ISE 540:338 Probabilistic Models in OR

Project Exercise #2: Wind Farm Maintenance Using Markovian Analysis

Final Submission: Electronic submission, December 9th, 2020 at 3:00pm

[20 pts]

OFFSHORE WIND FARM MAINTENANCE

Please read the following project description very carefully:

Today, wind turbines are the largest rotating machines on earth. With the increasing scale and sophistication of those massive structures, reliability and maintenance engineers have to be extremely careful when planning maintenance operations for wind turbines. Important questions include, when and how should we intervene and maintain a turbine so as to minimize the total downtime and maximize profits from electricity generation, bearing in mind that "pre-mature maintenance," i.e. doing maintenance too early may be too costly due to the production losses and system interruptions, while a "too delayed maintenance" increases the risk of major failures, which, in turn, would require major repairs. Complicating the problem is the fact that many modern-day turbines are placed in remote locations where wind is most favorable, including in areas where turbines may not be accessible for sustained periods of time due to unsafe wave heights (i.e. offshore wind turbines) or too strong wind speeds.

In this case study, your goal is to **use Markovian Analysis to find an optimal maintenance policy which maximizes total yearly profit.**

You are given the following problem description and inputs:

A turbine in an operational mode has a capacity of P_{cap} = 6MW/hour, which is sold in the electricity market at z = \$80/MW. You are interested in optimizing maintenance decisions in order to maximize the profit over one year (i.e. T = 8760 hours). The current practice implemented by the farm operator is a "corrective maintenance strategy," or in short, CMS. In this strategy, maintenance is only performed after the turbine experiences a failure.

Specifically, at each time step (here, one hour), if the turbine is in its operational mode, then the turbine may enter a "minor degradation" state with a probability of p_{deg} = 0.02, or remain in operational mode. If it's already in "minor degradation," then it may degrade further and enter a "major degradation" state with a probability of p_{deg}, or remain in "minor degradation" phase. Finally, if it's in "major degradation," then if it degrades further (again with a probability of p_{deg}), then it will enter a state called "failure by degradation."

Whether it's operational, minorly, or majorly degraded, there is always the possibility that it'd experience an unexpected failure with probability of p_{shock} = 0.001, and it'd enter a state called "failure by shock." Once in a failed scenario (whether failed by degradation or by shock), the turbine needs to be maintained in order to restore its operational mode. However, the turbine may be inaccessible due to unfavorable weather/marine conditions. Specifically, if it's in a failed state, then the turbine may be accessible with a probability of p_{access} = 0.60, and only then it can transit to the state of "under maintenance." Otherwise, it remains in its failed state (be it by degradation of by shock). Finally, if it's under maintenance, then there is a probability of p_{maint} = 5% that the maintenance team will be able to get it to fully operational within an hour. Otherwise, it remains under maintenance.

Understandably, degradation and failure come at a cost. When the turbine fails by degradation, it incurs a cost of \$7000/hour, while when it fails by shock, usually the cost is much higher and is estimated to be \$15000/hour. Moreover, maintenance costs the farm operator \$1000/hour as wages to the maintenance crew and technicians, as well as \$2500/**day** for renting a vessel equipped with a crane and necessary resources to access the turbine nacelle (note that vessels are rented daily, not by the hour). Degradation and failure also impact production: Under minor degradation, the turbine production drops to 80% of P_{cap} (for a 6MW turbine, it'd only produce 4.8MW/hour), and further drops to 60% of its P_{cap} in case of major degradation. Obviously, if the turbine has failed or is under maintenance, its production drops to 0 as it's shutdown until availability is restored.

Your yearly profit is computed as the difference between the revenue that you acquire by selling the electricity for the whole year, and the yearly costs you incur due to degradation, failure, and maintenance.

First, you need to model this problem as a Markov chain, and assess the current profit of the wind farm operator when implementing CMS (*Hint: You will have a total of 6 states and your total profit for CMS will be close to \$1,000,000*). In addition to profit, you can also evaluate the "goodness" of a strategy using metrics like total downtime, percent availability, number of vessel rentals, etc.

Second, you are required to find a maintenance policy that improves over CMS in terms of total profit (although you can also still report additional metrics like downtime, availability, etc.). Your strategy can be a combination of the following options:

1. <u>Conservative preventive maintenance strategy (CPMS):</u> Here, the turbine is maintained after it reaches the "minor degradation" phase. However, due to accessibility, the turbine may still move to "major degradation" or "failure by degradation." Specifically, if it's currently in minor degradation phase, then the probability of going to the "under maintenance" state is p_{access}, while that of going to "major degradation" is still at p_{deg}. The turbine can still also fail by shock with probability p_{shock}.

2. <u>Liberal preventive maintenance strategy (LPMS):</u> Here, the turbine is maintained after it reaches the "major degradation" phase. However, due to accessibility, the turbine may still move to "failure by degradation."

3. <u>Increase reliability by a factor:</u> There is an option of increasing the reliability of the system by installing a condition monitoring system, which can help self-correct the process when it deviates from normal behavior. In that case, you will pay a one-time investment cost, called C_{REL} (\$), which is computed as follows:
$$C_{REL} = \begin{cases} 0 & if\ r = 0.00 \\ 100{,}000 * \exp(5 * r) & if\ 0 < r < 1 \end{cases}$$
Where r is the fraction of decrease in p_{deg}.
In other words, if $r = 0.1$, then $p_{deg}^{new} = (1 - 0.1) * p_{deg}^{old} = 0.9 * \ p_{deg}^{old} = 0.9 * 0.02 = \ 0.018$
Also, $p_{shock}^{new} = (1 - 0.1) * p_{shock}^{old} = 0.9 * \ p_{shock}^{old} = 0.9 * 0.001 = \ 0.0009$.

4. <u>Increase capacity by a factor:</u> There is an option of increasing the capacity of the system by installing vortex generators on the turbine blades, which are small devices that boost the power production of the turbines. In that case, you will pay a one-time investment cost, called C_{CAP} (\$), which is computed as follows:
$$C_{CAP} = \begin{cases} 0 & if\ c = 0.00 \\ 300{,}000 * \exp(3 * c) & if\ 0 < c < 1 \end{cases}$$
Where c is the fraction of increase in P_{CAP}
In other words, if $c = 0.1$, then $P_{cap}^{new} = (1 + \ 0.1) * P_{cap}^{old} = 1.1 * \ P_{cap}^{old} = 1.1 * 6 = 6.6$MW.

5. Increase maintenance capability by a factor: There is an option of investing in advanced maintenance and repair technologies, which would increase p_{maint} by a factor. In that case, you will pay a one-time investment cost, called C_{MAINT} (\$), which is computed as follows:

$$C_{MAINT} = \begin{cases} 0 & if\ m = 0.00 \\ 50{,}000 * \exp(5 * m) & if\ 0 < m < 1 \end{cases}$$

Where m is the fraction of increase in p_{maint}

In other words, if $m = 0.1$, then $p_{maint}^{new} = (1 +\ 0.1) * p_{maint}^{old} = 1.1 *\ p_{maint}^{old} = 1.1 * 0.05 = 0.055$

Note that your final solution could be a combination of any of the above. That is, you can decide to implement CPMS with certain values for $r, c,$ and m. Note that the feasible values for $r, c,$ and m is between 0.00 and 1.00.

Your report has to consist of the following sections:

1. Modeling the CMS benchmark This includes modeling the CMS as a Markov chain (e.g. finding the 1-time step transition matrix, drawing a transition diagram). You will then find the steady-state transition probabilities, and compute the final yearly profit. You can also evaluate CMS in terms of other relevant metrics (e.g. total downtime, percent availability, number of vessel rentals, etc.)
2. Models and Methods: This section should include detailed information about your final maintenance policy (include your Markov model details). You have to show that you reached your method "methodically." You have to compare your method against the CMS benchmark + at least one more benchmark that you think is a viable candidate. You have to report the final realized profit, the percentage improvement in profit over CMS, and possibly other relevant metrics that you see fit.
3. Final Recommendation: One paragraph as a recommendation to the farm operator, including what is your profit, and how much you improved upon the current practice.

Deliverables:

On December 9th, 2020:

- **A 3-page report + Cover page (.pdf file).** The report should contain more figures/tables/equations than text. Your comments/findings on the figures/tables/equations should be concise but informative. A cover page to the report (does not count towards the 3-page limit) will include **your team name**, and team members**, as well as the contribution of each team member in the report in a Table.** The size of the contributions do not have to be perfectly even.
- **An Excel file (.xls file)** only including your final method calculations: your 1-step transition matrix, your steady state calculations, and your final profit calculations of your **selected method**. *Please make sure to highlight whatever is instrumental in different colors (the final profit, the steady state probabilities, etc.).*

Grading for this exercise: Total = 20 points

- Report organization and format + Cover page including required info [1 point]
- Quality of Figures/Tables/Equations [4 points]
- Models and Methods [7 points]
- Modeling of the CMS Benchmark [6 points]
- Final Profit [2 points guaranteed if your method is better than CMS].

Extra points:

- Up to +2 Bonus points that will be computed as follows:

$$\max\left(2 * \frac{PI}{MPI}, 0\right), \text{ where}$$

PI: Percentage improvement of your profit over the CMS, contingent on analysis being done right.
MPI: The maximum percentage improvement across all teams.

Few notes:

- One report, and one excel file per team. Team members have to work together to collectively integrate their efforts. Please avoid "patched" submissions, that is, the flow in the report has to be smooth. However, each member is still required to enter a submission on Canvas.
- When you submit your file to Canvas, call it: Teamname_ProjectExercise2
- Make sure to generate high-quality tables/figures/equations that are self-explanatory (font, colors, labels, etc.)
- Unlike homework and exams, you will not be evaluated based on the basis of your "Excel calculations," but rather on your narrative, methodology, report, and final performance.