Investigating the impact of wakes on single turbine availability

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Abstract. The current trend in wind energy leads to closely packed wind farms. These short distances result in a higher turbulence and consequently higher loads. In this paper an approach is proposed to evaluate single turbine availability losses due to the wake effect by modeling material fatigue behavior of selected turbine components. First, a characteristic wake scenario is defined: While one turbine is exposed to a wind field conforming to wind class IIB, another turbine experiences higher turbulence intensities according to Frandsen’s wake model. Using a dynamic multibody simulation, turbine loads are calculated which then are analyzed using the rainflow counting algorithm (giving load range and cycle counts) before being extrapolated to design lifetime of 20 years. Subsequently, artificial material curves are estimated representing the minimum load cycles to withstand during design lifetime. The slope of these curves is determined using the slope of a representative S-N-curve for each component. Position is then determined applying Miner’s rule with unity damage at the end of design lifetime. Lastly, failure behavior is approached by using a lognormal probability distribution. As a result increased failure probabilities for the rotor hub unit (main bearing and rotor hub) are found in the wake case. First results for an annual time in wake fraction of 20 % show an increase in total failure probability from 2.30 % to up to 41.85 % at a distance between the two turbines of 3D. Applying a mean down time per failure from literature (based on modern EU wind farms) finally leads to an overall technical availability decrease due to hub unit failure of 0.035 % in the wake case compared to the free stream case.

1. Introduction
Regarding annual increases in gross energy production from wind in the EU, the highest numbers were recorded in Germany over the past few years. While in the year 2016 a total capacity of 4.430 MW was installed, in 2017 this figure rose to a total capacity of 5.514 MW which equals an annual growth rate of 10.7 %. [1, 2]

Due to economical, legal and social restrictions the total landmass designated for wind farms is limited and spots with high yield become rare. To maximize profit one way is to increase the number of turbines in a wind farm which results in closely spaced turbines and aerodynamic interference also known as the wake effect. The wake effect is mainly characterized by slightly reduced wind speeds and a turbulence intensity significantly higher than in free stream. High turbulence intensities result in strong dynamics regarding the turbine components exposed to wakes and increase their mechanical loads [3]. Due to that, probability of material fatigue failure as well as annual turbine down time rise, finally leading to losses in single turbine availability. In [4, 5] showed an availability of 97 % upto 98.3 % based on field data. They detailed the loss of
availability for each component. However, it cannot clearly stated if fatigue lead to a component failure. [6] investigated the load influences due to wake flow situation and showed an increase of 4.0% considering equivalent load ranges. Also [7] indicated that the increased turbulence is mainly relevant for the fatigue the tower and the wind shear to the rotor. Nonetheless, a clear statement concerning the effect of wake loads onto the lifetime was not given so far.

In the present paper a characteristic wake scenario is considered using one turbine in free stream and another partly exposed to the wake effect. The defined wind situations for both turbines are represented by wind fields which subsequently are used as input for a dynamic multibody simulation. Furthermore a probabilistic material failure model is developed and multibody simulation results translated into failure probabilities. Lastly single turbine availabilities for both turbines are derived by applying a mean down time per failure and turbine component.

2. Characteristic wake scenario
In the characteristic wake scenario two identical turbines with different inflow conditions are investigated. The first turbine (turbine 1) is located in free stream (IEC wind class IIB), the second turbine (turbine 2) is placed within a horizontal distance of $\Delta s$ behind the first one (see figure 1).

![Figure 1: Definition of the wake scenario for wind field generation and dynamic load calculation; the horizontal distance between the turbines equals $\Delta s$](image1)

![Figure 2: Two-dimensional wind field for one time-step generated in TurbSim [8]; wind speed on a grid of 140 x 140 points covering the rotor area (dashed white line)](image2)

As a result of this setting the second turbine experiences inflow conditions according to the described wake situation which differ significantly from free stream conditions. To estimate wind speed and turbulence intensity in the wake case a wake model developed by Frandsen [9] is applied. For the downstream flow Frandsen finds a linear relation between diameter $D_{\text{wake}}$ and distance $s$ behind turbine 1 with rotor diameter $D$ and an estimated parameter $\beta_0 = 0.17$ (equation 1). The model of Frandsen suggest a non-linear wake expansion [10]. However, this approach follows an the linear wake expansion as an initial starting point. Such that an
appropriate method can be established.

\[
\frac{D}{D_{\text{wake}}} = \frac{1}{1 + \beta_0 s}
\]  

(1)

Taking the thrust coefficient \(C_T\) of turbine 1 into account, the wind speed \(U_{\text{wake}}\) behind the first turbine can be determined using the free stream wind speed \(U_{\text{free}}\) (equation 2).

\[
U_{\text{wake}} = U_{\text{free}} - \frac{1}{2} U_{\text{free}} C_T \left( \frac{D}{D_{\text{wake}}} \right)^2
\]

(2)

Frandsen derived an empirical formulation for the wake \(T_{\text{I add}}\) induced by rotor rotation of turbine 1 (see equation 3)

\[
T_{\text{I add}} \approx \frac{1}{1.5 + 0.3 s \sqrt{U_{\text{free}}}}
\]

(3)

Quadratic addition of free stream turbulence intensity \(T_{\text{I free}}\) and \(T_{\text{I add}}\) subsequently leads to the combined wake turbulence intensity \(T_{\text{I wake}}\) (equation 4).

\[
T_{\text{I wake}} = \sqrt{T_{\text{I add}}^2 + T_{\text{I free}}^2} \approx \sqrt{\frac{1}{(1.5 + 0.3 s \sqrt{U_{\text{free}}})^2} + T_{\text{I free}}^2}
\]

(4)

Alternative flow models like \[11\] can be used to determine the inflow of the wake induced turbulence intensity too. However, the aim of this paper was to develop an availability model. Therefore, the author wanted to keep the possibility of comparability, so the flow model suggested by IEC 61400-1 was used. The Frandsen’s wake model and the definitions made in the wake scenario are used to generate characteristic wind fields (figure 2). Thereby neglecting the difference due to atmospheric and wake induced turbulence. For each wind speed bin between cut-in and cut-out speed (margin of 0.5 m.s\(^{-1}\)), stochastic wind fields are created containing information on wind speed and direction on a three dimensional grid. The grid includes a vertical and horizontal dimension spanning the whole rotor area and a temporal dimension covering a interval of ten minutes. Spatial and temporal resolution are chosen on basis of IEC 61400-1 recommendations. The wind fields are generated using the TurbSim framework by NREL \[8\]. To ensure a statistical valuable result the wind field is generated with six different random seeds.

To evaluate the impact of wakes on single turbine availability, the scenario described above is modified. If turbine 2 solely experienced wake conditions during lifetime, the total accumulated load solely resulted from wind conditions according to equation 2 and equation 4. Nonetheless, this would be an unrealistic scenario. In order to meet real life conditions, the amount of time in which turbine 2 experiences wakes is reduced. This amount of time varies with respect to site, inflow angles, local site effects and so on. To reduce the amount of influences and to generated a benchmark case, measurement data from research platform FINO 1 (nearby wind farm Alpha Ventus in the North Sea) is used. FINO 1 is located to the west of Alpha Ventus and experiences its wake while the wind occurs from North-North-East up to South-South-East. These inflow direction have a probability of 20% of the wind turbine lifetime is used \[3\] at this location. FINO As a result two different cases can be defined:

(i) Case A: pure undisturbed free stream conditions
(ii) Case B: 80% (292 d per year) free stream conditions and 20% (73 d) wake conditions at a distance of \(\Delta s\)
3. Dynamic multibody simulation and turbine load evaluation

The loads on a wind turbine differ with respect to its location and status of operation. To standardize loads and resulting stresses, the International Standard IEC 61400-1 [12] defines Design Load Cases (DLCs) for different wind conditions and turbine operation modes. These DLCs vary along the lifetime from various extreme loads up to fatigue loads. To reduce computational aspects, the paper will only focus on DLC 1.2.

DLC 1.2 represents normal power production without any failures, meaning every wind speed between cut-in and cut-out wind speed using the Normal Turbulence Model (NTM). This case has the highest influence on component fatigue damage. During idling mode loads are significantly lower than during operation besides the constant rotor weight. Extreme weather conditions occur sporadically and are only of interest during low-cycle fatigue. Therefore, DLC 1.2 approximates the majority of contributions concerning fatigue failure.

3.1. Turbine and controller model

The benefit of a DLC is that free stream conditions are fully described through wind probabilities and turbulence models defined in International Standard IEC 61400-1. Subsequently, the wind can be described as a three-dimensional time-dependent wind field per average wind speed on a 10 minute interval. These wind fields are used as input data for a dynamic load simulation which is executed as a co-simulation in MATLAB/SIMPACK. In SIMPACK the wind speed, direction and fluctuation information is transformed into aerodynamic forces which are applied along the rotor blades. This is achieved using the AeroDyn framework by NREL [13].

The fluctuation in wind speed results in dynamic loading. Additionally, the wind turbine is a rather flexible structure especially with respect to rotor blades and tower. To estimate the resulting dynamic loads, the turbine is modeled as a flexible multibody system in SIMPACK. In the multibody simulation (MBS) a generic turbine model (called C3x126) which was developed at the Center for Wind Power Drives (the configuration can be seen in table 1) is used. Another source of excitation for the wind turbine is its control logic. While dynamic turbine behavior is calculated in SIMPACK, a controller model implemented in MATLAB/Simulink handles turbine control and data monitoring. The underlying control strategy uses a state-of-the-art PI controller, capable of handling shut-down and run-up of the turbine. The determined loads for turbine components out of the simulation environment are post-processed.

3.2. Simulation results and post-processing

The simulation results are available in form of time-resolved load signals for every degree of freedom per component, e.g. for hub yawing moment $M_{z,\text{hub}}$ or blade flapwise bending moment $M_{y,\text{blade}}$. To identify deviations between free flow loads and wake loads the time series are analyzed using a rainflow counting algorithm. The output of the rainflow counting algorithm is condensed to identify load range, load mean and load cycle counts [14]. Subsequently, each time signal of the DLC is analyzed based on load range and load mean spectrum. The loads are split into 100 bins, evenly distributed between minimum and maximum of the experienced load. Then cycle counts per bin are accumulated resulting into a three-dimensional condensed rainflow matrix (see figure 4, left). The load range is printed along the x-axis. The warmer the color, the more often does the load occur.

The condensed rainflow matrices of the simulated wind speed bins (and respective TI according to case definitions) are weighted using the Rayleigh distribution defined by IEC wind class IIB (average wind speed of 8.5 m/s). Next, the weighted rainflow matrices are extrapolated to a design lifetime of 20 years. Additionally the outputs are accumulated using the wake fraction defined in the wake scenario. As an approximation, the respective load mean is disregarded and total cycle counts per load range bin are added up (see figure 4, right). This approximation is based on the assumption of metallic components as in this case fatigue failure mainly depends
Table 1: Technical specifications of generic wind turbine model C3x126

| Parameter           | Value & Unit |
|---------------------|--------------|
| Nominal power       | 3 MW         |
| Hub height          | 115 m        |
| Rotor diameter      | 126 m        |
| Cut-in speed        | 3.0 m.s\(^{-1}\) |
| Nominal speed       | 11.0 m.s\(^{-1}\) |
| Cut-out speed       | 25.0 m.s\(^{-1}\) |
| Gearbox ratio       | 1:92.28      |
| Main suspension     | 4-point      |

on the load range. Subsequently, simulation results for both cases exist in form of lifetime extrapolated load cycle counts and corresponding load range.

Commonly, load spectra are compared using the respective damage equivalent load (DEL). The DEL reduces the load spectrum to a pair of load range and cycle counts which results in equivalent fatigue damage according to the linear damage accumulation rule by Palmgren and Miner (Miner’s rule, [15]). When calculating the DEL for both cases, one observes significantly higher values in the wake case [3]. However, based on the DEL no statement can be done regarding failure probability and availability losses. For that reason a material or lifetime model must be applied.

![Figure 3: Multibody wind turbine model C3x126 in SIMPACK with coordinate system for rotor hub unit](image)

![Figure 4: To the left: Condensed rainflow matrix visualizing load cycle counts for tuples of load range and mean load (a warm color indicates high load cycles count numbers); to the right: simulated loads in form of load range and corresponding load cycle counts](image)
4. Modeling component life and material fatigue failure

In the process of turbine design the manufacturer would compare actual stresses inside the components to material data obtained through fatigue tests to guarantee a certain component lifetime [12]. Then safety factors, due to impact of failure and material data reliability, would be applied and component design be reconsidered. In that process component dimensions could be enlarged or a different material be used. In the planning phase of a wind farm as well as in the case of wind farms being operated, detailed information on individual turbine component design often are not available. The approach described in this paper is using only material failure characteristics and linear damage accumulation. For that reason it is not necessary to consider actual stresses but rather take care of load ranges and load cycles. For that reason each load component (force or torque) is considered individually by estimating theoretical material curves with load cycle counts to withstand by the respective component.

4.1. Estimation of theoretical material curves

The general shape of the theoretical material curves is defined by the slope of the S-N-curve \( (m) \) of the component’s material. Slopes of S-N-curves equals the Woehler exponent of the material to be inspected. For cast metal specimens the slopes are in the range of \( m = 3...5 \) [16]. In case of reinforced glass fibre composites usually values of \( m = 9...10 \) are used [17]. Combining the load spectrum based on the load amplitude \( S \) (equals to the load range divided by two) with the component material’s S-N-curves for alternating load into one graph leads to figure 5 (a). However, the theoretical material curve is not fixed inside the graph and is able to be shifted along the load cycles. In the next step, the material curve must be positioned, meaning the y-intercept has to be set. To do so, Miner’s rule is applied (see equation 5). According to Miner’s rule material fatigue failure is reached when \( D = 1 \). In that case the sum over all partial damage factors \( n_i/n_{i,f} \) per load amplitude bin \( i \) equals one. Here \( n_i \) is the actual load cycle and \( n_{i,f} \) represents the load cycle that can be withstood. Subsequently, equation 5 is used to fit a curve with the predefined slope \( m \) and \( D = 1 \) by estimating \( n_{i,f} \) for each load amplitude bin and a total design lifetime of 20 years. This is done for every load component and especially both cases individually (see figure 5 (b)).

\[
D = \frac{n_1}{n_{1,f}} + \frac{n_2}{n_{2,f}} + \cdots + \frac{n_N}{n_{N,f}} = \sum_{i=1}^{N} \frac{n_i}{n_{i,f}} 
\]

(5)

4.2. Impose lognormal distribution for material fatigue failure

After the theoretical material curves are determined, material fatigue failure probability must be modeled. For that reason a lognormal probability distribution is chosen which approximates fatigue failure probability of metallic components such as the hub unit with good accuracy [17, 16]. The probability density function (PDF) for a lognormal distribution is shown in equation 6 [18].

\[
p_{\Lambda}(x|\sigma,\mu) = \begin{cases} 
\frac{1}{\sigma\sqrt{2\pi x}} \exp \left\{ -\frac{(\ln x - \mu)^2}{2\sigma^2} \right\} & \text{for } x>0 \\
0 & \text{otherwise} 
\end{cases}
\]

(6)

By using the load cycles \( n_f \) as the characteristic value \( x \) and approximating population behavior using an empirical standard deviation \( \hat{\sigma} \), the shape of the PDF for material fatigue failure is fully determined. This distribution can be fixed onto the theoretical material curve (see figure 5 (c)). The corresponding cumulative probability density function (CDF, see equation 7) as well as a
Figure 5: In (a): Simulated load spectra for both cases (the same load component each) and curve with material-characteristic S-N-curve slope; in (b): Estimation of theoretical material curves for cases A (solid) and B (dashed) by applying linear damage accumulation with a Miner damage sum equal to one after a period of 20 years ($D_{A/B}^{20} = 1$); in (c): Modeling material fatigue failure probability by assuming a lognormal probability distribution (probability density function, PDF); in (d): Assuming design failure probability according to IEC 61400-1 [12] for design case A ($P_{fA}$) combining it with the cumulative density function (CDF) of lognormal distribution to estimate increased failure probability for case B ($P_{fB}$)

design failure probability are required to do so.

\[
P_A(x|\sigma, \mu) = \begin{cases} 
\frac{1}{\sigma \sqrt{2\pi}} \int_0^x \exp \left\{-\frac{(\ln t - \mu)^2}{2\sigma^2}\right\} \frac{1}{t} \, dt & \text{for } x > 0 \\
0 & \text{otherwise.}
\end{cases}
\]

(7)

Design failure probabilities are implicitly defined in IEC 61400-1 by the material data used for fatigue design and strength verification. IEC 61400-1 recommends the use of S-N-Curve data with a cumulative failure probability of $P_1 = 2.3\%$ in case of metallic materials and $P_1 = 5\%$ for composites. The design cumulative failure probability is applied in load case A (see figure 5 (d), $P_{fA}$). Consequently, the increase in failure probability can be determined. The horizontal distance between the material curves (i.e. the difference in load cycles to withstand during
design lifetime $\Delta n_{i,f} = n_{i,f,B} - n_{i,f,A}$) is calculated. This constant offset is used to determine failure probability in load case B finally quantifying the wake influence (see figure 5 (d)).

### 4.3. Availability loss due to fatigue failure

Based on the shown approach, a failure probability $P_{f,i}$ for each individual load situation can be obtained. The failure probability then needs to be transformed into an availability loss. To do so, information on mean down time per failure has to be included. Firstly, based on the assumption that the lognormal distribution defined through the empirical standard deviation $\hat{\sigma}$ depicts the entire population, an annual failure rate $r_{f,i}$ per component $i$ can be calculated (see equation 8).

$$ r_{f,i} = \frac{P_{f,i}}{n_{\text{life}}} \quad \text{with} \quad n_{\text{life}} = 20 \text{ years} \quad (8) $$

Multiplying the annual failure rate with a mean down time per failure $t_{f,i}$ (of the component $i$ of interest) the resulting down time per year and component $T_{f,i}$ is determined (see equation 9).

$$ T_{f,i} = r_{f,i} t_{f,i} \quad (9) $$

Finally, applying equation 10 leads to the availability loss $\Delta \alpha_{i}^{A-B}$ due to the wake effect. Here the difference in annual down times (between cases A and B) is compared to the total time of availability in a year $T_{\text{av,th}}$.

$$ \Delta \alpha_{i}^{A-B} = \frac{T_{f,i}^{B} - T_{f,i}^{A}}{T_{\text{av,th}}} \quad \text{or} \quad \Delta \alpha_{i}^{A} = \frac{T_{f,i}^{A}}{T_{\text{av,th}}} \quad \text{and} \quad \Delta \alpha_{i}^{B} = \frac{T_{f,i}^{B}}{T_{\text{av,th}}} \quad (10) $$

### 5. Results for failure probability and turbine availability in the wake scenario

In the following, results for failure probabilities and availability losses regarding the rotor hub, consisting of hub, main bearing and no rotor blades, are presented. The hub unit was assumed to be cast iron with S-N-curve slope of $m = 5$ [19] and empirical standard deviation for lognormal failure distribution of $\hat{\sigma} = 0.30$ [16]. The authors decided to focus on the rotor hub due to the fact that metal is an isotropic material and is independent of the loading direction. Following Pfaffel et al. [4] a mean down time per hub unit failure of 6.67 d was used to calculate availability losses. Figure 6 shows simulation results, theoretical material curves and failure probability calculation. The results are based on a horizontal distance between turbine 1 and turbine 2 of $\Delta s = 4D$ and $\Delta s = 6D$ respectively. For both distances load case A represents the free stream condition. When comparing simulation results for case A to those of case B (left curve pair) higher load cycles at high load amplitudes are observed. Additionally, the maximum load amplitude increases from case A to case B. The increased load cycles at high load amplitudes in case B result in a material curve which is shifted to the left to higher load cycles. This means reaching theoretical design lifetime without failure requires enhanced material fatigue behavior. Vice versa, in case of constant material properties failure becomes more likely. In terms of actual values the wake effect (case B) results in a failure probability of $P_{f,\text{hub}}^{B} = 21.43\%$ for a wake at $4D$ and $P_{f,\text{hub}}^{B} = 9.51\%$ at $6D$.

Additionally, the wake condition at $3D$, $5D$ and $7D$ were simulated. The calculated failure probabilities for each load component at the rotor hub unit are shown in figure 7. The high turbulence intensities in near wake lead to high load amplitudes and cycle counts which result in higher failure probabilities. Especially hub pitch and hub yaw moment show significantly higher probabilities in case B compared to case A. A quadratic relation between failure probability and horizontal distance $\Delta s$ can be observed. This can be traced back to Frandsen’s wake model.
Figure 6: Hub pitch moment $M_y$: Simulation results (curves to the left), theoretical material curves (in the center) and failure probabilities (small graph) for case A (solid) as well as case B (dashed); horizontal distance between turbines of $\Delta s = 4D$ in (a) and $\Delta s = 6D$ in (b).

Figure 7: Failure probabilities for every load component at the rotor hub unit; highest failure probabilities are observed for pitch and yaw moments $M_y$ and $M_z$; failure probabilities increase more or less quadratic with decreasing distance $s$.

Figure 8: Calculated availability losses due to hub failure for multiple horizontal distances between turbines and both cases (solid); reference availability loss due to hub system failure from literature [4] (dashed).

which determines the inflow turbulence depending on the square root of the undisturbed wind speed.

Subsequently, for the five horizontal distances maximum failure probability is determined and used in combination with a mean down time taken from Pfaffel et al. [4] to calculate availability.
losses according to equations 8 to 10. It should be mentioned that only the highest of failure probabilities of all degrees of freedom is considered (e.g. 21.43% for the whole hub unit at $\Delta s = 4D$). It is assumed that the component failure occurs as a result of the load component with the highest failure probability. The results are shown in figure 8. In addition, also a mean availability loss is derived from the data in [4] and represented by the dashed line in figure 8. Comparing simulation results to [4] enables the possibility for a validation of the proposed approach. With an average availability loss of $\Delta a_{i}^{\text{ref}} = 0.011\%$ literature data is of the same magnitude as simulation results. The database considered by Pfaffel et al. includes over 4,300 individual wind turbines, taken from research by the University of Zaragoza called CIRCE. Unfortunately, there is no detailed information on distances between the turbines given in [4]. However, assuming an average distance between turbines of $s = 4D...5D$, common value for inner wind farms spacing, the findings seem accurate and are a good approximation. In table 2 simulation results and calculations for the wake scenario are summarized. Compared to other components of a wind turbine (e.g. electrical components), the loss of availability does not occur relevant. However, the electrical components do not break down due to a similar origin. And an holistic perspective should be taken to increase the interests of wind energy.

6. Conclusion and future research

In this paper an approach was introduced to determine the reduction in availability due to a wake inflow onto a turbine. The model showed the expected behavior that a wind turbine in a near wake field is more likely to experience an early fatigue failure than the one in a far wake. Leading to an aspect that the inner spacing should be considered not just due to wake losses but also due to introduced loading. In the case study at $4D$ distance and $20\%$ amount of time inside a wake the losses are rather low. However with increased amount of time, closer spacing and partial wake loading, the availability will be reduced even further. Thereby, possibly resulting in an economical inefficient project.

The model can be further improved by considering a mean stress correction and the overall precision. Also the model can be improved by integrating non-metallic components. This was not achieved due to the lack of data regarding mean load influence as well as the fact that non-metallic components vary their behavior due to load and material orientation. However, the model is computationally fast and can be used in a wind farm optimization. The reduction of availability will influence the annual energy production and logically the levelized cost of energy.

Table 2: Summary of simulation results in form of failure probabilities; mean down time is taken from literature [4]; availability losses are calculated using equation 10

| system component $i$ | distance $s$ | critical load $s$ | $P_{f,i}^A$ [%] | $P_{f,i}^B$ [%] | $t_{f,i}$ [d] | $\Delta a_{i}^A$ [%] | $\Delta a_{i}^B$ [%] | $\Delta a_{i}^{A-B}$ [%] |
|----------------------|--------------|------------------|----------------|----------------|----------------|------------------|----------------|------------------|
| hub                  | $3D$         | $M_y$            | 2.30           | 41.85          | 6.67           | 2.10 E-3         | 3.66 E-2        | 3.45 E-2         |
| hub                  | $4D$         | $M_y$            | 2.30           | 21.43          | 6.67           | 2.10 E-3         | 1.75 E-2        | 1.54 E-2         |
| hub                  | $5D$         | $M_y$            | 2.30           | 11.55          | 6.67           | 2.10 E-3         | 6.49 E-3        | 4.39 E-3         |
| hub                  | $6D$         | $M_y$            | 2.30           | 9.51           | 6.67           | 2.10 E-3         | 4.83 E-3        | 2.73 E-3         |
| hub                  | $7D$         | $M_y$            | 2.30           | 6.49           | 6.67           | 2.10 E-3         | 2.71 E-3        | 6.10 E-4         |

| system component $i$ | distance $s$ | critical load $s$ | $r_{f,i}$ [a$^{-1}$] | $t_{f,i}$ [d] | $\Delta a_{i}^{\text{ref}}$ [%] |
|----------------------|--------------|------------------|------------------|----------------|------------------|
| hub                  | -            | -                | 0.006           | 6.67           | 1.10 E-2         |
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