Modeling the Operation and Maintenance Costs of a Large Scale Tidal Current Turbine Farm*

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Abstract- **Among the many ocean energy technologies under development, the tidal turbine farm has been proposed as an environmentally friendly ocean energy converter application. Although the technology and capital costs of ocean energy turbines are understood, the economics of operating a gang of turbines as an energy farm has yet to be analyzed. In this paper, a planning, operation and maintenance model for tidal turbine farms is proposed. The system is modeled using life-cycle assessment, incorporating a variety of time-dependent variables. Model components include farm construction and planning, operation strategy, regular maintenance, and emergency maintenance. Preliminary numerical simulation results are shown in a case study for a potential site.**

I. INTRODUCTION

Ocean energy includes ocean wave, tidal and tidal current, salinity, geothermal, offshore wind, and others. Among the various technologies to harness ocean energy, Tidal Power (TP) technology was one of the first to be commercialized. A large-scale barrage was built in the 1960s in La Rance, France and some small-scale barrages have been constructed in Canada, China, and other locales. However, TP has yet to be widely adopted. Obstacles to commercialization of early TP technologies have been widely discussed (Rulifson & Dadswell 1987, Van Walsum 2003, Eaton and Harmony 2003). As noted by Lang (2003), however, a new generation of TP technology that utilizes many tidal turbines in a farm configuration promises to make TP significantly more feasible and attractive. Key to the adoption of tidal turbine farms will be the economics of their operation. A recent survey of tidal power experts (Eaton and Harmony 2003) suggests that the largest barrier to the diffusion of tidal turbine farms is uncertainty over the economics of tidal turbines operated as a system. To help reduce this uncertainty, in this paper we introduce an economic model of a tidal turbine farm that includes both operations and maintenance (O&M) and capital costs. We show how the model can be applied in planning farm capacity and scheduling.

II. OCEAN CURRENT TURBINE TECHNOLOGY

Marine current turbines are not a completely new technology, because they are similar in many aspects to wind turbine, which are already well developed and commercialized. Theoretical and experimental study of marine current turbines was launched in the early 1980’s by the National Research Council of Canada. Recently, some pre-commercial prototype turbines were demonstrated offshore in the UK (Frankel 2002) and in Canada (Pearson L.B College 2005). Figure 1 shows the Horizontal Axis Tidal current Turbine (HATT) constructed by Marine Current Turbine Ltd (MCT) in UK offshore.

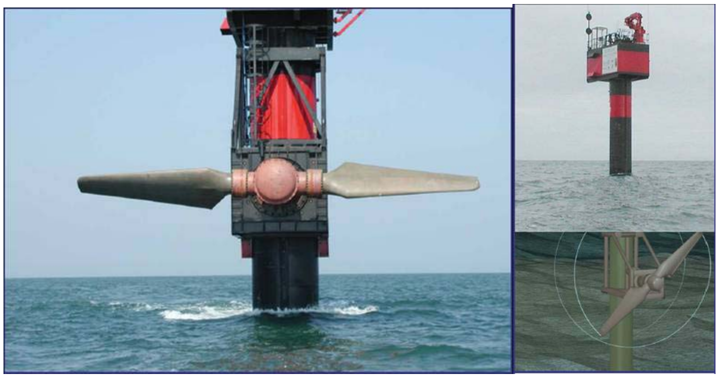

Figure 1 a) MCT turbine raised out of water b) MCT turbine in the water (Courtesy of MCT Ltd)

Like wind turbines, marine current turbines come in two types: horizontal axis as shown in Figure 1, and vertical axis tidal current turbine (VATT). In general, these two technologies work by the same principle in that they use a blade to extract the kinematic energy from ocean flow, convert mechanical energy to electrical energy by generator, transfer the electricity to a shoreside power conditioning station by underwater cable, and finally transmit the electricity by overhead transmission line to an existing electricity grid.

A number of analyses evaluating tidal turbine configurations have been published. Templin (1974) and Gorlov (1998) describe the status of technology development and present some detailed turbine designs. Others have evaluated the potential for energy production from tidal turbines. For instance, Meyers and Bahaj (2005) and Triton (2002) estimate tidal turbine potential at sites in the UK and Canada, respectively. Garrett (2002) analyzes how turbines across a bay should be distributed to maximize power extraction. In the ocean sciences community, research has focused on flow change induced by turbines. Miles (1981) and Garrett and Cummings (2004) report flow information with the farm treated as black box. Although sites for tidal power are limited to particular coastal regions, the size of the potential tidal power resource worldwide is estimated to be 500~1000

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* This work was done when Ye Li was a visiting scholar at the Carnegie Mellon Electricity Industry Center (http://wpweb2.tepper.cmu.edu/ceic/)

TWh/yr (Hammons 1993) and remains largely untapped. In the operation and planning fields, Prandle (1984) and Hoeller et al (1985) discuss general planning strategies. Only a few papers have touched on cost issues, albeit without getting into much detail (e.g., Fraenkel 2002). To better support investment decisions regarding tidal turbine systems, the factors affecting cost performance have to be quantified. Although the capital costs of tidal turbines are many times greater than lifetime O&M costs, the latter are considerably more uncertain. In this paper, we describe a detailed model of O&M costs to explore the plausible range of this cost element and to identify components that contribute most to this uncertainty. Cost effectiveness is chosen as the metric of analysis. O&M cost per unit energy production is defined as

$$\text{unit O\&M cost} = \sum_i omc_i \Big/ Energy \qquad (1)$$

where

omc_i is the discounted value of operation and maintenance cost in year i, a function of operations strategy

$Energy$ is the lifetime energy output of the entire farm

Basically, the power of the tidal current energy conversion device can be expressed as follows,

$$Energy = f_m f_e f_t f_o \left(\frac{L}{2} \rho A V^3 \right) \qquad (2)$$

where

f_m – fraction of full capacity lost for mechanical reasons

f_e - fraction of full capacity lost for electrical reasons

f_t - fraction of full capacity lost from tidal cycle

f_o - fraction of full capacity lost from other influences

L – plant lifetime

ρ – density of sea water

A – turbine area

V – maximum design velocity of tidal current

The power factors f_m, f_e, f_t, and f_o are averages over the design lifetime. Note that one would expect aging of mechanical and electrical components to degrade reliability and performance over time. Although the power factors in Eq. 2 are an important component of cost-effectiveness, we focus the remainder of this paper on O&M cost itself.

III. FACTORS AFFECTING O&M COST

O&M costs are affected by component reliability, environmental factors, farm configuration, and other factors. Contributors to each of these are as follows.

Component lifetime and failure rate:

- Blade
- Support column
- Gear box
- Electricity generator
- Shaft
- Brake
- Cable

Environmental factors:

- Weather (Rain, fog etc)
- Sea conditions(wind and wave etc)
- Tidal flow speed

Farm configuration:

- Offshore distance
- Device geometry(size, shape etc)
- Farm size

Other factors

- Labor and materials discount rates
- Nominal operational life time of components
- Transmission coefficients
- Electrical efficiency coefficient
- Mechanical loading

The lifetime of the device will significantly affect O&M costs, both because older equipment requires more attention, and because O&M costs incurred in the years furthest in the future are the most highly discounted. Tidal turbine lifetime might be extrapolated from that of current offshore platforms, which typically extend to 30 years or so. Designers of tidal turbines in the UK and Canada have projected lifetimes of 20-30 years for their designs (Pearson 2005). Although accurate estimates of operational lifetime of tidal turbines will not be available until more experience is gained with full-scale devices, some cause for optimism lies in the fact that pre-commercial testing of some near-shore turbines has resulted in turbines operating without failure over a five-year period, despite the lack of a systematic maintenance program.

Farm size affects O&M costs for tidal turbines in a manner that is similar to that for offshore wind farms, with the spacing between turbines being a key variable. Turbine farms have two alternative spacing modes: (i) side-by-side, creating a "tidal fence" and (ii) wide spacing. Spacing that is close decreases turbine efficiency because the flow through each turbine affects the flow through its immediate neighbors. Wide spacing, on the other hand, drives up maintenance by exposing more cable, and requiring higher maneuverability of maintenance craft.

IV. MODEL AND SIMULATION

In order to understand and investigate the sensitivity of all factors, a mathematical model is proposed to show the detailed relationships between all factors that comprise total O&M cost. Figure 2 shows the main model of the ocean turbine O&M cost estimation. In this model, following Eqn 2, the annual O&M cost per unit energy depends upon routine maintenance cost, emergency maintenance cost, and annual energy output.

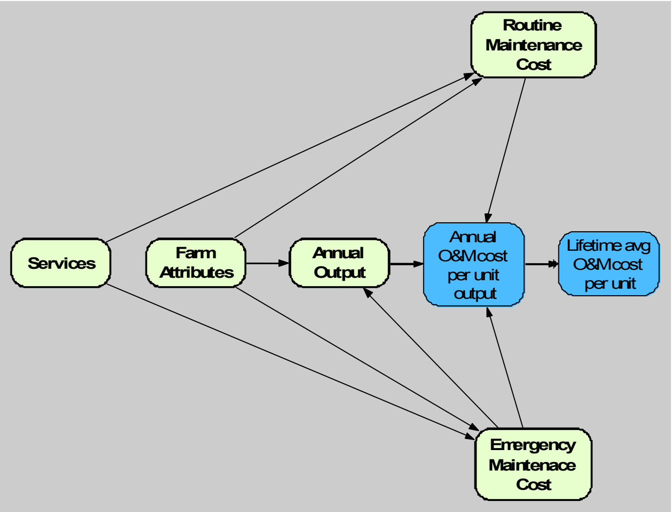

Figure 2 The top-level of the O&M model

The model shown in Fig. 2 is implemented in Analytica [Lumina Decision Systems, Los Gatos, CA], a stochastic modeling package with a user-friendly graphical interface.

Maintenance costs are computed separately for routine and emergency maintenance. Figure 3 shows the model for routine maintenance. Routine maintenance is done once per year for totally submerged devices [†](most HATT) and once or twice per year for partially submerged devices (some VATT). Routine maintenance includes various tasks that can only be performed on site such as vibration and seal checks. Factors that figure into the costs of routine maintenance include the number of turbines, the number of man-hours per turbine that are needed to perform a maintenance operation, skilled labor rates, transport costs for the maintenance crew, and the cost of diagnostic equipment. In addition, some routine maintenance procedures might require the turbine to be taken temporarily off-line, thus entailing indirect costs of lost power.

Figure 4 shows the model for emergency maintenance. Emergency maintenance entails fixing an existing or pending failure on one or more devices. The major cost components of emergency maintenance are failure rates, the replacement cost for broken components, and turbine downtime.

Figure 5 shows the model's graphical interface, which allows users to easily check the sensitivity of cost estimates to changes in various inputs.

Both emergency and routine maintenance costs are computed from estimates of failure rates and inspection/repair times for each of nine turbine components listed above. Electrical energy output is adjusted for turbine downtime resulting from failure and off-line maintenance. The following assumptions are made

1. Increasing energy losses from year to year caused by equipment degradation over time are offset by energy gains from improved management strategies and monitoring technologies.
2. Turbine hardware is assumed to be fixed over the device lifetime so turbine efficiency per se will not increase over time.
3. Traveling distance for routine maintenance is neglected
4. Routine maintenance frequency and its effect on emergency maintenance are assumed to be constant over time.
5. Labor and materials discounts are function of the farm plan(size, distance etc). For example, the larger the farm size, the cheaper the unit cost of material.
6. The time delay needed to acquire replacement parts is assumed to be constant. That is, logistics delays will not be affected by the weather, type of the failure etc.
7. Maintenance vessel performance is assumed to be perfect so that there are no additional costs due to vessel failure.

V. RESULTS AND DISCUSSIONS

With environmental data on British Colombia from Environment Canada and device data from MCT(BBV 2001) some case studies are done using this O&M model.

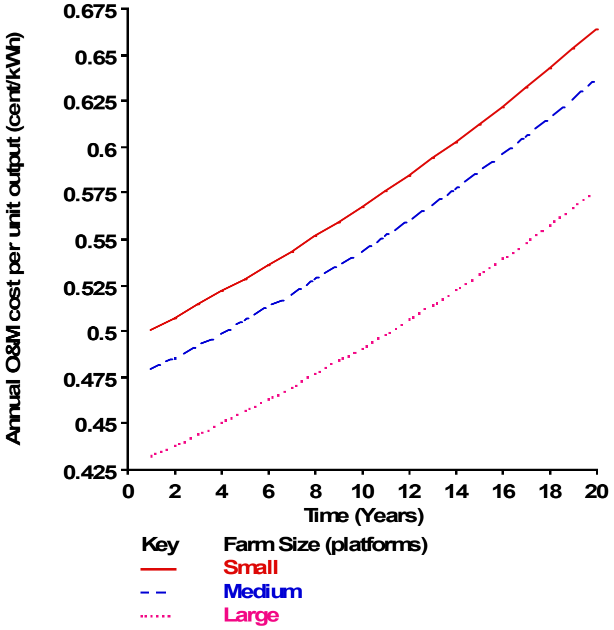

Figure 6 Annual O&M cost per unit

Figure 6 demonstrates how O&M cost per unit energy is affected by farm scale for a hypothetical turbine farm at Seymour Narrow, British Columbia, one of the best tidal power sites in North America. Under the high current speeds at this site, O&M costs are low and are quite sensitive to farm size. Given the limited area of Seymour Narrow, however, a large size farm would not fit into the site. [Farm size categories are defined in Table 1.]

[†] "Submerged" here refers to the generator, irrespective of whether other components of the device extend above the water.

Table 1 Turbine farm index

Farm Size	Small	Medium	Large
Device Number	30	50	100

Figure 7 shows results for annual O&M costs for a hypothetical turbine farm off the northeast United States. Because of challenging wind and wave conditions and slow current speed, O&M costs at this site are substantially higher than those for a more favorable site such as Seymour Narrow, British Columbia.

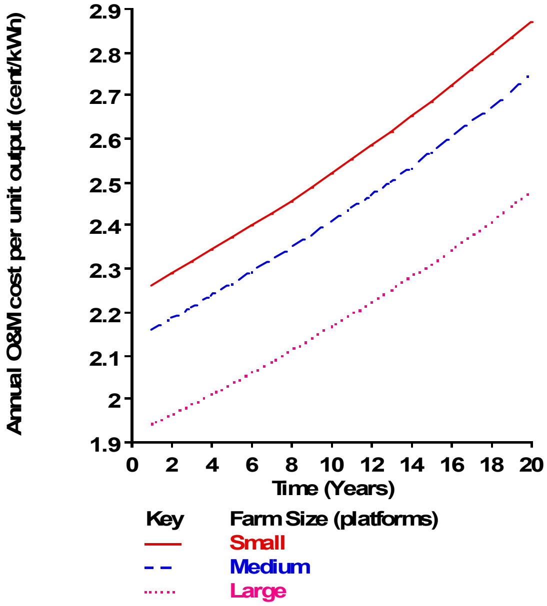

Figure 7 Annual O&M cost per unit energy for turbine farm off the northeastern US

VI. CONCLUSION

In this work, the factors affecting the O&M cost of a tidal current turbine are summarized and discussed. A numerical model is developed by integrating previous studies from different research disciplines and new approaches.

Our analysis shows that, besides tidal flow velocity, the two most important control variables for O&M cost are farm size and offshore distance. O&M costs per unit energy production are minimized by building farms with larger numbers of turbines closer to shore.

VII. FUTURE WORK

The model described here incorporates a number of lumped parameters, estimates for which are provided using subjective judgment. In future work, these lumped parameters will be deconstructed to allow more complete use of empirical data to calibrate the model.

ACKNOWLEDGMENT

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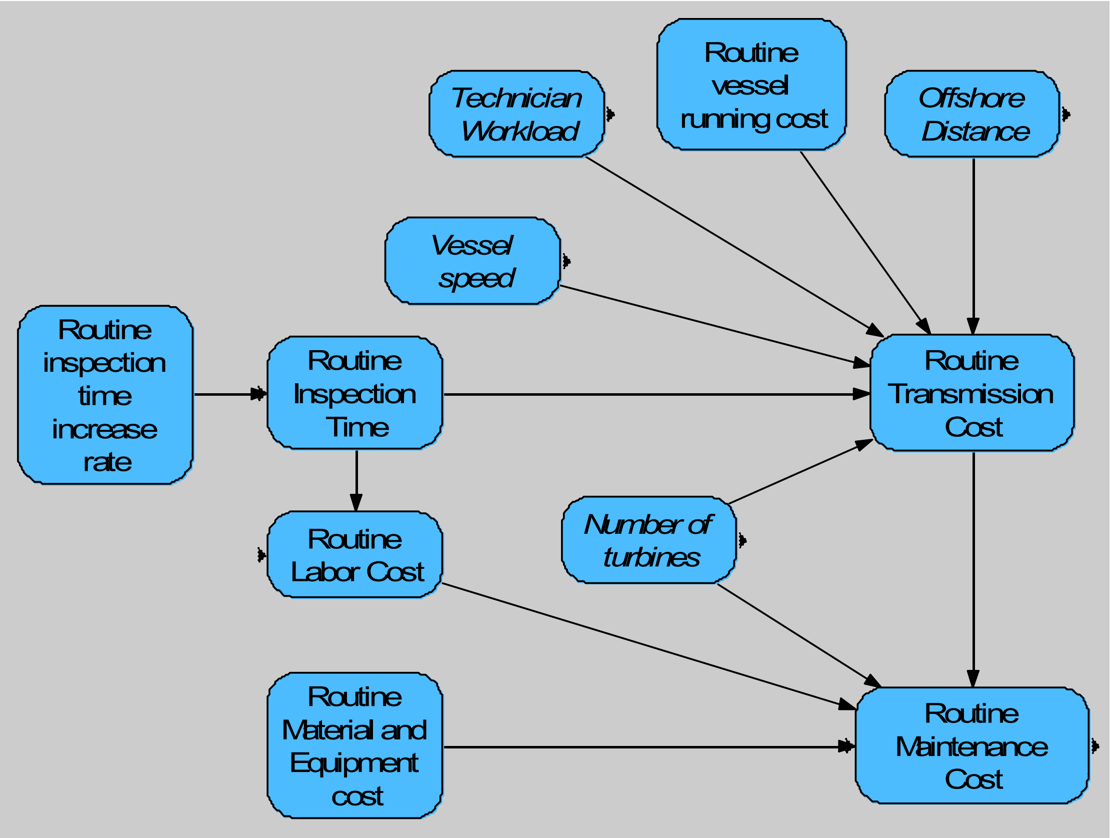


Figure 3 The routine maintenance model

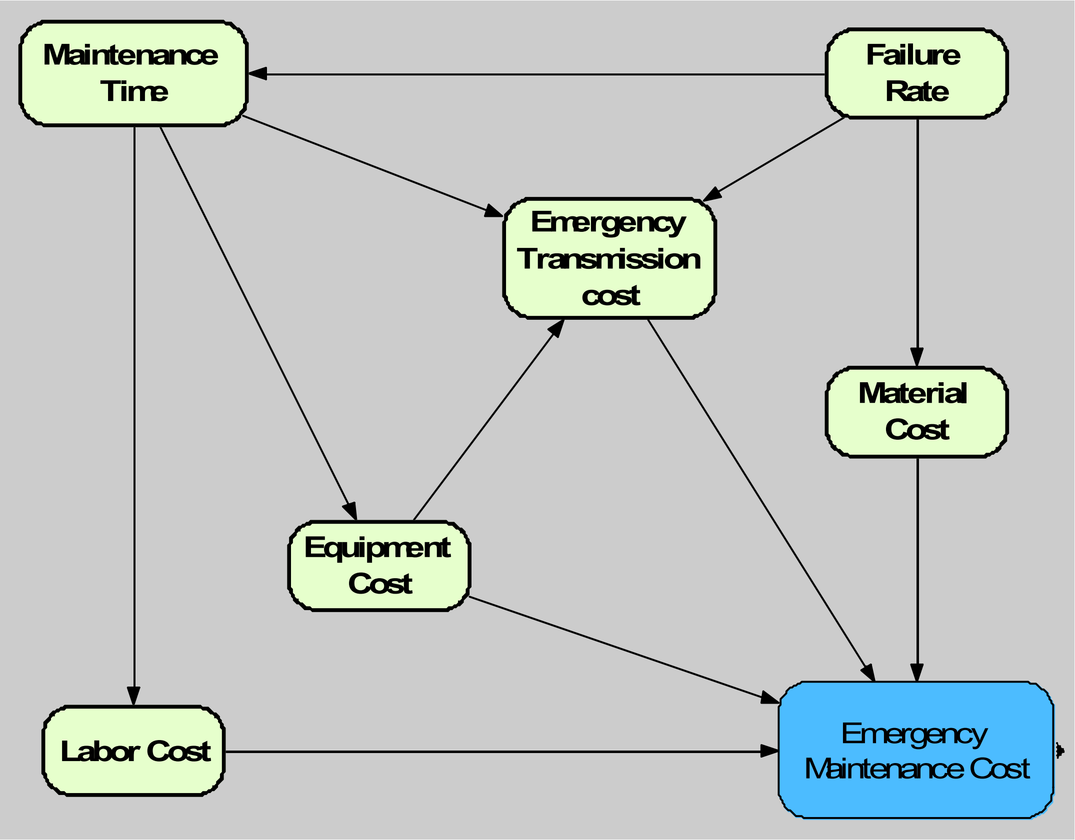
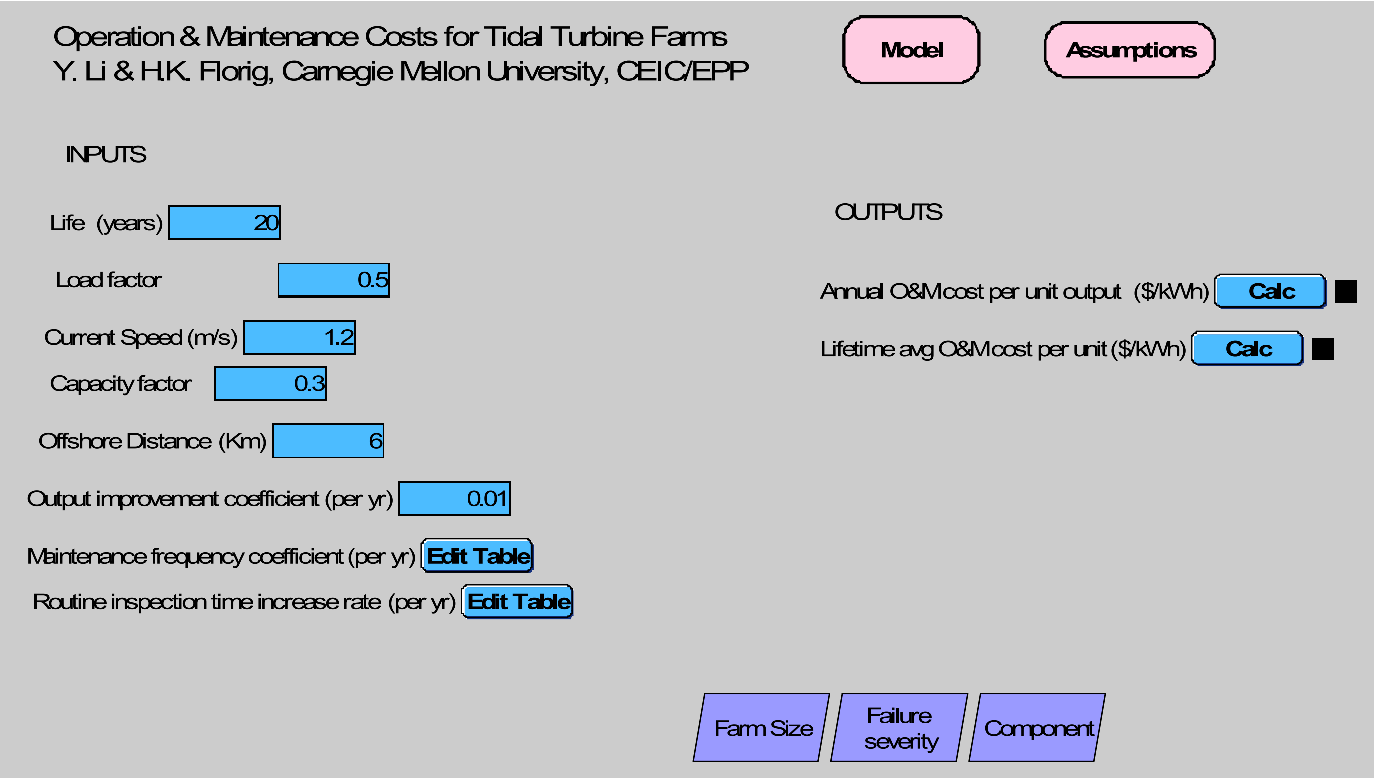


Figure 4 The emergency maintenance model



Operation & Maintenance Costs for Tidal Turbine Farms
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INPUTS

Life (years) 20
Load factor 0.5
Current Speed (m/s) 1.2
Capacity factor 0.3
Offshore Distance (Km) 6
Output improvement coefficient (per yr) 0.01
Maintenance frequency coefficient (per yr)
Routine inspection time increase rate (per yr)

OUTPUTS

Annual O&M cost per unit output ($/kWh)
Lifetime avg O&M cost per unit ($/kWh)

Figure 5 The graphical user interface of the simulation