windThrow

An open source toolbox for ice [and blade] throw simulations

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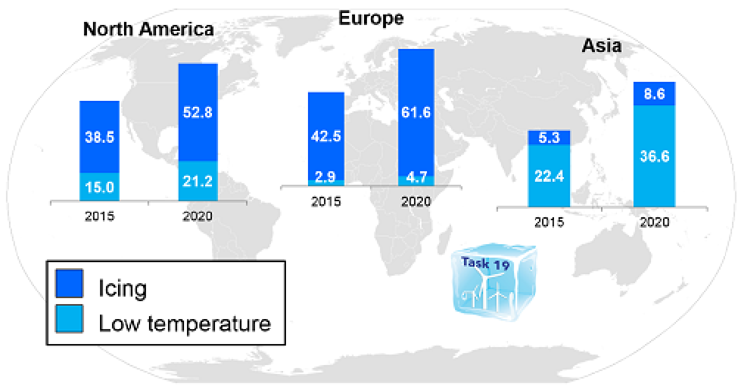
Motivation

- Known advantages, but:
- Increases in fatigue loads
- Decrease in power production
- Ice risks are much more significant than blade/fragment failure (Frequency blade failure 10 -3 /year; ice throw > 10/year)
- According to the legislations, the danger of getting hit by ice fragments needs to be assessed already during planning phase

Cold climate markets 2015-2020 [GW]



Media considerations

DTU

WIND ENERGY PRODUCTION IN COLD CLIMATE (WECO) Tammelin, Cavaliere, Holttinen, Morgan, Seifert, Säntti, FINNISH METEOROLOGICAL INSTITUTE.

Ice throw calculation methods

- Empirical formulas: e.g. d = 1.5 (D + H) for Ice throw
- Simple ballistic models (vacuum)
- Realistically detailed aerodynamic models
  - Risk assessment
  - Other modelings
- High fidelity CFD

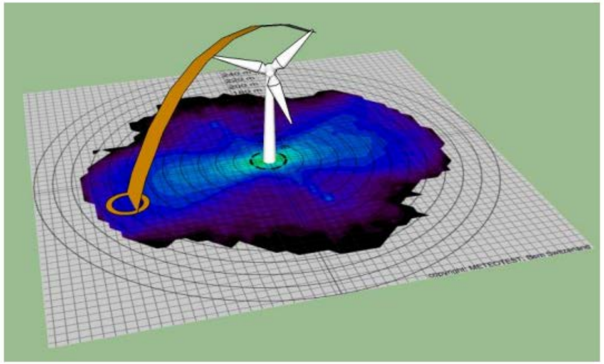


Figure 2: From one trajectory to a probability distribution (Source: courtesy of Meteotest)

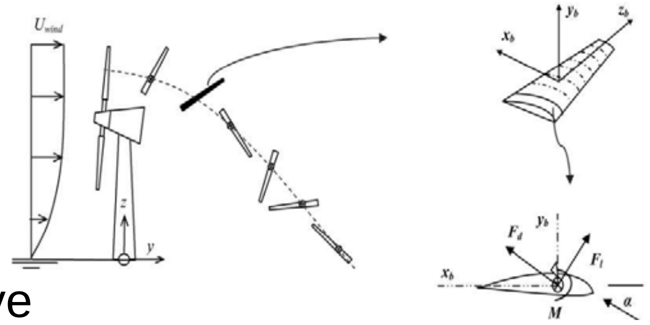
Ice throw model at DTU

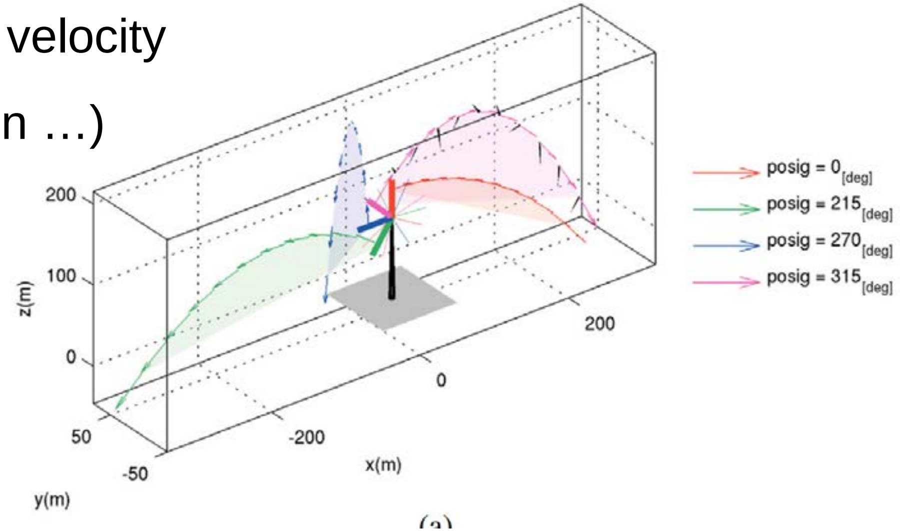
Originally developed in the 80s: SAVBAL, FORTRAN 77

For blade throw

Enhanced:

- Program restructure, new features from F90 and above
- Dyn. Stall, Inflow turbulence, non-uniform inlet velocity
- Ability for ice throw simulations (time integration …)
- Coupled with Matlab (postprocessing)
- Ice throw unit named “windThrow”
- Monte-Carlo toolbox added
- Received a GUI (Python)



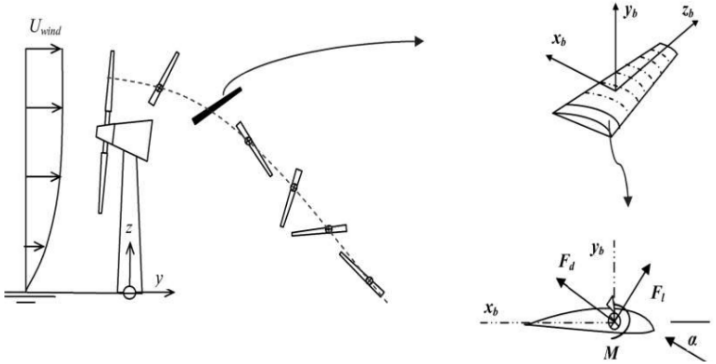


(Sarlak and Sørensen, WE, 2016)

Numerical model

Gov. equations and transformation matrix

$$\begin{bmatrix}\vec{r}_1\\\vec{r}_2\\\vec{r}_3\end{bmatrix} = [\mathbf{R}]\begin{bmatrix}\vec{i}\\\vec{j}\\\vec{k}\end{bmatrix} = \begin{bmatrix}r_{11} & r_{12} & r_{13}\\ r_{21} & r_{22} & r_{23}\\ r_{31} & r_{32} & r_{33}\end{bmatrix}\begin{bmatrix}\vec{i}\\\vec{j}\\\vec{k}\end{bmatrix} \text{ and similarly, } \begin{bmatrix}\vec{i}\\\vec{j}\\\vec{k}\end{bmatrix} = [\mathbf{R}^{-1}]\begin{bmatrix}\vec{r}_1\\\vec{r}_2\\\vec{r}_3\end{bmatrix} \quad (1)$$



$$m\underline{\ddot{x}}_g = \underline{F} + m\underline{g} \quad (2)$$

$$\underline{\underline{I}}.\underline{\dot{\omega}}_b = \underline{\omega}_b \times (\underline{\underline{I}}.\underline{\omega}_b) = \underline{M} \quad (3)$$

$$\underline{\dot{r}} = \underline{\omega} \times \underline{r} \quad (4)$$

Local rel. wind velocity seen by the blade fragment,

$$\vec{u}_{pb} = [\mathbf{R}].(\vec{u}_{wind} - \vec{u}_g) - \vec{\omega}_b \times \vec{r}_{pb}$$

(5)

```
Program SAVBAL(ABL and turbine parameters, initial conditions)
    Call initiate                                   ! Evaluate initial position,
                                       orientation and velocities of fragment
                                                   at t_0 in it's local coordinate
    while z_g ≤ 0 do                                 ! main loop of the program,
                                        iteration until the body hits the ground
        Call trans1  Y^old ← [R, og_b, v_b, ω_b]^old    ! Arrange a set of 18 ODE's
        Call local velocity  v_local ← R, v_b, ω_b, v_wind(h,t)   ! Calculate relative
velocities
        Call aerodynamics  F_total, M_total ← R(α), v_local, ω_b   ! Calculate loads
        Call RungeKutta  Y^new ← [Y, F_total, M_total]^old         ! time integration
        Call Trans2  [R, og_b, v_b, ω_b]^new ← Y^new               ! update new values
    End while
End Program
```

Aerodynamic loads

$$L_i = \frac{1}{2}\rho v_i^2 A_i C_{Li}, \quad D_i = \frac{1}{2}\rho v_i^2 A_i C_{Di}$$

Dyn. Stall, irrelevant for ice throw $C_{l,dyn} = f_s C_{l,inv}(\alpha) + (1-f_s)C_{l,fs}(\alpha)$

Wind profile (incl. ABL stability) $u_z = \frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) + \psi(z, z_0, L)\right]$

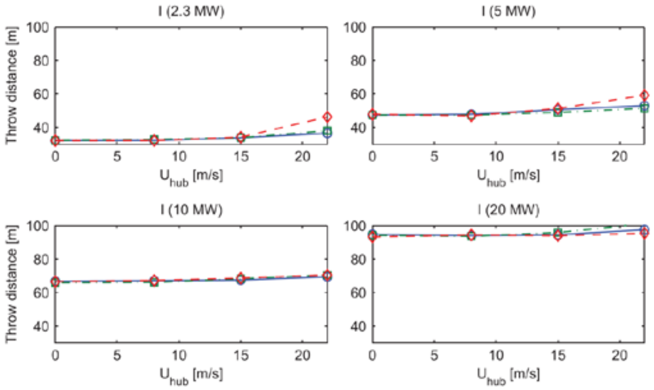
1d von Karman Turbulence spectrum

(Sarlak and Sørensen, WE, 2016)

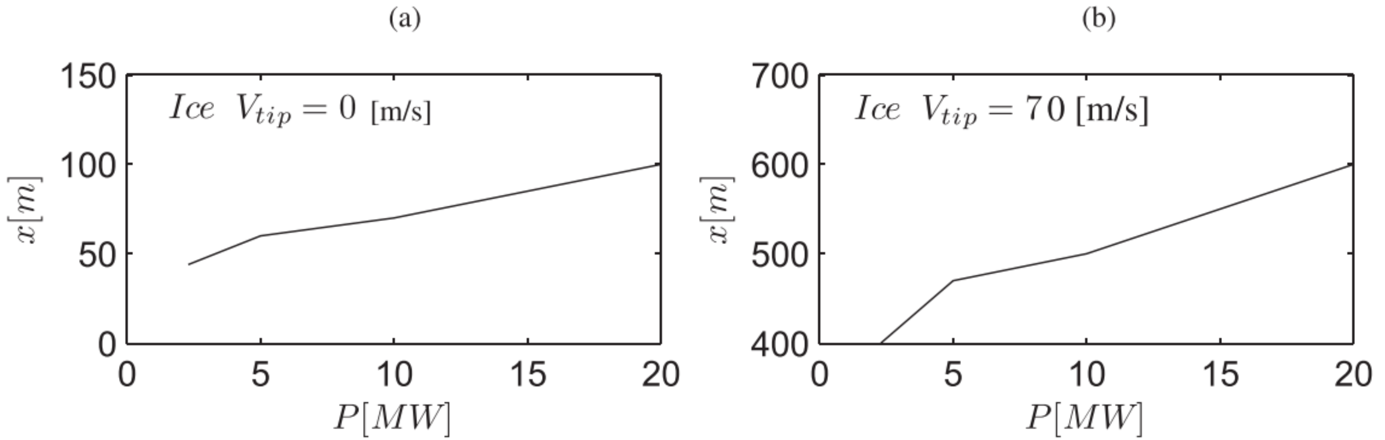
Results of ice throw simulations

Table IV. Aspect ratios, reference chord length C_{ref} and detached mass m of the ice fragments ($\rho_{ice} = 0.7$ kg/m^3) used for throw simulation of turbines of different sizes.

	2.3 MW		5 MW		10 MW		20 MW	
Cases — AR	C_{ref} (m)	m (kg)	C_{ref} (m)	m (kg)	C_{ref} (m)	m (kg)	C_{ref} (m)	m (kg)
$AR = 1$		0.18		0.43		0.97		2.16
$AR = 2$	0.1	0.36	0.15	0.87	0.2	1.95	0.3	4.33
$AR = 3$		0.54		1.31		2.94		6.49



Throw distance calculations of ice fragments for three different aspect ratios for 2.3, 5, 10 and 20 MW turbines in standstill operation ($V_{tip} = 0$ m/s). ◇ ◇ ◇: $AR = 1$; □ □ □: $AR = 2$; and ○ ○ ○: $AR = 3$.

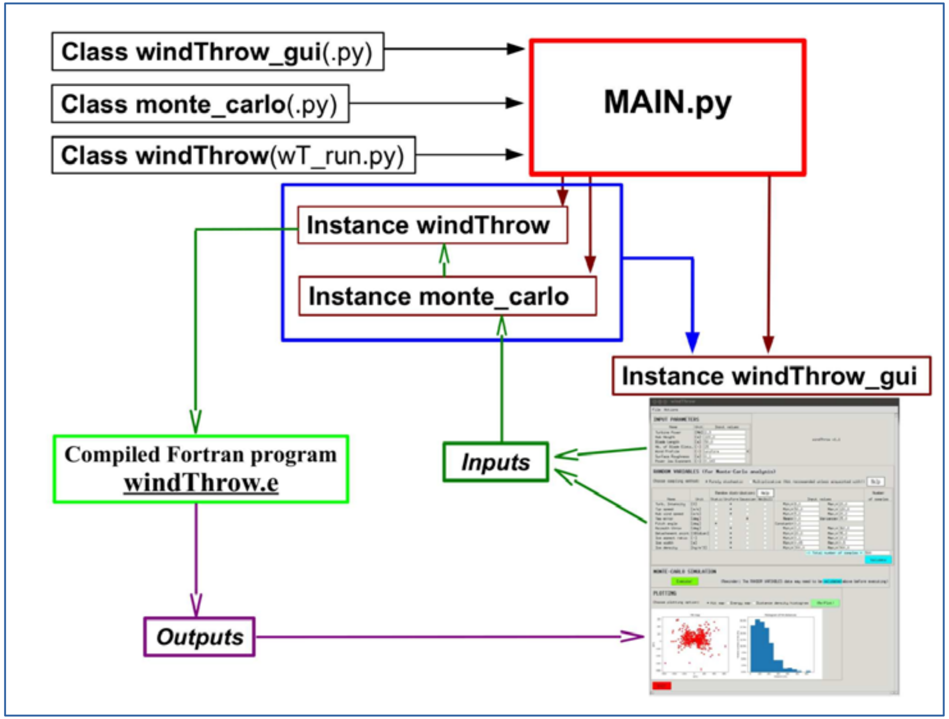


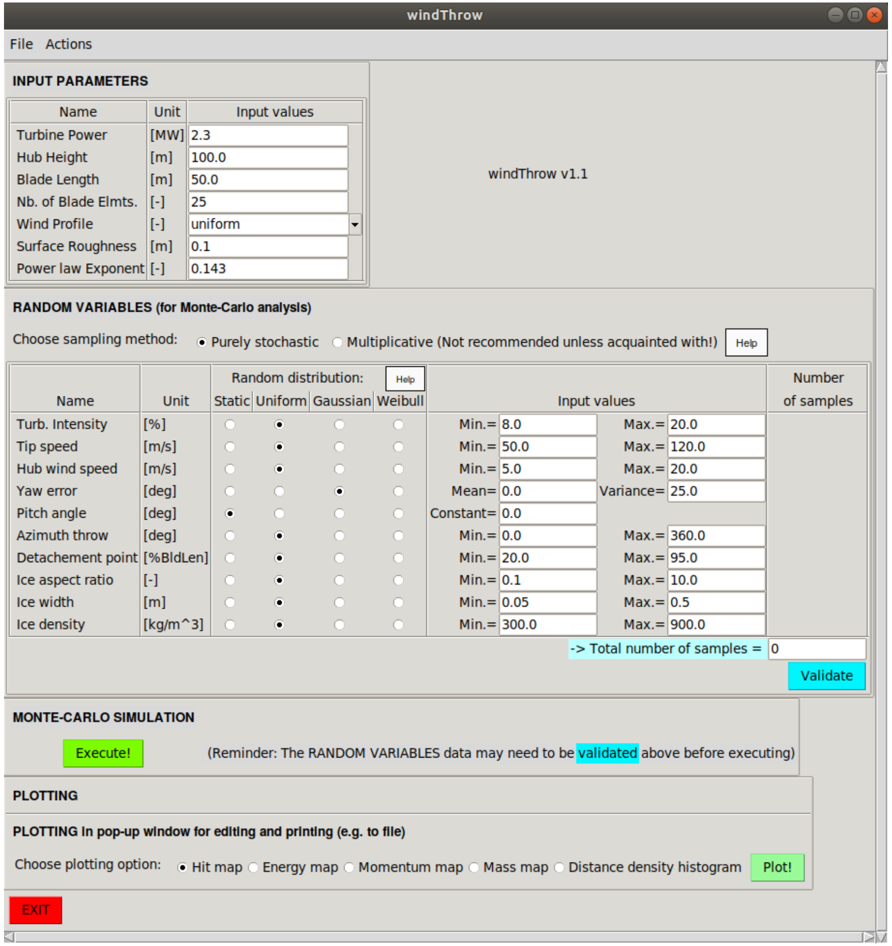
Maximum throw distances obtained for the ice throw in (a) standstill operation, i.e., $V_{tip} = 0$ m/s and (b) normal operating condition, i.e., $V_{tip} = 70$ m/s as a function of turbines power.

(Sarlak and Sørensen, WE, 2016)

New user interface and capabilities

windThrow v1.1





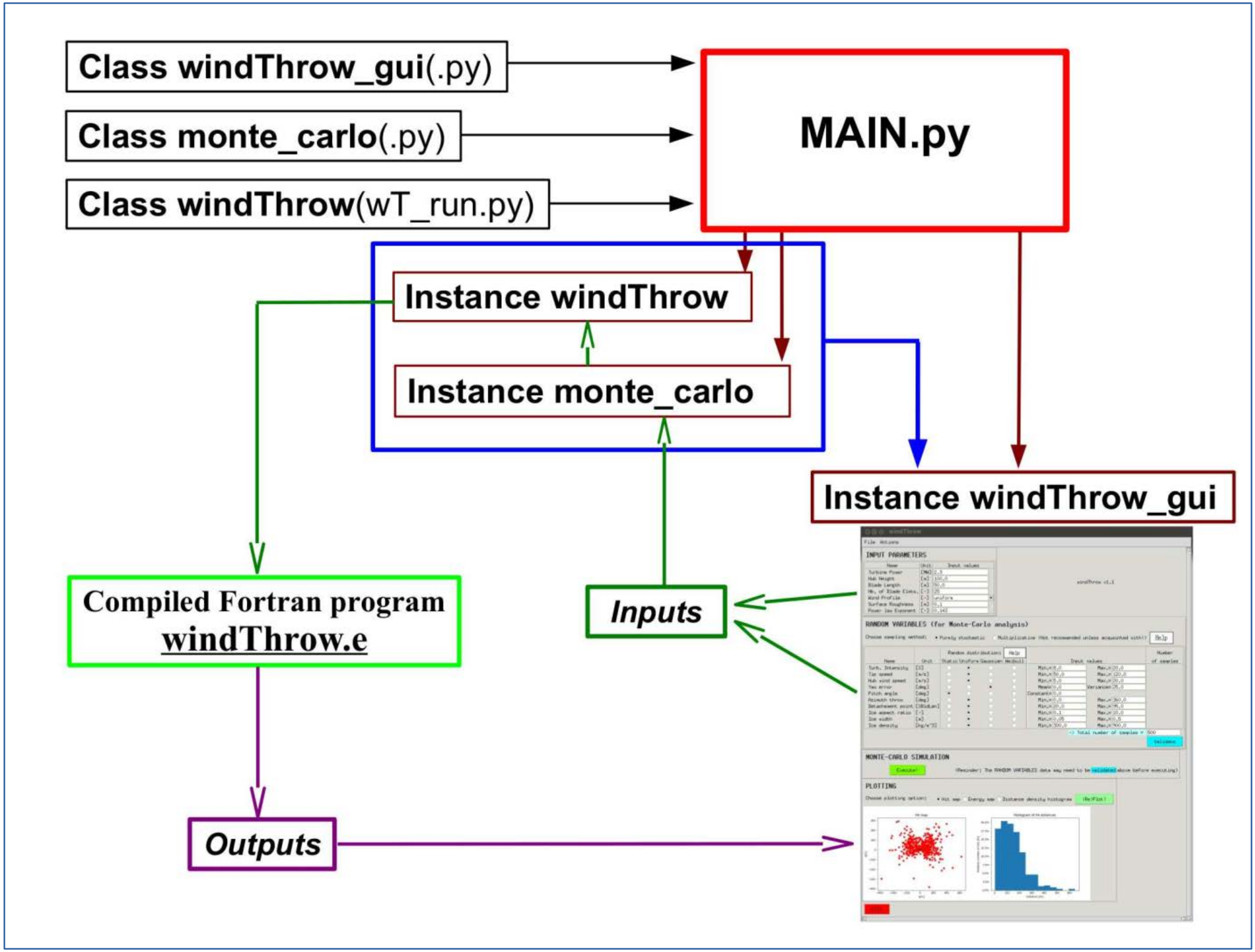
(Bertagnolio and Sarlak, Tech.report under preparation)

New user interface and capabilities

windThrow v1.1

Idea is to make the code more useful to the community …

Open source
Integration of other throw models
Integration of guidelines and datasets
Complex terrain
WRF integration (?)
...



Taking IEA recommendations into consideration

Trajectory Model,

Modelling the Ice Fragment,

Wind Turbine Characteristics,

Environmental Characteristics,

Amount of Ice,

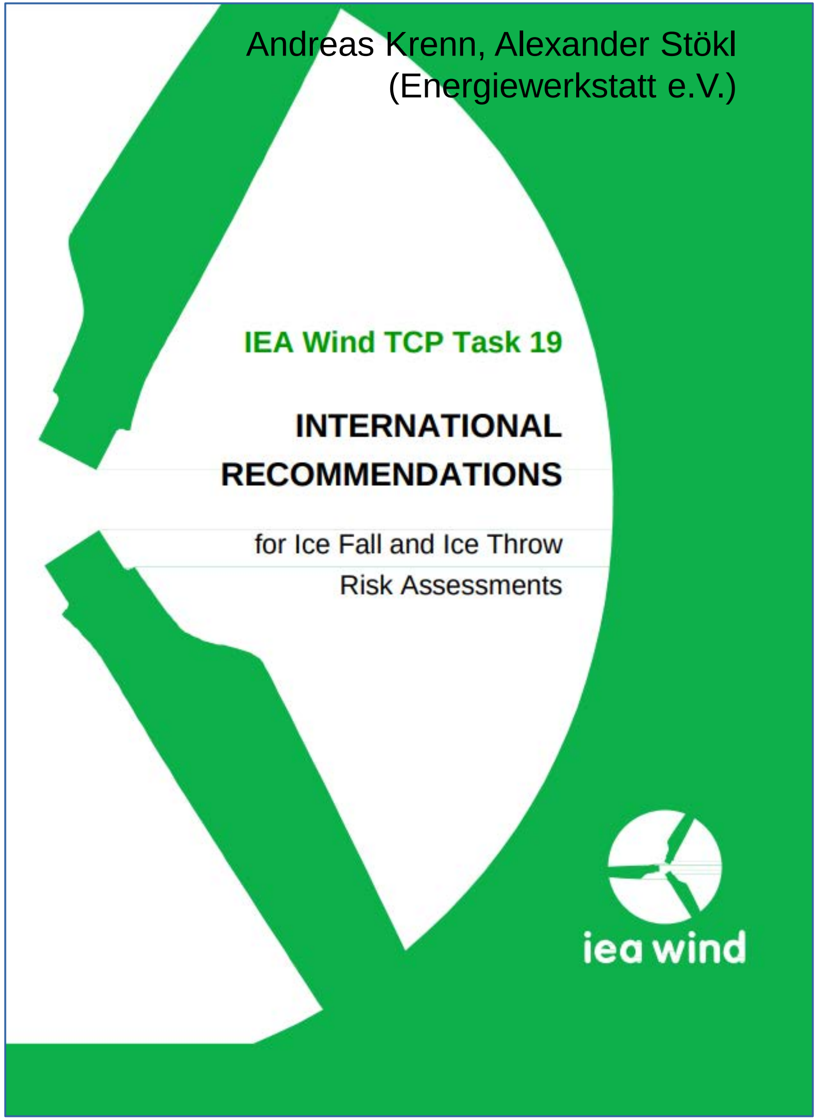
Properties of Ice Pieces,

Site and turbine Icing Conditions,

Methods of Risk Analysis,

Risk Acceptance Criteria,

Effect of Risk Reducing Measures to the Result



Closure:

windThrow software will be freely available to the public for ice throw calculations

What is still needed?

- Improved databases, uncertainties and risk assessment methodologies
- Validation of windThrow against available databases
- Closer industry and academia collaboration needed (database)

Thanks. Willing to discuss?

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