Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT)

Rob Hammond and Aubryn Cooperman

National Renewable Energy Laboratory

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List of Acronyms

CTV	crew transfer vessel
ECN	Energy Research Centre of the Netherlands
O&M	operations and maintenance
MTBF	mean time between failures
MW	megawatt
NREL	National Renewable Energy Laboratory
WOMBAT	Windfarm Operations and Maintenance cost-Benefit Analysis Tool
WTIV	wind turbine installation vessel

Executive Summary

This report describes the Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT), which models the operations and maintenance (O&M) phase of a wind power plant. The model calculates both direct and indirect O&M costs, along with power production, safety, and efficiency of operations at a distributed, land-based, or offshore wind power plant. Because O&M costs comprise roughly one-third of the total life cycle costs for a wind power plant, it is important to understand how technological and process-based innovations might help drive down those costs.

WOMBAT is a medium-fidelity, scenario-based, trade-off analysis tool with a modular code base that allows for extensive customizations to account for technological innovations, maintenance strategy or methodological improvements, and site conditions. The most important benefit to the model being highly modular and flexibly composable is that there is no difference in how distributed wind, offshore wind, or land-based wind energy technologies are modeled. The flexibility of the software enables users to model wind power plants with any number of wind turbines. Similarly, any number of maintenance tasks and potential failures can be modeled on each turbine. Additionally, the flexible selection of service equipment enables users to model maintenance of land-based or offshore wind turbines, using appropriate constraints and capabilities for each type of service equipment.

This report details the functionality, implementation, conceptual background, and performance of WOMBAT. It describes the concepts underlying WOMBAT for readers who are interested in using the software and provides more details of the software implementation for users interested in customizing WOMBAT for their own analyses. First, the report presents the motivation and requirements for a free and open-source O&M software, then moves into the underlying data models that enable the core functionality of the software. It then describes how the simulation itself works, presents some of the end results that WOMBAT can generate, and summarizes our model validation exercises.

WOMBAT is actively being developed with new functionality and methodologies being implemented to continuously serve the needs of users. Therefore, this report is based off the release of Version 0.5.1, which is available at https://www.github.com/WISDEM/WOMBAT/. In addition to this report, up-to-date documentation, use cases, and examples can be found at https://wisdem.github.io/WOMBAT.

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1 Introduction

Operations and maintenance (O&M) represents around one-third of the total wind power plant life cycle cost (Stehly and Duffy 2022) with annual cost ranges of $15−$27/kilowatt (kW)/year for land-based wind energy (Liu and Garcia da Fonseca 2021) and $40−$60/kW/year for offshore wind energy (Wood Mackenzie 2021). Innovations such as remote inspection and repair, remote and automated maintenance, condition-based maintenance, improved methods for personnel transfer, and improvements in weather forecasting (Valpy et al. 2017) are expected to reach the market over the next decade and decrease O&M costs. However, it is difficult to accurately assess how each of these innovations will impact costs due to the wide variety of methods for cost estimation, lack of transparency surrounding modeling methodology, and the overall lack of publicly available and up-to-date data for modeling.

1.1 Background

While there are many ways to assess the impact of innovations and provide cost estimates for O&M, the tools that currently exist are often proprietary, so users cannot examine the code to understand how the model generates results, nor update it to include new innovations. Other published models rely on scaling relationships derived from industry estimates. These scaling relationships can rapidly become outdated as technology developments allow wind turbine and site parameters to expand beyond the range used to derive the original cost estimates.

The lack of software that is both flexible and modular enough to model current wind power plant capabilities and respond to new innovations with ease is what inspired the creation of the Wind Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT). WOMBAT is flexible enough to model land-based and offshore wind power plants ranging from distributed to utility scale. Also, WOMBAT is open source and freely available for anyone to download and customize for their own analyses. The input structure gives the user a high level of control over each element of operations and maintenance.

1.2 Modeling Approach

The primary purpose for WOMBAT is to help users compare O&M scenarios. It does not seek to optimize O&M costs or performance but provides users with quantifiable impacts of new technologies, maintenance strategies, and site conditions on the costs of operating a wind power plant. WOMBAT is a scenario-based tool that uses a discrete event simulation framework, which means that no changes occur between events. The discrete event framework lessens computational time by allowing the simulation to skip over periods in which no events occur. Events in WOMBAT include component failures, scheduled maintenance tasks, and mobilization of equipment to carry out repairs.

One of the core goals of WOMBAT is to be flexible and modular so that new technologies and strategies can be handled with ease, and this separation enables each step of the process to be highly configurable and open to expansion when innovations are introduced. This approach enables WOMBAT to model various trade-offs between O&M strategies and technologies by allowing for 1) the flexible and user-specific composition of wind turbine(s) through their failures and associated maintenance schedules at an arbitrary level of precision, 2) the use of site-specific conditions, 3) the flexible definition and scheduling of service equipment, and 4) the configuration of fixed costs associated with power plant operations. These features enable WOMBAT to model a wide variety of wind power plants with ease.

An important benefit to the model being highly modular and flexible is that there is no difference in how land-based, offshore, or distributed wind power plants are modeled. At a high level, the key elements of O&M are the timing of failures and repairs, how service equipment is dispatched, how environmental conditions affect operations, and ultimately, plant performance and operating costs. By aiming to represent those core aspects of a wind power plant, WOMBAT can capture the differences in wind power plant type through the choice of service equipment, equipment costs, site conditions, wind turbine power curves, and maintenance strategy.

2 High-Level Overview

WOMBAT simulates the lifetime operations of a land-based or offshore wind power plant with prescribed maintenance schedules and component-level failures that require responsive repairs. The model conducts maintenance and repair operations at an hourly timescale and with custom equipment that a user can select from a common library. Inputs including process times (the time required for activities such as traveling to a wind turbine or replacing a component) and operational constraints (such as a maximum wind speed for repairs at height) can be configured to define how the equipment performs in the field, which affects the downtime and performance of the wind power plant. A strength of the model is its ability to define and compare different O&M strategies. Throughout the simulation, WOMBAT tracks power production, downtime, O&M costs, and availability.

There are two architectures that comprise WOMBAT: the software itself, and the simulation. While these components are conceptually different, their development is cyclical, so that the needs of the simulation inform how the software is developed, and the strengths and limitations of the software can drive the possibilities for simulation modeling.

2.1 Software Architecture

Figure 1 shows the WOMBAT layout, with a clear separation between the core simulation components (left), wind farm model (center), and general utilities (right). Within this architecture, WOMBAT has five overarching models that comprise the simulation architecture (outlined with a dashed red line): 1) the environment, 2) wind farm, 3) repair management, 4) service equipment, and 5) port. Each of these models operate independently but are still interconnected to coordinate the repair and maintenance tasks.

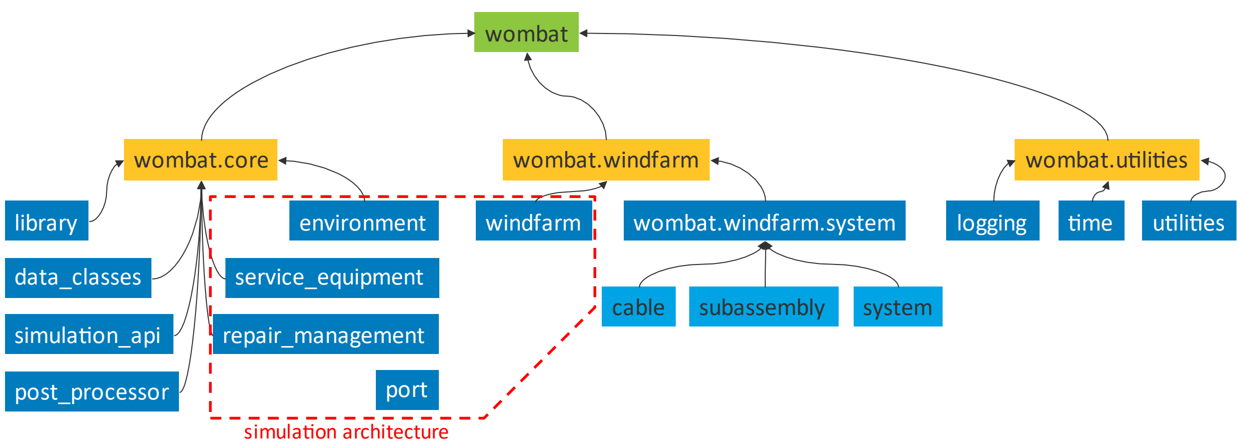

Figure 1. Diagram of the WOMBAT software architecture

Broadly, the environment manages weather conditions and timekeeping within the simulation. The wind farm encompasses the wind power plant's layout and generation for each of the systems: substations, cables, and wind turbines, and their subassemblies. Figure 2 shows which subassemblies comprise each of the systems, and how the subassemblies fit within the wind farm model. The primary function of a subassembly is to model scheduled (maintenance) and unscheduled (failure) tasks, whereas the system's primary function is to hold these subassembly models and to communicate with the wind farm and environment.

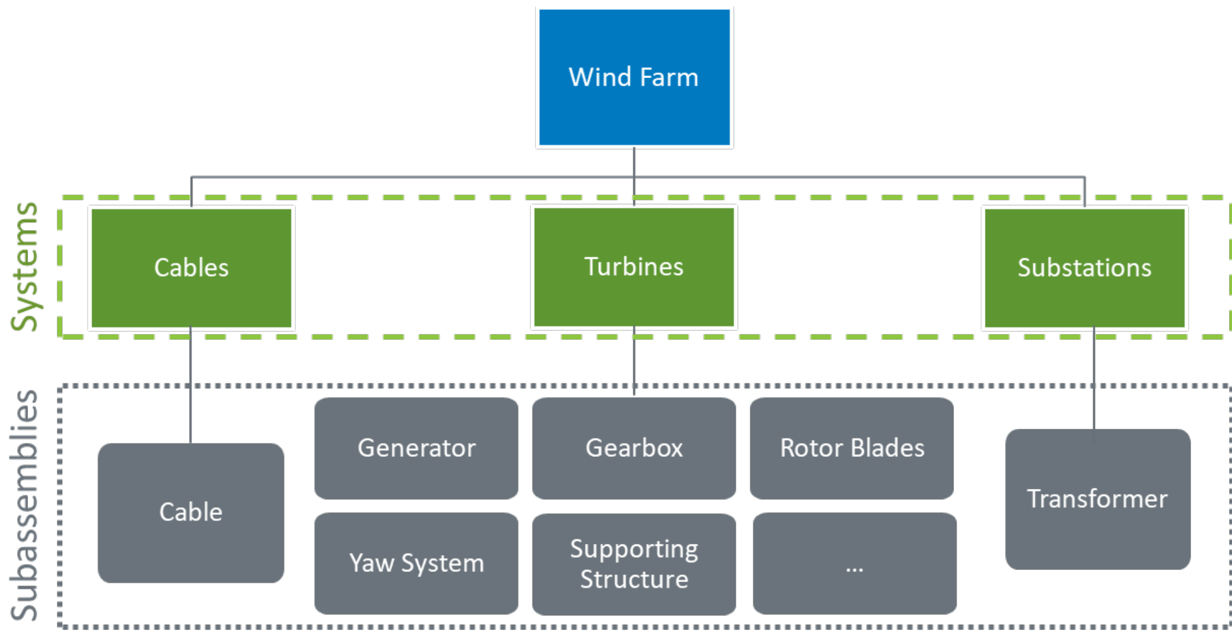

Figure 2. Conceptual overview of the wind farm model's structure. Subassemblies, including those shown here, are defined by the user to enable a wide variety of use cases

The repair management model receives all subassembly failures and maintenance tasks from system objects, then assigns those tasks to the appropriate service equipment. Centralized repair management allows tasks to be grouped and sequenced efficiently. The service equipment performs the actual repairs according to its capabilities and the requirements of the task at hand. Table 1 shows the broad categories that can be assigned to each service equipment object and provides examples of equipment that fits into each category. The port is only used for offshore wind O&M scenarios. Its role is to manage repair tasks that occur in port, which rely on separate equipment than that used at the wind power plant site.

Table 1. Brief Overview of the Service Equipment Categories

Capability	Description
CTV	Crew transfer vessel/vehicle; in most cases it is available year-round, and its primary function is to move crews around
SCN	Small crane or similarly equipped vessel, such as a cherry-picker or field support vessel that is relatively easy to dispatch, with lower costs than a large crane
LCN	Large crane or similarly equipped vessel, such as a crawler crane or heavy-lift vessel that is more expensive and has longer lead times
CAB	Cabling equipment, such as a cable-specific vessel for offshore wind that can lift cables from the seafloor
RMT	Remote; any kind of remote reset capability that might be performed from a control center and no specific equipment interactions are required
DRN	Drone; uncrewed service equipment that can perform inspections autonomously or via remote operation
DSV	Diving support vessel; offshore-specific designation for equipment used for inspecting substructures or cables
TOW	Tugboat; offshore-specific designation to enable tow-to-port simulations, and requires the use of the port model
AHV	Anchor-handling vessel; an offshore-specific designation for a tugboat that can repair mooring lines and anchors

2.2 Simulation Architecture

The overarching software structure allows different systems in the wind power plant to be simulated in parallel while sharing common information effectively. Figure 3 illustrates how a single task is handled within the simulation and how it relates to the rest of the simulation as a proxy for the many system and subassembly models that are occurring simultaneously. At the start of a simulation all the defined systems and subassemblies, weather profiles, and service equipment are created from the user inputs and are placed in a ready-to-run state. After initialization, the environment runs the simulation within the bounds of the provided weather time series, which is determined primarily by the subassembly failure models and maintenance tasks. Each of these events begins once a specified time has elapsed (failures randomly sample the time to the next failure using a Weibull distribution and maintenance tasks use a set interval between events) and once that occurs, the rest of the simulation pieces start moving.

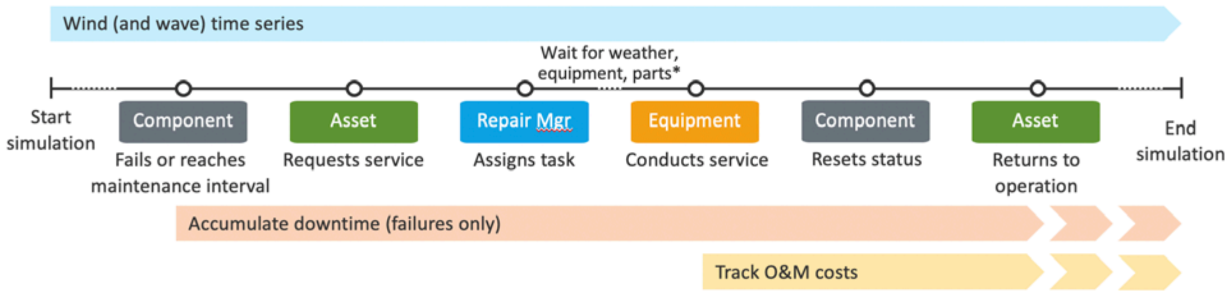

Figure 3. Conceptual overview of a single event within the simulation architecture

To describe the simulation steps, we use a gearbox failure as an example, but this same logic applies to all other failures or maintenance tasks for any subassembly on a wind turbine, cable, or substation. The failure event begins when the simulation reaches time step t_{fail}, which has been randomly selected from the Weibull distribution assigned to gearboxes in the model configuration. First, the gearbox notifies the turbine that the failure has occurred, which causes it to stop or reduce its operating capacity, pass a request to the repair manager, and log the event. The repair manager then passes this request to an appropriate piece of service equipment (e.g., remote reset, crane, crew transfer vessel [CTV]). Once the service equipment is assigned to the task, it will travel to the turbine and repair the gearbox. The service equipment accumulates downtime when weather conditions are outside of safe operating conditions and during nonwork hours (e.g., nighttime if the equipment is not configured for 24-hour operation) by recording events in the logging infrastructure. After the repair is complete and the time and costs are appropriately logged, the service equipment triggers the turbine to reset the gearbox with a new, randomly selected time to failure and the system returns to operation until the next failure or maintenance event occurs. Throughout this process, all downtime and costs are tracked by the environment's centralized logging infrastructure that can be retrieved once a simulation is completed.

The modularity and separation of the varying models that comprise WOMBAT are not only necessary to power this simulation as it is now, but also to enable users to modify it in the future, so new technologies and maintenance strategies can be integrated with ease.

3 WOMBAT Implementation

Section 2 provided a high-level overview of the software and simulation. This section provides a more comprehensive description of WOMBAT at the time of this publication intended for users of the model or those seeking more details about the implementation and its assumptions (Version 0.5.1 available at https://www.github.com/WISDEM/WOMBAT). For details about model improvements and detailed changes between versions, see the Changelog, and for more information on the current functionality, see the code documentation at https://www.wisdem.github.io/WOMBAT.

In addition to the documentation, WOMBAT creates easily customizable building blocks to support a wide variety of simulation needs. This design enables the modeling of distributed, land-based, and offshore wind power plants without any explicit definition or specialized internal control flow. Because of the complexity required for creating a model from a scratch, the simulation class provides a convenient user interface wherein the basic model settings and configurations can be provided with the software handling the rest of the configuration and initialization procedures.

In the remaining sections, we build up the software model from its lowest-level components to its highest-level components to describe how the model and simulation operate.

3.1 Data Classes

Most of WOMBAT's capabilities are enabled through how a user configures its lowest-level structures, so it will be helpful to understand how these operate to better comprehend what functionalities exist and how to use them. Table 2 provides an overview of the core data classes, but for a more in-depth review of the inputs and outputs, see either the online documentation or Appendix A.

Table 2. WOMBAT Data Classes and Their Roles

Data Class	Purpose
Maintenance	Stores maintenance task timing, cost, and equipment requirements data
Failure	Stores failure parameters to enable the randomly simulated time between failures, cost and timing data, and equipment requirements
SubassemblyData	Centralized repository for the maintenance and failure parameters for a modeled subassembly
RepairRequest	Stores the essential repair/maintenance parameters in one place for easy hand off throughout the simulation
ServiceEquipmentData	Stores the operational limits and conditions for service equipment, including mobilization, maintenance strategy and threshold, and crew transfer time
PortConfig	Stores and validates the port configuration data for tow-to-port simulations
FixedCosts	Parameterizes the hierarchical fixed costs for O&M

3.1.1 Failure and Maintenance Models

The failure and maintenance data classes define many of the attributes of service tasks, including the amount of time they take to complete, the cost of materials, the type(s) of service equipment that can perform the work, and how frequently each task occurs. The main distinction between the failure and maintenance models is how event time-outs occur. The failure and maintenance objects trigger the time-out events, or state changes, that determine when wind turbines, cables, and substations need to be serviced, and therefore when service equipment must be brought to site. The maintenance model is based on regular service intervals; for example, an annual inspection task would generate a request every 365 days. On the other hand, the failure model is based on randomized timing between events, with the length of each failure interval generated from a statistical distribution input by the user.

The failure model in WOMBAT generates times between events based on Weibull distributions. The Weibull distribution is commonly used in failure modeling and has been applied to wind turbine reliability analysis in many instances (e.g., Scheu et al. [2017] and Faulstich et al. [2016]). WOMBAT requires the user to input two parameters that define the Weibull distribution for each modeled failure: scale and shape. A shape parameter of one represents a time-independent (random) failure, whereas failures that become more or less likely over time are described by shape parameters that are greater or less than one, respectively. Fatigue and corrosion are examples of processes that increase the likelihood of failure over time, whereas failures related to flawed installation or manufacturing defects are more likely to occur early in a component's lifetime. For time-independent failures, the scale parameter is equal to the mean time between failures (MTBF) in years (conversion from years to hours occurs within the code to match the simulation time step). When a WOMBAT simulation is initialized, a time to failure is randomly sampled from each Weibull distribution that the user has provided for the various subassemblies. This process is repeated to produce a separate time to failure for every instance of a given subassembly.

3.1.2 Subassemblies and Requesting Service

Each subassembly is built up from one or more failure and maintenance model(s) described in Section 3.1.1. This structure allows a user to model varying levels of granularity, ranging from the whole turbine to the subassembly to the component level. Enabling the user to input as many, or as few, of each of these models provides greater flexibility when data access is a concern. For users with abundantly available data on failure rates, costs, and so on at a granular level, they may choose to model turbines in great detail rather than relying on the limited publicly available data to simulate an entire wind farm. This type of analysis could quantify the cost impacts of specific innovations such as improving the reliability of an individual component. Users with more limited access to O&M data can opt to carry out higher-level analyses; for example, by modeling major and minor repair categories without distinguishing costs and frequencies between individual subassemblies.

Using the data contained within a given system, subassembly, and the failure or maintenance task that gets triggered, the RepairRequest data class provides a data object that can be passed between the system, repair manager, and service equipment without needing to have a complex web of interactions. For instance, if a wind turbine drivetrain is due for maintenance, the turbine will compile the maintenance task details, the drivetrain identifier, and its own identifier into the data object and send it to the repair manager for assignment to a piece of service equipment. In the case of a cable repair, the identities of upstream turbines are also included in the repair request.

3.1.3 Service Equipment Data Class

As previously mentioned, the service equipment performs the repair or maintenance, so having the correct data model is imperative. The ServiceEquipment data class has more inputs than any of the other models because of the varying costs and constraints associated with repair processes. This data class can control the equipment rate, labor rates, types of labor, non-standard working hours for specific equipment types, operational weather constraints, mobilizations, crew transfer durations, equipment classification, and maintenance strategy.

The current capabilities for modeling service equipment encompass crew transfer vessels/vehicles, small and large cranes, cabling vehicles/vessels, drones, remote resets, and three offshore-specific designations: diving support vessels, tugboats, and anchor handling vessels, as described in Table 1. While much of the nature of these interactions is defined by both the request being fulfilled and the equipment itself, the capability setting allows for a clear mapping between potential repairs and the service equipment that will perform the work. In specific instances, such as the AHV and TOW capabilities, requests with these designations will signal separate processes that will send the repair request to the port to either schedule a tugboat repair or trigger a tow-to-port repair.

3.1.4 Fixed Costs

The fixed costs data class is used in the simulation postprocessing to incorporate a large suite of indirect O&M costs. This model was set up to be flexible enough to account for lower-level costs, such as third-party liabilities, as well as higher-level, general costs, such as insurance. There are three high-level cost categories that operate in this manner: operations management and administration, insurance, and annual lease fees. There are also four stand-alone categories that cannot be broken down: operating facilities, environmental health and safety monitoring, onshore electrical maintenance, and labor. It should be noted that the labor category should only be used when there are no labor costs associated with individual categories of service equipment, otherwise labor costs will be counted twice.

3.2 The Wind Farm Model

The wind farm model relies on the environment and repair manager objects that are created in the first steps of the initialization with the wind farm layout. The layout file is a flexible wind power plant configuration file, which at a minimum requires a description of how the turbine(s) connect to the substation(s) and the name of the configuration files for any substations, turbines, and cables being modeled. Figure 4 shows a more complete configuration, wherein we gathered spatially resolved wind turbine and substation positions from the Dudgeon Offshore Wind Farm Notice to Mariners (Dudgeon Offshore Wind Farm undated).[1] For a full set of inputs, see the documentation site[2] or Appendix A.1.

[1] Specifically, the coordinate data from the 21-12-2018 Notice to mariners was used. It should be noted that WOMBAT does not model custom cable paths, but precise cable lengths are optional inputs.
[2] https://wisdem.github.io/WOMBAT

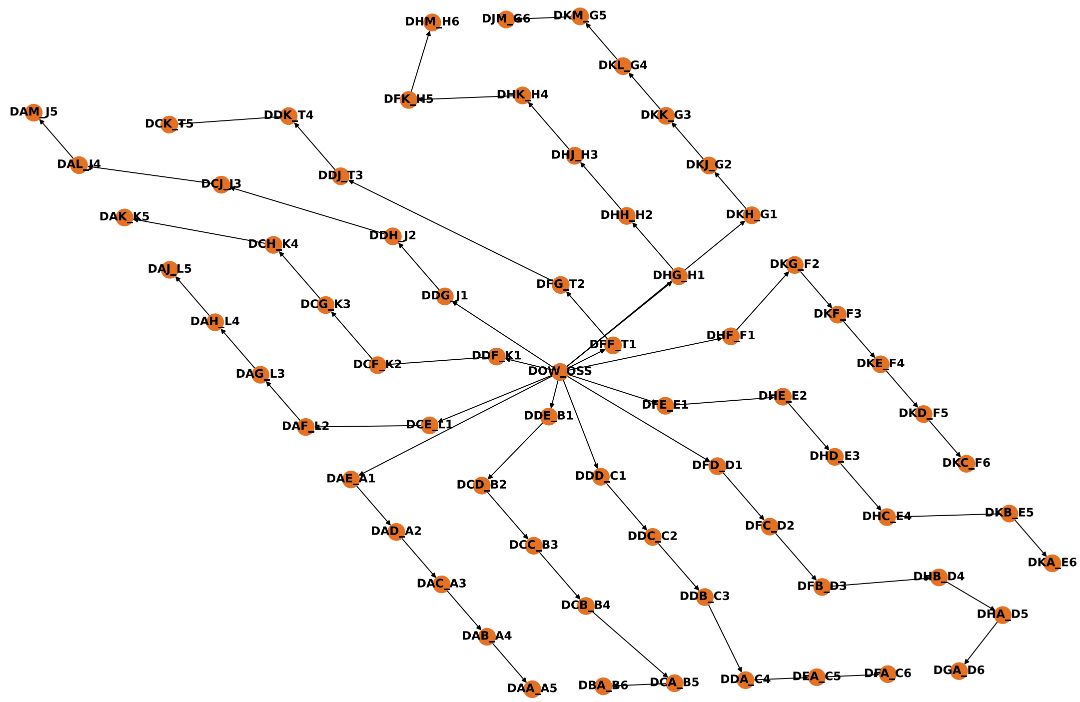

Figure 4. The graph model of the spatially resolved wind turbine and substation locations at the Dudgeon Offshore Wind Farm in the United Kingdom

The primary functionality of the wind farm model is to create a *NetworkX* (Hagberg, Schult, and Pieter [2010] 2022) directed graph of the wind farm, initialize the substation(s), wind turbine(s), and cable(s), and offer convenience methods for accessing objects at the simulated wind power plant. The graph layout creates a complete model of each node and edge with the encoded attributes of each, such as cable length, coordinate position, descriptive names, and system objects.

3.2.1 Systems

The asset models referenced in Figure 2 show turbines, substations, and cables in one category; however, the turbines and substations operate differently than the cables, and therefore have separate classes. The primary reason for separating into two classes is because the turbines and substations act as nodes in the wind farm graph layout, whereas the cables act as edges. Because the cables form the connections between systems, a cable failure has the potential to force all of the upstream systems to shut down; therefore, requiring different core functionality. In Section 3.3.3, we will go into more of the differences pertaining to cable modeling.

Whether a wind turbine or substation is being modeled, the same inputs are required: the simulation environment, the repair manager to submit requests to, an ID and short name, the subassembly configuration file, and an indicator for which system is being modeled. In the case of the turbine, there are a few optional inputs for the power curve modeling in the subassembly data. The system is used for three primary factors: the subassemblies, overall operating system level, and potential power produced.

In the case of a wind turbine, all of its subassemblies will be initialized using the subassembly data from the input file specified in the wind farm layout, then an International Electrotechnical Commission power curve will be created from the user-provided power curve data (IEC 2017). Similarly, a substation will run the same initialization.

While the simulation is running, the wind turbine will pass the repair or maintenance request log from a subassembly that has timed out to the repair manager, and when required it will compute the product of all the operating subassemblies to get a complete system operating level. After the simulation, the wind speed data will be passed to each turbine's power curve function to get the power potential and multiplied by the turbine's operating capacity at that time step to attain the actual power production. Each turbine's potential can then be summed to attain the wind power plant potential, and the power production can be summed and multiplied by the substation's operating capacity to get the actual power production of the wind power plant.

3.2.2 Subassemblies

Both land-based and offshore wind turbines can be modeled in WOMBAT using the appropriate subassemblies. Although there is a high degree of overlap between the two technologies, certain subassemblies such as the support structure can be quite different—for example, a concrete spread foot foundation versus a moored semisubmersible—and require the user to input appropriate failure rates and maintenance tasks. The subassembly model is used for all subassemblies and is one of the most sophisticated pieces of WOMBAT because it simulates each of the maintenance and failure tasks. To successfully do this, each subassembly must be able to shut down the whole system in case of a catastrophic failure, understand if the system is being serviced, and not restart any failure or maintenance models in case of suspended operations.

3.2.3 Cables

The cable model contains all the functionality of the system model. It can also shut down all upstream cables and turbines in case of a catastrophic failure, whereas the system is only able to shut itself down. This seemingly subtle nuance is important because a wind power plant is a network, and if any edge is removed, power is unable to flow through that section. In addition, the remaining parts of the string become islanded and are shut down to not fatigue any upstream turbines and cables unnecessarily.

3.3 The Simulation Environment

In this section, we discuss the overarching simulation mechanisms, such as the environment itself, repair management, and operation of the service equipment. In Section 3.1, we spoke of the data classes that define some of these simulation objects, but in the following subsections we examine the nature of the simulations themselves.

3.3.1 Recordkeeping in the Simulation

The WOMBAT environment is where all of the simulation controls are located, ranging from date and timekeeping to weather conditions and the simulation's logging infrastructure. First and foremost, to run a simulation, a weather profile, starting and stopping year, the project's working hours, and a data directory for files to be loaded from and saved to are required. The environment is the most central simulation object and is, therefore, the first item that is created in the simulation process and inherited by every simulation object, so that timekeeping, weather tracking, and logging can occur centrally throughout the simulation.

The centralization of time, weather, and logging enables an arbitrary number of cables, turbines, substations, and service equipment to operate in harmony without concerns for time consistencies. With each piece of the simulation operating mostly independently, this framework allows for flexibility in what type(s) of wind power plants, technologies, and maintenance strategies can be simulated.

While every system and piece of service equipment in the simulation can create its own log, they are all passed through the environment to be written to one of two log files: an events log for all actions in the simulation ranging from failures to weather delays to repairs, and an hourly operations log that keeps track of the operating capacity of each turbine. At the end of the simulation, the operations log can be used in conjunction with the turbine power curve(s) to calculate both the power production potential and realized power production, which can be used for later O&M metrics computations.

3.3.2 Repair Management

The other simulation element that is central to the rest of the simulation objects is the repair manager, which acts as a central repository for all of the submitted maintenance and repair requests until they are completed. By creating a central location for all requests, and a streamlined way to transfer the requests to service equipment, the equipment and wind power plant components can maintain their independence from one another.

3.3.3 Service Equipment

The service equipment model uses the service equipment data class described in Section 3.1.3 in conjunction with the simulation environment, wind farm model, and repair manager to travel to the wind power plant and perform repairs and maintenance work. An important distinction, and what makes WOMBAT a medium-fidelity model, is that repairs and maintenance tasks rely on a set time to complete the task as opposed to modeling specific subprocesses of a repair process. However, because of the long timescale and high variability in any given process, this allows the code base to easily accommodate procedural improvements by simply changing the repair time, as opposed to adding in new tasks or changing the repair steps. This is yet another example of how we sought to ensure the software and the resulting simulation can be highly flexible to enable a broad variety of modeled scenarios.

While specific repair processes are not modeled, key elements such as equipment mobilization, crew transfer, weather delays, and shift restrictions are modeled to understand how the timing of repairs impacts costs, downtime, and how long a work crew spends at sea. For instance, it is important to know if it is not worthwhile to attempt major repairs during specific seasons, due to weather and safety limitations that increase costs, or if the improved downtime will counterbalance the lost revenue. Additionally, the labor calculations for the service equipment account for hourly, contracted, and/or salaried labor in addition to the equipment rates where labor can be a loaded cost.

Figure 5 and Figure 6 show the process for making a repair or performing maintenance and the control flow for transferring a crew from service equipment to a system and back.

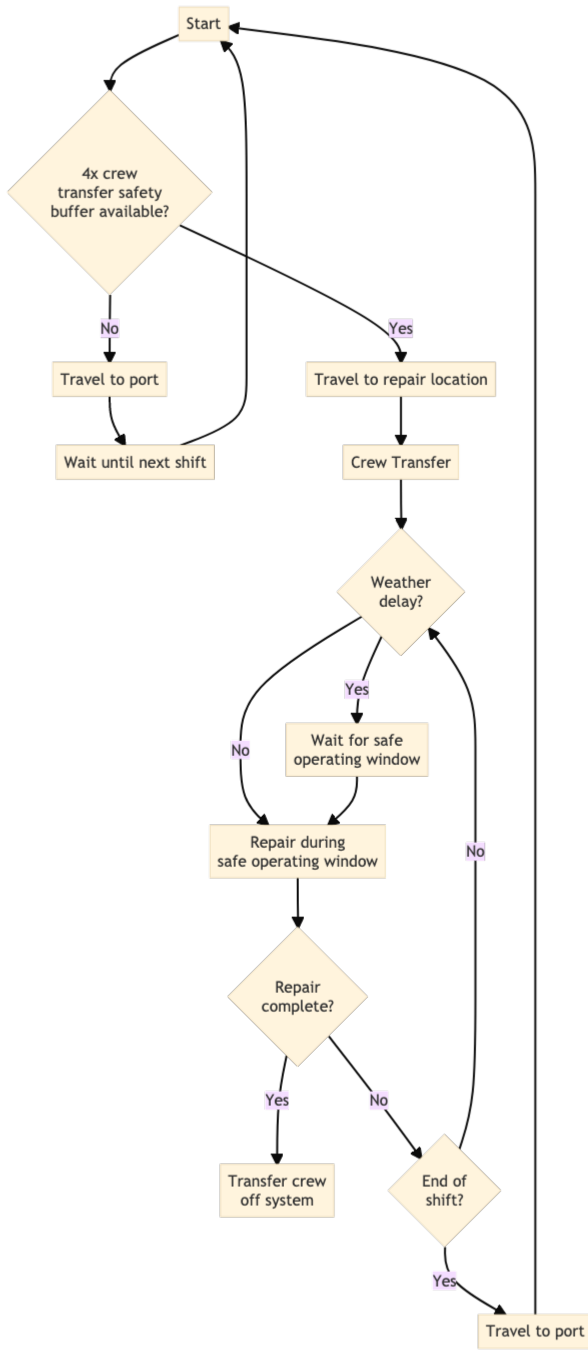

Figure 5. Flow diagram depicting the logic for the service equipment repair process

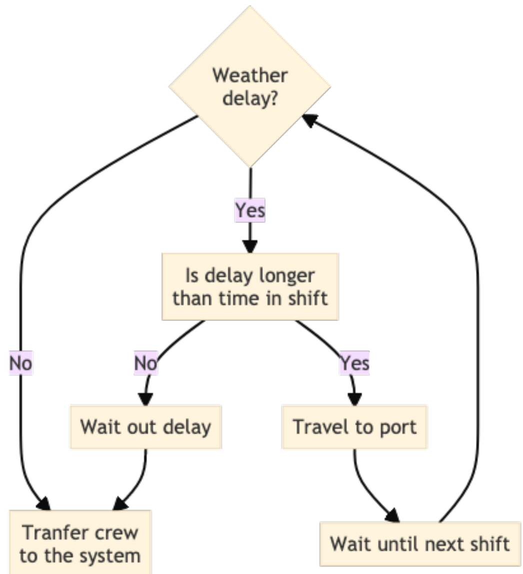

Figure 6. Flow diagram demonstrating the logic for crew transfer from the service equipment to a system

3.4 Maintenance Strategies

While most of the WOMBAT configuration entails technology selection and capabilities, there are also four maintenance strategies available: scheduled in situ repairs, requests-based in situ repairs, downtime-based in situ repairs, and unscheduled tow-to-port repairs. Each of these strategies is configured at the service equipment level, so that a crawler crane or heavy-lift vessel gets called to the site based its own customization. This structure enables some equipment, such as pickup trucks or CTVs, to be available year-round, whereas more expensive, less frequently used equipment can be mobilized based on an operating capacity or number of repairs threshold.

The scheduled in situ maintenance strategy relies on a user providing a predetermined visit schedule for the duration of a simulation. The visit schedule requires a start and end date, and the years in the weather profile for when the visit should occur. For this scenario, the mobilization, if required, is calculated to ensure that the service equipment will arrive for the start of the first scheduled shift in the charter period. This scenario is most useful for service equipment that is intended to stay on-site for the duration of the wind power plant's life cycle, such as CTVs.

Given the unpredictability of when failures might occur, or the cost implications of mobilizing equipment that may not be needed, WOMBAT also has two unscheduled in situ maintenance strategies: a number of requests basis and downtime basis. In both strategies, the repair manager keeps track of the equipment associated with each strategy type and their threshold. For a number of requests basis, each repair request that is submitted with a qualifying capability counts toward this threshold, and once the specified number of results is reached, the first service equipment in line will be mobilized to the wind power plant and start operations. For the downtime basis scenario, instead of a set number of repairs required to trigger the mobilization, the wind power plant must hit the specified downtime threshold. Unlike in the requests basis scenario, the repair manager will mobilize all service equipment that have at least one matching repair.

The fourth maintenance strategy—tow to port—is triggered similarly to the requests basis scenario with a threshold of one repair request. The primary differences, however, are that this is an offshore-only scenario, requiring a port and repairs that must occur at port.

3.5 Postprocessing and Metrics

WOMBAT also has a robust metric computation module that is powered by the simulation logging and metadata, fixed costs, optional settings for project financials, and an inflation rate. For most of the metrics, they can be calculated at the project level, or more details can be captured at the annualized, monthly, and even month-by-year levels. For some metrics, there are further, relevant breakdowns by the appropriate categorizations, enabling a full suite of results to either dig deep into the simulation details or get a high-level project overview. The included set of metrics relate to availability, project costs, downtime, power production and potential, timing, and project financials. For a complete set of metrics, see the WOMBAT documentation site,[3] or Appendix A.2.

Using the included set of metrics, different comparisons can be made (as shown in the following examples) for a simple set of model scenarios. It should be noted that while this example is for an offshore wind farm, a land-based or distributed example could also be used here. In each of these cases, we are using an offshore reanalysis weather profile collected from ERA5 (Hersbach et al. 2018) near the coast of Massachusetts, a single CTV that is available year-round, a single wind turbine installation vessel (WTIV) and cabling vessel that are chartered for a fixed period each year, and failure rates from the Energy Research Centre of the Netherlands tool (Braam et al. 2009). Using these assumptions, we consider the following five scenarios that, while not representative of industry practices, are useful to demonstrate that WOMBAT outputs shift in the correct directions as inputs are varied:

1. Base: 3-month summertime (June-August) WTIV and cabling vessel visit
2. Doubled MTBF: the failure rate is halved, or the mean time between failure is doubled
3. 12-month visit: the WTIV and cabling vessel are on-site all year
4. No visit: there is no service equipment available for the entire simulation period
5. No weather: 3-month summertime (June-August) WTIV and cabling vessel visit with wind speed and wave height set to zero.

In Figure 7, the monthly availability across the 20-year simulation period is shown, using the time-based availability metric for each simulation. Effects visible in this figure include the impacts of service equipment availability (12-month visit and no visit), the impacts of weather delays on repairs (comparing no weather to all other scenarios), and the impacts of improved technologies (doubled MTBF).

[3] https://wisdem.github.io/WOMBAT

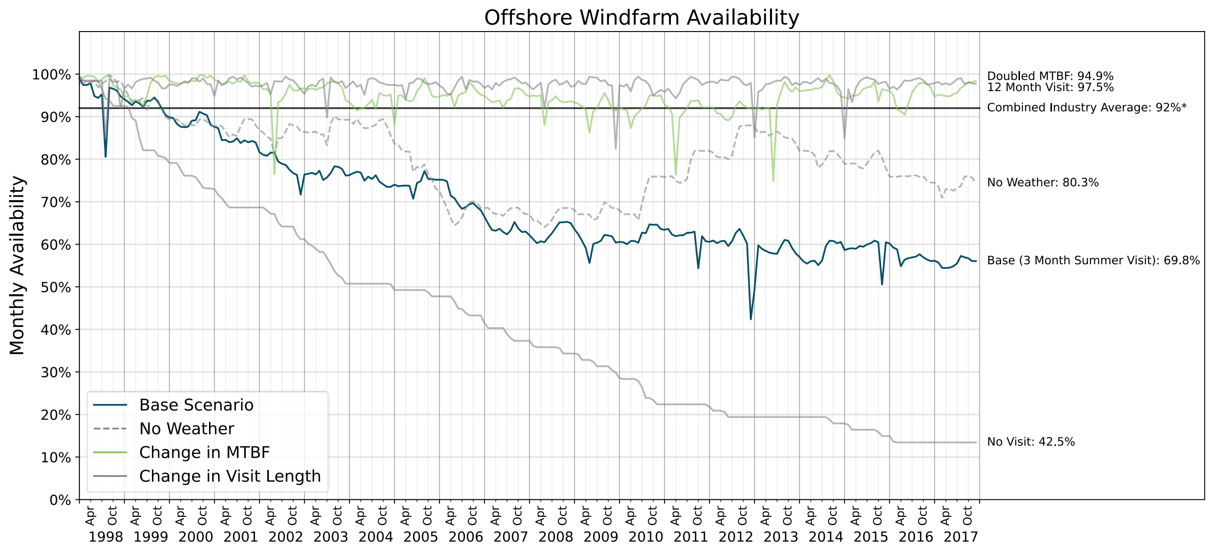

Figure 7. Monthly availability for the 20-year simulation of each scenario compared to an industry average

In conjunction with the availability data, users can also compare the total or annualized costs of operating a wind power plant, broken down by each cost category. In Figure 8, each of the scenario's average operating costs are compared to further assess the variability of each scenario and the trade-offs in enabling higher or lower levels of availability at the wind power plant.

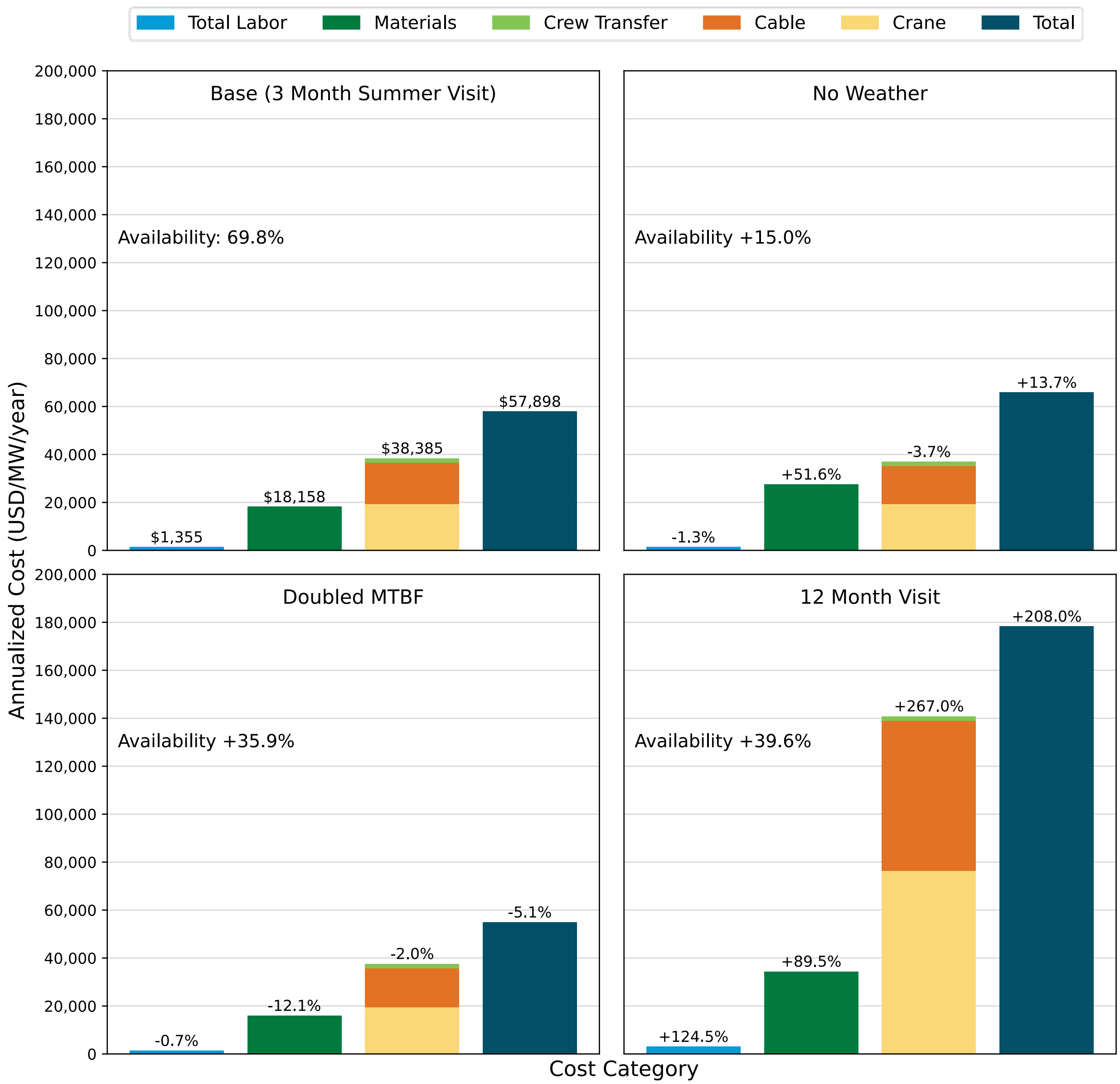

Figure 8. Direct average annual O&M costs per megawatt (MW) of capacity

4 Model Review

To ensure the validity of the model, we conducted three exercises: an industry review, a code review, and a code-to-code comparison. The industry review gathered feedback from reviewers in eight different organizations with experience in wind farm operations or cost modeling. For the code review, two internal software engineers that did not participate in the development of WOMBAT assessed the code and evaluated whether it matched the ideals it sought to embody. In the code-to-code-comparison, we assessed how WOMBAT performed in comparison to two publicly available O&M modeling software reviews. We performed these three tasks to ensure that the WOMBAT software lives up to industry expectations and best practices and aligns with peer-reviewed results for similar modeling scenarios.

4.1 Industry and Code Reviews

In this project, we took a dual approach of validating our methods and assumptions through conversations with industry stakeholders and validating the software with internal code reviews. This unique approach ensured that not only are we modeling O&M correctly according to industry best practices and assumptions, but that we are following software best practices. Given the reliance on software for contemporary science and technology research, it is imperative to build high-quality software to ensure the reliability of the studies themselves.

The industry review of WOMBAT comprised a conceptual review of the model architecture and performance with opportunities for feedback and discussion at every stage. All of the reviewers had experience with modeling wind O&M costs from a range of industry and academic backgrounds. The reviewers included 17 people across eight organizations spanning offshore and land-based wind energy who could potentially use WOMBAT to inform their own operations or for broader industry model benchmarking.

Reviewers were positive about the approach WOMBAT took, and the flexibility it demonstrated to model the primary dynamics of wind O&M. The reviewers were overwhelmingly satisfied with the software's flexibility. In most cases, discussions about specific scenarios of interest to reviewers were able to identify ways to model those scenarios using WOMBAT. In addition, the modular architecture demonstrated a straightforward path to modification, so partners could implement features they might need. These discussions also helped to validate our software and model road map, which is described in more detail in Section 5.2. Ultimately, many of the interests of our reviewers overlapped with the WOMBAT development team's interests for future studies and benchmarking exercises, opening up the possibility of future collaborations.

In tandem with our industry review, our internal code reviewers also provided positive feedback. The code styling, repository maintenance, and architecture all received positive remarks with no major areas for improvement. Recognizing that much development is currently underway and, on the road map, the biggest areas of improvement stemmed from the need for more documentation to describe higher-level dynamics and how each piece of the software fits together as well as contributor guidelines for future collaborators. The focus on the modularity, flexibility, and documentation of the software within the code proved to be successful strategies to develop high-quality software that uses an industry-approved model.

The success of both the industry and code review demonstrated that a dual focus on methods and implementation can be achieved without sacrificing quality in either category. By making the software itself and the methods it implements core requirements for a new modeling software and incentivizing the success of both, we lay a framework for future projects and those that currently exist.

4.2 Code-to-Code Comparisons

The code-to-code comparison is arguably the most tangible and useful component of this review because it asks the question: given the same modeling parameters as published results, can WOMBAT achieve the same or similar results? Overwhelmingly the answer was yes, WOMBAT does perform similarly to other O&M simulation software systems while living up to the industry and software best practices. The two papers used to conduct this validation exercise are the International Energy Agency (IEA) Wind Task 26 paper (Smart et al. 2016) and the Offshore Wind Reference Cases paper (Dinwoodie et al. 2015).

4.2.1 IEA Wind Task 26 Comparison

The IEA Wind Task 26 study (Smart et al. 2016) establishes a baseline offshore wind power plant that is representative of plants installed between 2012 and 2014 globally. The baseline provides a means for comparing the costs of new projects coming online, so the major cost drivers can be better understood, especially as they vary regionally. In the context of this report, the study offers a baseline for modeled results that we can compare to WOMBAT. Smart et al. (2016) use two different modeling tools to provide baseline O&M costs: the Energy Research Centre of the Netherlands Offshore Wind O&M Tool and the NOWIcob model developed by Sintef. Each model was run with the same input parameters and the results are presented in the paper. We used the same inputs for WOMBAT. For complete details of the originally modeled parameters, please refer to Smart et al. (2016), and for the settings used in the report, please refer to WOMBAT's GitHub,[4] wherein the comparison will be kept up to date with the latest version of the model. One input that was not specified by Smart et al. (2016) was the level of operational reduction associated with each failure type. This parameter describes the wind turbine's level of operation between the time of failure and the arrival of repair equipment (full shutdown is assumed while any repair is in progress). We modeled two alternatives with WOMBAT: one with no operational reduction for subassemblies with minor failures and remote resets, and one (marked with *) with 100% operational reduction for minor failures and remote resets. Major failures and replacements were modeled to result in 100% operational reduction in both cases.

Table 3 shows WOMBAT's ability to model costs, availability, and downtime in the same range as other publicly available models. While there are some discrepancies, such as in the case of infrequently used vessels, we see promising overall results. Differences are apparent between results from WOMBAT and the other two models in the vessel costs for jack-up and cable lay vessels, as well as the downtime associated with major replacements and balance-of-system

[4] The Jupyter notebook for this analysis can be found at: https://github.com/WISDEM/WOMBAT/blob/main/examples/iea_26_validation.ipynb, and the underlying data are located at: https://github.com/WISDEM/WOMBAT/tree/main/library/code_comparison/iea26.

repairs that rely on these vessels. Scheduling these vessels appears to be a bottleneck within WOMBAT that can lead to longer downtimes.

Table 3. Published Model Results Comparison to Two WOMBAT Modeling Cases

	NOWICOB	ECN	WOMBAT	WOMBAT*
AVAILABILITY (%)				
TIME-BASED	93.3%	94.9%	96.7%	90.5%
ENERGY-BASED	92.6%	94.8%	96.8%	90.9%
COSTS (MILLION €/YR)				
TOTAL ANNUAL COSTS	25.4	28.4	26.9	24.7
TECHNICIANS	3.0	2.3	3.0	3.0
SPARE PARTS	7.8	7.9	7.3	6.6
VESSELS	14.5	18.2	16.7	15.1
- CTV	3.8	1.8	2.6	2.5
- JACK-UP	9.5	15.5	13.3	12.1
- DIVING SUPPORT	1.1	0.9	0.5	0.5
- CABLE-LAYING	0.1	0.1	0.3	0.0
DOWNTIME (DAYS/TURBINE/YEAR)				
TOTAL DOWNTIME	26	19	12	30
MANUAL RESETS	7.0	4.0	0.3	9.9
MINOR REPAIR	7.0	4.0	0.5	3.9
MAJOR REPAIR	2.0	1.0	0.8	1.0
MAJOR REPLACEMENT	5.0	6.0	8.6	8.1
REMOTE RESET	1.0	1.0	0.2	3.3
ANNUAL SERVICE	3.0	2.0	1.2	0.0
BALANCE OF SYSTEM	1.0	1.0	0.1	3.3

* WOMBAT results in the left column have no operational reduction for minor repairs and remote resets; in the right column WOMBAT* has 100% operational reduction for minor repairs and remote resets. Major repairs and replacements cause 100% reduction in both cases.

4.2.2 Offshore Wind Reference Cases Comparison

The offshore wind reference case study in Dinwoodie et al. (2015) provides a series of verification analyses to compare new O&M models to the similarities and differences between varying models. The paper tests four separate models across 16 different scenarios to demonstrate how each model responds to various parameters. By modeling the scenarios presented in the study, we can understand how WOMBAT will differ from other available O&M modeling tools. For full details of the study, refer to Dinwoodie et al. (2015), and for its implementation in WOMBAT, refer to GitHub,[5] which will stay up to date with each iteration of the model.

In Figure 9 and Figure 10, we compare the availability and cost data for the base case as modeled by both WOMBAT and the published results in Dinwoodie et al. (2015). Costs fall within or close to the range of values reported for the four models in the original study. Availability is somewhat higher, in particular among the cases with fewer CTVs, technicians, and higher failure rates; however, these cases had notably low availability in Dinwoodie et al.'s results.

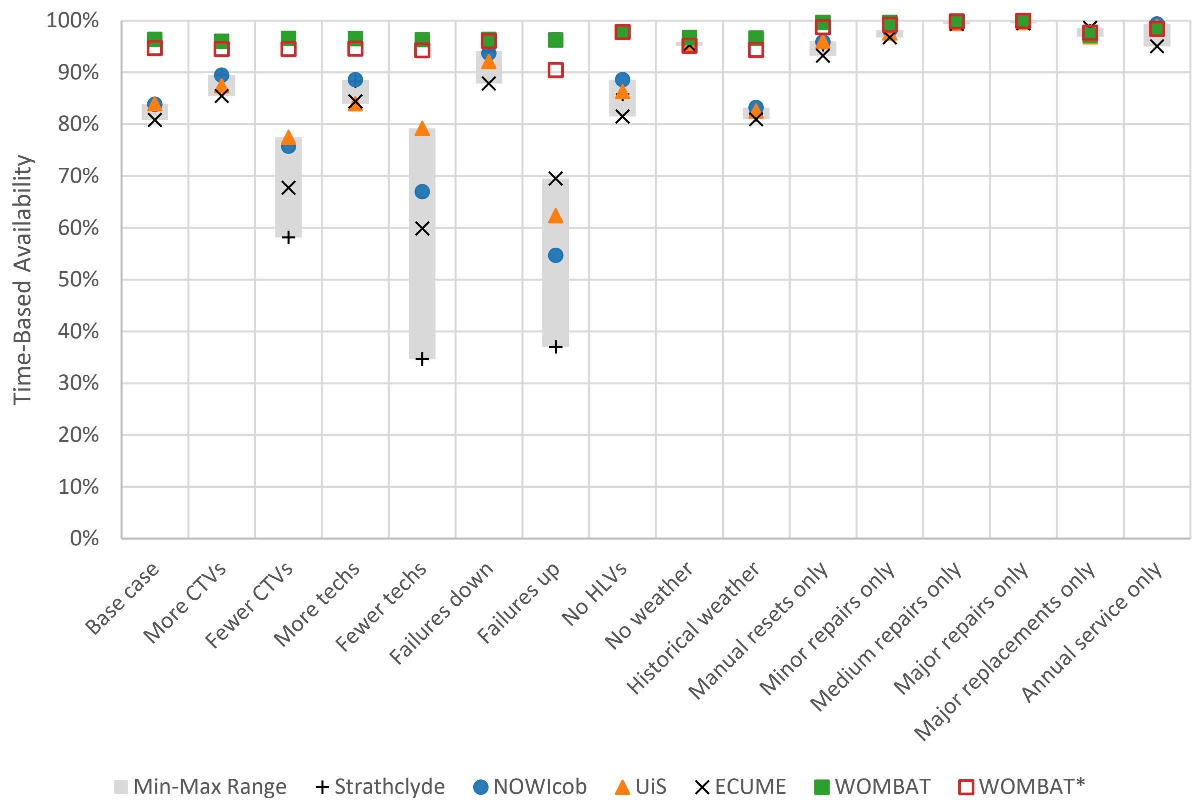

Figure 9. Average time-based availability from (Dinwoodie et al. 2015) with simulation results from WOMBAT, including having 100% operating reductions for all failures (WOMBAT*)

[5] The Jupyter notebook for this analysis can be found at: https://github.com/WISDEM/WOMBAT/blob/main/examples/dinwoodie_validation.ipynb and the underlying data is located at: https://github.com/WISDEM/WOMBAT/tree/main/library/code_comparison/dinwoodie.

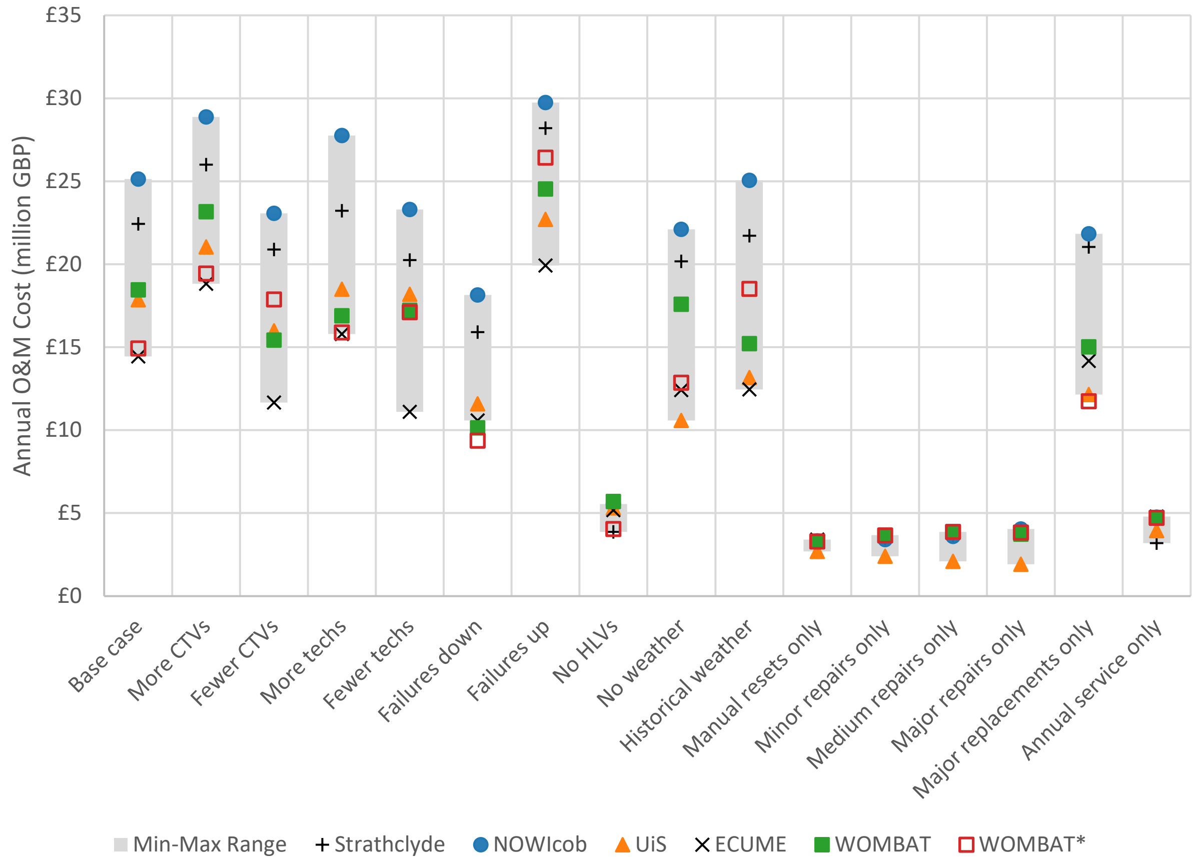

Figure 10. Average annual O&M cost from (Dinwoodie et al. 2015) with simulation results from WOMBAT, including having 100% operating reductions for all failures (WOMBAT*)

5 Conclusion

WOMBAT provides an open-source model for researchers to explore trade-offs in various wind power plant and O&M scenarios. WOMBAT's discrete event simulation approach provides the desired functionality for an O&M cost model and aligns with other approaches taken for scenario-based modeling within the O&M research community.

By creating a model that focuses on the trade-offs between approaches to O&M strategies and wind power plant technologies, we were able to appeal to a broad user base, ranging from academia to industry, that each had their own niche interests. By modeling scenarios instead of optimizing the decades-long lifespan of a wind power plant, users can better understand the wide range of cost implications to more efficiently and effectively allocate their research and development funds.

In conjunction with scenario-based modeling, prioritizing modularity and flexibility in the model itself enables this same broad base of users to model their niche interests in the O&M space. In most of the use cases we discussed with our industry review participants, we were able to propose ways to model varying scenarios during the conversation, without modifying the code. This approach to meet users where they are in terms of data availability and modeling capabilities further enticed our industry reviewers and opened up much conversation about potential model scenarios.

5.1 Future Work

In its current state, WOMBAT is a valuable tool for understanding O&M costs and how they change when different maintenance technologies and strategies are implemented. Future work will involve continuing to improve the software's core capabilities, as well as aiming for stronger integration with the National Renewable Energy Laboratory's other tools for full life cycle cost assessment. Coupling WOMBAT with land-based or offshore balance-of- plant cost models, wake loss analysis tools, and financing parameters will provide all of the information needed for a detailed assessment of levelized cost of energy and other metrics.

Specific improvements that will support new users include expanding the reference cases to include more examples of subassemblies, such as mooring lines or permanent-magnet generators. Additional examples of service equipment will also enhance WOMBAT's modeling capabilities.

A common theme from several discussions with academic and industry reviewers was the value to be gained from incorporating uncertainty through Monte Carlo modeling methods. In place of modeling a single life cycle with a set Weibull failure parameterization, it would be beneficial to model a distribution of failure rates to better understand the uncertainty of our failure modes. While including a Monte Carlo framework on top of the simulation architecture will be relatively straightforward, the main bottleneck as of this publication is runtime. To accommodate running dozens or even hundreds of models, we will have to further optimize the runtime of the simulation itself through more efficient, validated logic as well as reducing the input/output overhead of our logging mechanisms to attain at least subminute simulation times.

While properly creating and accommodating a Monte Carlo framework will be challenging, other improvements will be straightforward to implement. These improvements include additional weather constraints and checks for service equipment, such as temperature as a proxy for sea surface ice or icing in cold weather climates, or visibility for helicopters; updating repair times to accurately capture maintenance crew familiarity; changing failure rates to better capture deterioration; and enabling user-defined subassembly labels to support the modeling of new or alternative system configurations.

In addition to the easy-to-implement functionality, we will need to continue incorporating new strategies and refining modularity within WOMBAT to ensure that it will support industry and its varied innovations going forward. Another such modification to the core logic will be transitioning the logging infrastructure to best align with operational analysis libraries such as OpenOA (Perr-Sauer et al. 2021), or modifying the output to be usable within these libraries. In the same operational analysis vein, we could better align with real-world power production by incorporating wind turbine loss statistics that account for wakes and environmental conditions.

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Appendix A. Inputs and Outputs

This appendix provides further details on the inputs and outputs of WOMBAT. A class in this context is the blueprint that defines what an object is and how it can interact with the other aspects of the code. A data class is then a type of class that is designed to ingest, standardize, and validate input data. By combining input data and classes, we create objects, which are the realization of a blueprint, or more commonly: the instantiation of an object. The data classes used in the simulation are based on the *attrs* data class library (Schlawack 2022). The use of *attrs* allows for a standardized and comprehensive data validation and object composition for current and future functionality. Additionally, documentation refers to docstrings: the descriptions of a section of code; self-documenting code: verbose variable and method naming so a user inspecting the code can read it like sentences and paragraphs; inline documentation: the use of inline comments to explain sections of code that may not be straightforward; and a documentation site: the website where a user can find examples, thorough explanations of high-level concepts, and implementation specifics. Finally, type hinting is the practice of stating what data type is being used at each step of implementation, which helps ensure that code and data are being used appropriately.

To ensure the codebase is modular and flexible, we provide extensive documentation on the aforementioned documentation website, and within the code itself through docstrings, inline comments, and self-documenting code styling. A core component that was embraced to enable this documentation was via type hinting and static validation of these mechanisms. We also used a *precommit* (Sottile [2014] 2022) workflow to ensure the validity and formatting of code contributions across contributors.

A.1 Inputs

Table A1. Simulation Configuration File Inputs and Descriptions of the Data Expected

Configuration Key	Value Description
name	The name of the simulation; used for log naming conventions
library	The file path to the library folder
project_capacity	Total project capacity, in megawatts
weather	Hourly weather profile file name
service_equipment	A list of the service equipment file names to be used
layout	The file name for the wind farm layout
fixed_costs	The file name for the fixed costs data
workday_start	Starting hour of a standard work shift
workday_end	Ending hour of a standard work shift
start_year	Starting year for the simulation (optional, default is the first year of the weather profile)
end_year	Ending year for the simulation (optional, default is the last year of the weather profile)
inflation_rate	Inflation rate to be applied posthoc to all cost data

Table A2. Wind Power Plant Layout Columns and Descriptions of the Data Expected

Layout Column	Value Description
id	Unique identifier, without spaces, for the substation(s) and wind turbine(s)
substation_id	Identifier of the substation that the wind turbine is connected to (same as "id" for substations)
name	Descriptive name for the system
longitude	Longitude of the system, in WGS-84
latitude	Latitude of the system, in WGS-84
string	An integer that indicates which string the wind turbine is in (no value for substations)
order	The order the wind turbine occurs on the string (no value for substations)
distance	Customized distance between the wind turbine and its closest upstream system
subassembly	The file name for the subassembly configuration file
upstream_cable	The file name for the upstream cable configuration file

Table A3. Highest Level Configurations for the System Configuration File

Configuration Key	Value Description
capacity_kw	Nameplate capacity of the wind turbine, or maximum capacity of substation
capex_kw	The replacement cost of the system, per kilowatt
power_curve: file	The file name for the wind turbine's power curve profile (turbine configurations only)
power_curve: bin_width	Desired wind speed bin width for the power curve (turbine configurations only)
maintenance	A list of maintenance task configurations (see Table A4)
failure	A dictionary of failure configurations, with severity level as the key (see Table A5)

Table A4. Maintenance Configuration Settings and Descriptions of the Data Expected. These Data Comprise the Maintenance Section of a Subassembly in a System Configuration File

Configuration Key	Value Description
description	Short description of the maintenance task
time	The number of hours required to complete the maintenance task
materials	The cost of materials consumed during the maintenance task, can be expressed as a dollar value or as a fraction of the system's replacement cost
service_equipment	Service equipment capability (see Table 1) required to perform the maintenance, can be multiple entries
frequency	Number of days between events

Table A5. Maintenance Configuration Settings and Descriptions of the Data Expected. These data Comprise the Failure Section of a Subassembly in a System Configuration File.

Configuration Key	Value Description
description	Short description of the repair task
scale	Weibull scale parameter: equal to mean time between failure, in years, if "shape" = 1
shape	Weibull shape parameter
time	The number of hours required to complete the repair task
materials	The cost of materials required for the repair task, can be expressed as a dollar value or as a fraction of the system's replacement cost
service_equipment	Service equipment capability (see Table 1) required to perform the repair, can be multiple entries
operation_reduction	The percentage reduction in operations caused by the failure

Table A6. Power Curve Description

Power Curve Column	Value Description
windspeed_ms	The wind speed, in meters per second
power_kw	The power produced at the corresponding wind speed, in kilowatts

Table A7. Scheduled Service Equipment Configuration Description

Configuration Key	Value Description
name	Name of the service equipment
equipment_rate	Daily rate for equipment operations
start_month	The starting month of the annual charter
start_day	The starting day of the annual charter
end_month	The ending month of the annual charter
end_day	The ending day of the annual charter
start_year	The starting year of the annual charter
end_year	The ending year of the annual charter
onsite	Boolean flag for if the service equipment is considered to be an on-site piece of equipment
capability	Three-letter identifier (see Table 1) defining the types of repairs and maintenance that can be performed
mobilization_cost	Cost to mobilize the equipment
mobilization_days	Number of days required to mobilize the equipment
speed	The traveling speed for the service equipment
max_windspeed_transport	Maximum wind speed at which the service equipment can travel at full speed
max_windspeed_repair	Maximum wind speed at which the service equipment can operate during a repair before incurring a weather delay
max_waveheight_transport	Maximum wave height at which the vessel can travel at full speed
max_waveheight_repair	Maximum wave height at which the vessel can operate during a repair before incurring a weather delay
workday_start	Starting hour of the workday, if different from the simulation's main configuration
workday_end	Ending hour of the workday, if different from the simulation's main configuration
method	"turbine" or "severity" flag to indicate if repairs and maintenance will be processed on a current turbine first basis or highest severity first basis, respectively
strategy	"scheduled" to indicate the service equipment is scheduled beforehand
crew_transfer_time	Time, in hours, required to transfer the crew from the service equipment to the wind turbine
n_crews	Number of crew members the service equipment carries
crew:day_rate	Day rate for salaried crew members
crew:n_day_rate	Number of crew members for which a day rate is applied
crew:hourly_rate	Hourly rate for contracted crew members; no cost accrual when equipment is not operating
crew:n_hourly_rate	Number of crew members for which an hourly rate is applied

Table A8. Unscheduled Service Equipment Configuration Description

Configuration Key	Value Description
name	Name of the service equipment
equipment_rate	Daily rate for equipment operations
charter_days	Number of days the service equipment will be chartered
onsite	Boolean flag for if the service equipment is considered to be an on-site piece of equipment
capability	Three-letter identifier (see Table 1) defining the types of repairs and maintenance that can be performed
mobilization_cost	Cost to mobilize the equipment
mobilization_days	Number of days required to mobilize the equipment
speed	The traveling speed for the service equipment
tow_speed	Maximum transit speed, when towing, in kilometers per hour. Only required when using the “TOW” capability.
speed_reduction_factor	Reduction factor for traveling in inclement weather; default 0. A reduction factor of 0 stops the equipment from traveling when either wind speed or wave height reach or exceed their limit. Increasing the reduction factor to 1 allows the equipment to travel at full speed under these conditions.
max_windspeed_transport	Maximum wind speed at which the service equipment can travel at full speed
max_windspeed_repair	Maximum wind speed at which the service equipment can operate during a repair before incurring a weather delay
max_waveheight_transport	Maximum wave height at which the service equipment can travel at full speed
max_waveheight_repair	Maximum wave height at which the service equipment can operate during a repair before incurring a weather delay
workday_start	Starting hour of the workday, if different from the simulation’s main configuration
workday_end	Ending hour of the workday, if different from the simulation’s main configuration
method	“turbine” or “severity” flag to indicate if repairs and maintenance will be processed on a current turbine first basis or highest severity first basis, respectively
strategy	“requests” or “downtime” to indicate if the service equipment is dispatched to a site based on the number of requests, or wind power plant downtime
strategy_threshold	Threshold value to trigger dispatch of the service equipment. If “strategy” = “requests”, this is the number of requests that require this equipment’s capability. If “strategy” = “downtime”, this is the wind power plant operating capacity (between 0 and 1) below which the service equipment will be dispatched for tasks requiring its capability.
unmoor_hours	The number of hours required to unmoor a floating offshore wind turbine to tow it to port
reconnection_hours	The number of hours required to reconnect a floating offshore wind turbine after towing back to its position
port_distance	The distance, in kilometers, between the port and the site
crew_transfer_time	Time, in hours, required to transfer the crew from the service equipment to the wind turbine
n_crews	Number of crews the service equipment carries (serves future functionality)

Configuration Key	Value Description
crew:day_rate	Day rate for salaried crew members
crew:n_day_rate	Number of crew members for which a day rate is applied
crew:hourly_rate	Hourly rate for contracted crew members; no cost accrual when equipment is not operating
crew:n_hourly_rate	Number of crew members for which an hourly rate is applied

A.2 Outputs

Table A9. Metrics Provided Through WOMBAT's Postprocessing Application Programming Interface

Metric	Wind Farm Resolution Options		Time Resolution Options				Other Options	Description
	System	Wind Farm	Project	Annual	Monthly	Month by Year		
Time-Based Availability	x	x	x	x	x	x		Proportion of operational hours out of the total simulation hours
Production-Based Availability	x	x	x	x	x	x		Proportion of energy produced compared to the potential maximum energy production for the simulated wind speed time series
Capacity Factor	x	x	x	x	x	x	net, gross	Proportion of energy produced compared to constant production at nameplate capacity
Task Completion Rate		x	x	x	x	x	scheduled, unscheduled, both	Proportion of tasks completed ([scheduled] maintenance and [unscheduled] repair) out of those submitted to the repair manager
Equipment Costs		x	x	x	x	x	by equipment	Total costs related to the service equipment (or broken down by

Metric	Wind Farm Resolution Options		Time Resolution Options				Other Options	Description
	System	Wind Farm	Project	Annual	Monthly	Month by Year		
								each simulated service equipment)
Service Equipment Utilization		x	x	x				Proportion relating the number of days each piece of service equipment is used to the total number of days it is on site
Labor Costs		x	x	x	x	x	by type	Total costs of labor, which can be broken out by salary vs. hourly
Equipment and Labor Cost Breakdown		x	x	x	x	x	by category	Total cost for each of the delay, repair, maintenance, mobilization, crew transfer, and travel processes
Component Costs		x	x	x	x	x	by category, by action	Total cost associated with each subassembly, which can be broken out by categories: materials, labor, and equipment; or actions: repair, maintenance, and delay
Project Fixed Costs		x	x	x	x	x	high, medium, low resolution	Total fixed operating costs for the wind farm, broken down by resolution desired: high (overall cost), medium (broad categories), and low (every category)
Process Times		x	x	x	x	x		For each category, total number of hours from the time of request to the time of completion, total number of hours a process took to be

Metric	Wind Farm Resolution Options			Time Resolution Options			Other Options	Description
	System	Wind Farm	Project	Annual	Monthly	Month by Year		
								completed once started, total number of reduced operations hours, and total number of processes in that category
Power Production	x	x	x	x	x	x		Total power production, in kilowatts
Net Present Value	x	x	x	x	x	x		Non-PySAM net present value calculation
Net Present Value		x	x					PySAM net present value, only if PySAM settings are provided
Real Levelized Cost of Energy (LCOE)		x	x					PySAM real LCOE, only if PySAM settings are provided
Nominal LCOE		x	x					PySAM nominal LCOE, only if PySAM settings are provided
Internal Rate of Return		x	x					PySAM after-tax internal rate of return only if PySAM settings are provided