

The paper presents how offshore facility maintenance performance can be improved by reducing delay and suspension times and the related cost in a dynamic environment. Two important constraints of offshore maintenance service have been introduced to build a schedule model. Based on these, we are able to generate a reasonable schedule recommendation to resolve the challenges. However, the two constraints are not universally applicable; particularly, the work center occupation constraint can be altered when the work center ongoing maintenance activities are not critical, more than one MWO can be proceed simultaneously at that work center. We will examine more complicated scenario in our further research. Finally Thank China Scholarship Council and Norwegian Research Council for supporting this research project.

6 Listing References

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