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RENEWABLE ENERGY

Item-based Reliability-centered

Life-Cycle Costing using Monte Carlo Simulation

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Objective

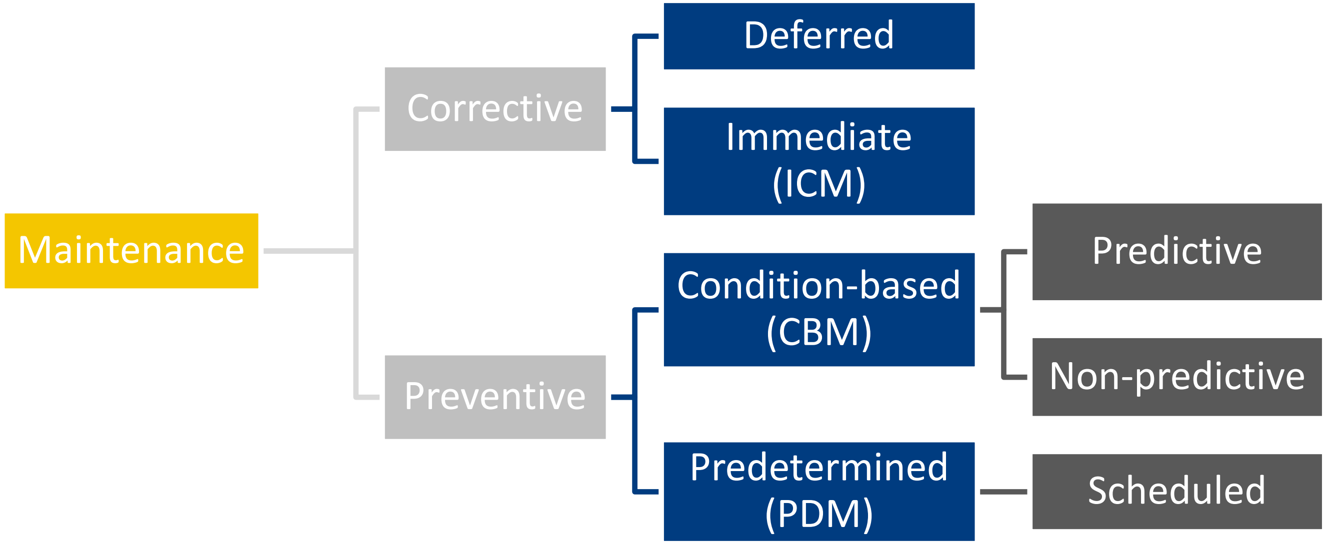
- Derivation and implementation of a method to find the maintenance strategy, that minimizes item[1]-based life-cycle costs

Consideration of

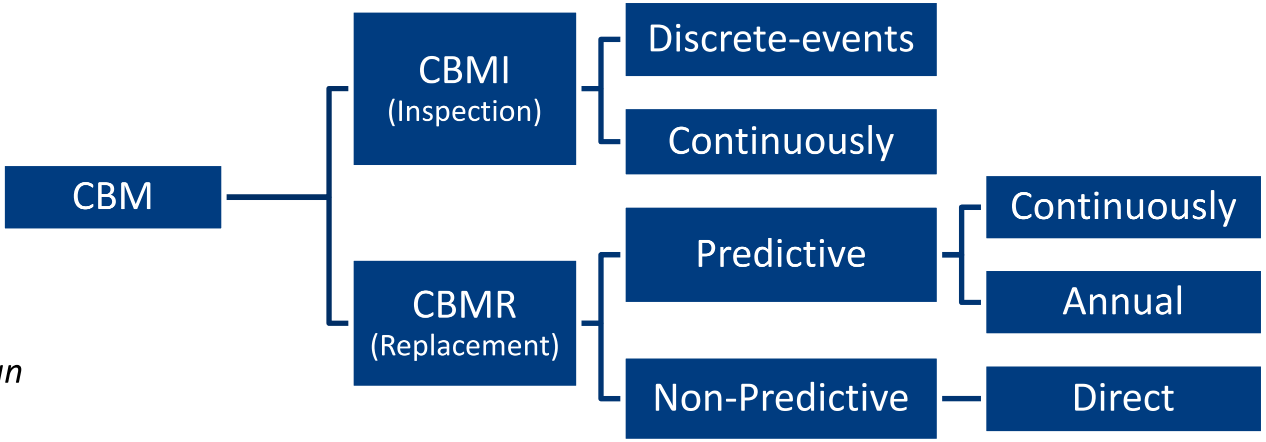
- All relevant maintenance types (Din EN 13306)
- Up to four failure modes (Weibull) with associated P-F interval (Normal distribution)

Method

- Time-sequential (event-discrete) Monte Carlo simulation technique used



Classification of maintenance types based on the timing of the intervention (based on DIN EN 13306:2017, p. 60)



Classification of condition-based maintenance

[1]*Any part, component, device, subsystem, system, or functional unit of an offshore wind turbine that can be individually described and considered*

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Model Development

Model Requirements

- **Realistic execution of maintenance events:**
  - Regardless of combination and number of maintenance types included
  - Execution of CBMR depend on success of CBM inspections (detectability function)
  - Start of CBMR depending on life-margin and lead time
- **Strategy efficiency metrics:**
  - Output: *LCC, LCoE, Lost Profit, Downtime, Number of Events*
  - Calculation for each iteration step based on executed maintenance events
  - Stated in NPV to account for time of event occurrence
- **Simulation**:
  - Modeling of renewal process
  - Definition of correlation of stochastic inputs
  - Annual or monthly time discretization to simulate
- **Usability and operability**: Input tested for plausibility, possibility of test runs, multi-case input, case handling features

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Model Development

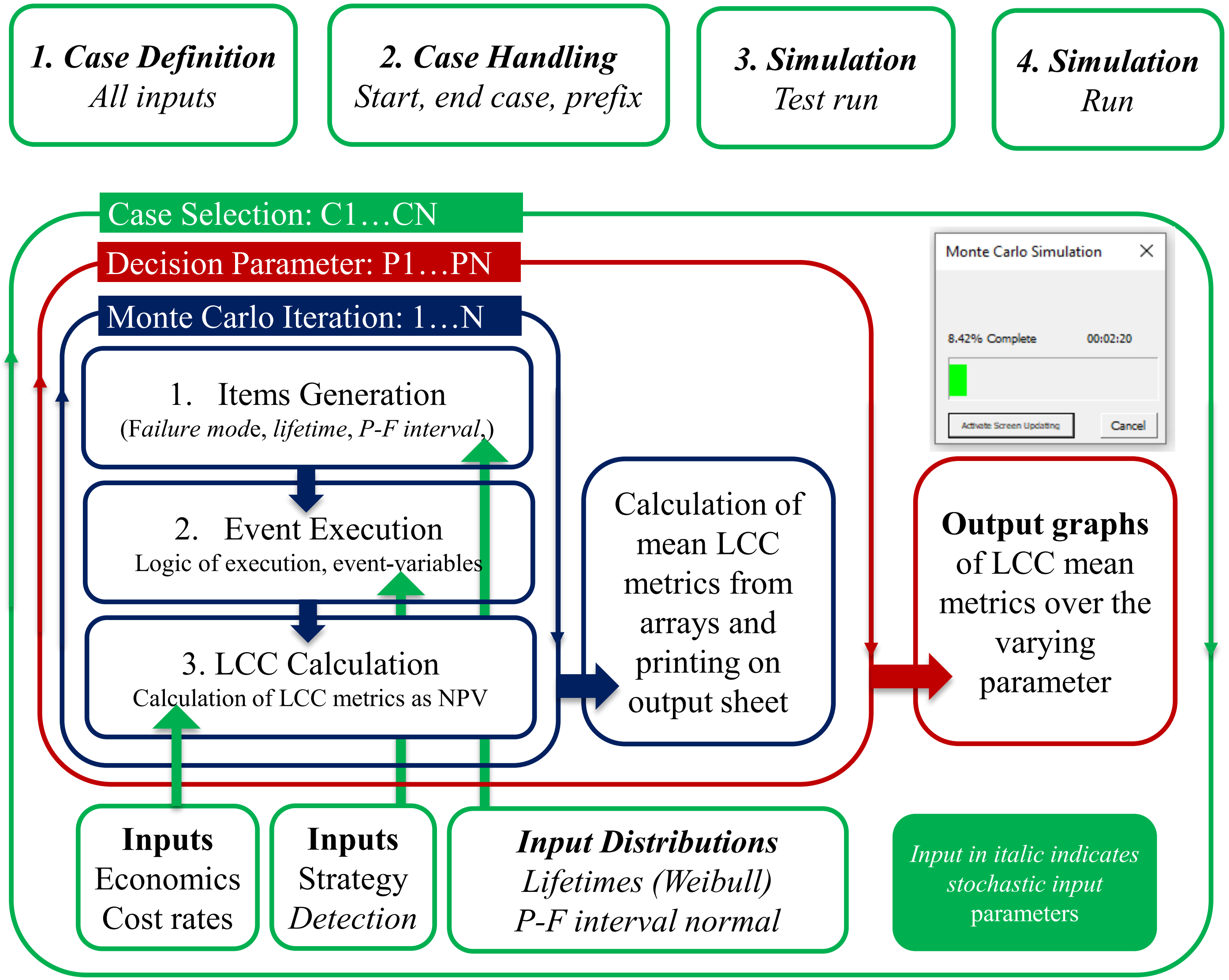
Model Concept and Simulation Process

1. **Case definition**
   - Failure characteristics
   - Windfarm data & Economics
   - Maintenance actions (costs, response times, repair times etc.)

2. **Case handling**
   - Define start case, end case
   - Define case prefix

3. **Test run**
   - Check of input inconsistences
   - Error log prepared

4. **Simulation**
   - Recommended iterations
   - Convergence criterion as stopping rule



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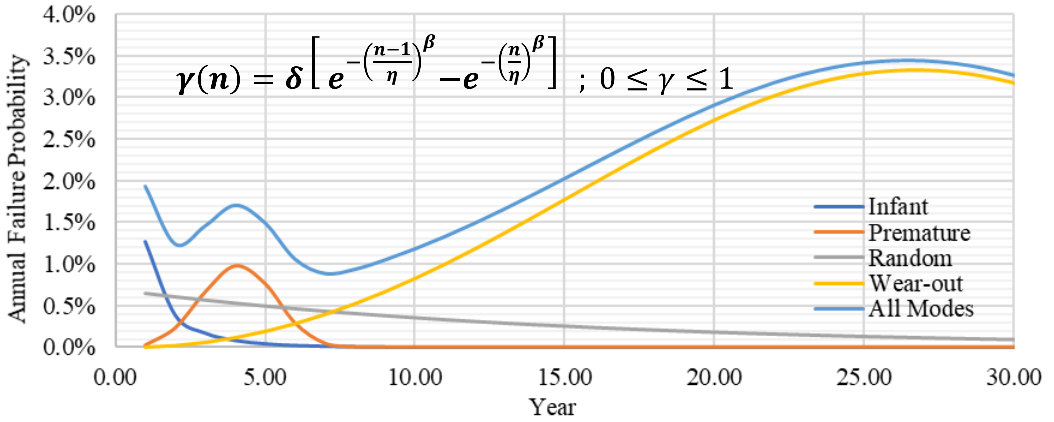
Model development

Item Generation

Generation process of r single component $X \in \{0,1,2 \ldots N \cdot r\}$:

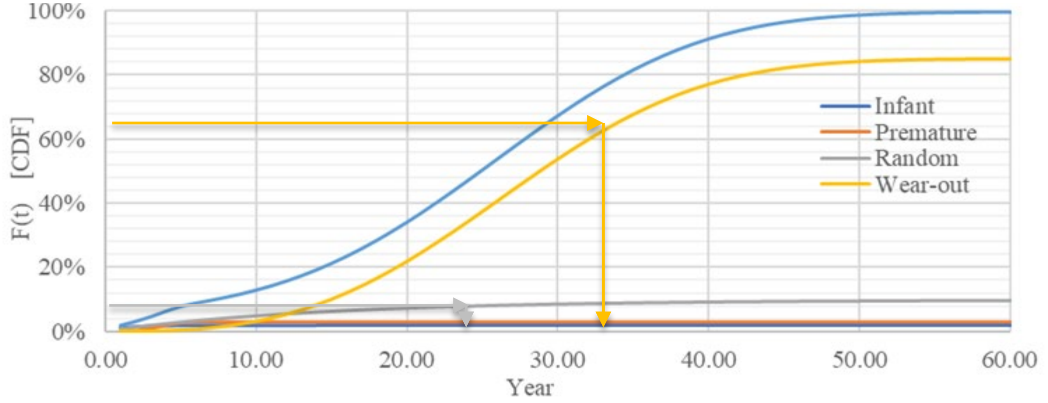
1. **Determination of failure mode**
   - Infant, premature, random, wear-out
   - Use of *random numbers or correlated random numbers* and mapping to failure mode



2. **Determination of lifetime**
   - Based on the inverse function of the Weibull CDF as

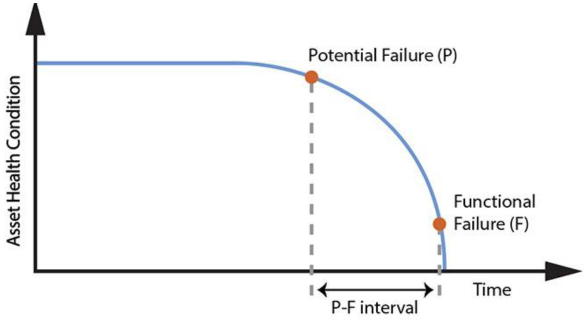
$$t = \eta\left(-LN(1-p)\right)^{\frac{1}{\beta}}$$

   - With *p* being a random or before-generated correlated random number (Cholesky decomposition)



3. **Determination of P-F interval**
   - Defined as time between potential and functional failure
   - Start of CBMR as *f(life-margin, lead time, time2F)*
   - P-F interval of random failures is zero

	Failure Generation		
	Failure Mode	Lifetime	PF Interval
		1	
	Random	**8.51**	
1	Infant	**0.20**	3.31
2	WearOut	**25.98**	3.05
3	Premature	**2.80**	3.75
4	WearOut	**22.98**	2.26
5	Random	**6.29**	
6	WearOut	**26.20**	3.06
7	WearOut	**24.04**	2.82
8	WearOut	**23.83**	3.48
9	WearOut	**11.87**	3.87
10	WearOut	**25.72**	4.13



Conclusion
Summary and Outlook

Summary

- LCC tool was developed and implemented as Excel VBA / Python application
- Tool can enable windfarm operators to reduce maintenance costs effectively
- Results are presented as means for fleet optimization and histograms estimating probability distributions if the results are evaluated as means of windfarm level (instead of item level)

Exemplary use cases at SGRE

- Minor components:
  - Hydraulic & coolant hoses
  - UPS batteries
  - Motors, Pumps

Limitation

- Reliability module as core element of the model
- The failure mechanisms must be adequately determined
  - Systems used in other industries with comparable operating environment
  - Sufficient failure history in offshore wind (wear parts with >12 failures per failure mechanism)
  - Accelerated life testing (ALT)

Outlook

- Treating more input variables as stochastic inputs (e.g. repair & response times) and define correlations
- Use of advanced convergence criterion as stopping rule
- Integration into computerized maintenance management system (CMMS)

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