Post processing of Design Load Cases using Pdap

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Post processing of Design Load Cases using Pdap

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Pdap provides functions for post-processing and documentation of a set of hawc2 result files, e.g. a full design load case. This report describes the input and its syntax, the mathematical foundation and the output in terms of statistic files and standard reports.
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1. Summary
Pdap provides functions for post-processing and documentation of a set of hawc2 result files, e.g. a full design load case.

This report describes the input and its syntax, the mathematical foundation and the output in terms of statistic files and standard reports.
2. Introduction

Pdap, Python Data Analysis Program, is a program for post processing, analysis, visualization and presentation of data e.g. simulation results and measurements[1]. It provides a toolbox for post processing of a set of HAWC2 result files, e.g. a full design load case, that includes:

- Extraction of sensor statistics
- Ultimate (extreme value) analysis
- Fatigue analysis

The Pdap post processing functions take as input an excel workbook and generates a statistic file for each sensor specified in the input workbook. Based on these files, report elements or a full standard report can be generated.
3. Post processing input workbook
The post processing input workbook contains three sheets:

- DLC
- Sensors
- Variables

1. The DLC sheet

<table>
<thead>
<tr>
<th>Column name (case insensitive)</th>
<th>Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>DLC</td>
<td>DLC group id</td>
<td>“11”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“dlc22b”</td>
</tr>
<tr>
<td>Load</td>
<td>Include in ultimate (extreme) analyses and/or fatigue analysis.</td>
<td>“U”: Include in ultimate analysis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“F”: Include in fatigue analysis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“FU”, “F/U”, “F,U”: include in both</td>
</tr>
<tr>
<td>PSF (optional)</td>
<td>Partial safety factor</td>
<td>“1”: Max and min values is used directly</td>
</tr>
<tr>
<td></td>
<td>Safety factor for ultimate analysis related to this dlc group. Default is 1</td>
<td>“1.3”: Max and min values are multiplied with 1.3 in ultimate analysis</td>
</tr>
<tr>
<td>WSP</td>
<td>Wind speed [m/s]</td>
<td>See xxx</td>
</tr>
<tr>
<td>-------------</td>
<td>------------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>DLC_dist</td>
<td>Fatigue dlc distribution.</td>
<td>See xxx_dist</td>
</tr>
<tr>
<td>WSP_dist</td>
<td>Fatigue wind speed distribution</td>
<td>See xxx_dist</td>
</tr>
<tr>
<td>xxx(optional)</td>
<td>Values distributed by xxx_dist</td>
<td>• “0”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• “0:15:345”: 0,15,30,…,345</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• “0/350/10”: 0,350,10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• “0,350,10”: 0,350,10</td>
</tr>
<tr>
<td>Variables</td>
<td></td>
<td>Variables defined at the Variables sheet may be used, e.g. (x=10):</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• “x/x+2/x-2”: 10,12,8</td>
</tr>
<tr>
<td>xxx_dist(optional)</td>
<td>Fatigue distribution of values in xxx</td>
<td>• “80/10/10”: 80% at first value, 10% at second and third values</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• “Weibull”: see wind distribution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• “Rayleigh”: see wind distribution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• “#1000/#50/#50”: 1000 x first value pr. Year, 50 x second and third wsp pr year. (e.g. 1000 startups at Vin, 50 at Vr and 50 at Vout)</td>
</tr>
</tbody>
</table>

### Wind distribution

For wind speeds specified in the “start:step:stop” format, e.g. “4:2:26”, the “Weibull” or “Rayleigh” tags can be used in the wsp_dist column. Both tags yields the probability:

\[
P(wsp) = e^{-\left(\frac{wsp \cdot \text{step}}{2u} \right)^2} - e^{-\left(\frac{wsp+\text{step}}{2u} \right)^2}
\]

Where:

- \(u\): 0.2Vref
- \(Vref\): Reference wind speed of the wind class, defined at the Variables sheet
- \(wsp\): each wind speed, e.g. 4,6,8,…,26
- \(\text{step}\): The step between wind speeds, e.g. 2

### Optional distributions

A number of optional values and corresponding distributions may be added. The order of these columns must be similar to the order of the tags in the filename.
Typical values and distributions are wind direction, wake direction etc.

For each xxx of these the sheet must have a “xxx”-column and a corresponding “xxx_dist”-column.

**Probabilities**

A group is a set of files that has the same values in the distribution tags, i.e. dlc, wsp and xxx, but different values in the tags that are not specified with a distribution in the sheet, e.g. seed etc.

The probabilities of a group are the product of the xxx_dist-probabilities calculated from right to left until all distribution probabilities have been multiplied or a “#xxx” value is seen.

“#xxx”, e.g. “#1000” means 1000 of this simulation pr. year. I.e. the probability is the length of the simulation in seconds, len(file), divided by number of seconds pr. year, $S_{PR\_YEAR}$. In this case all files in the same group must have the same length.

The probability of each file in the group is the probability of the group divided by the number of files in the group ($Nfiles$).

<table>
<thead>
<tr>
<th>Dlc</th>
<th>Dlc_dist</th>
<th>Wsp</th>
<th>Wsp_dist</th>
<th>Wdir</th>
<th>Wdir_dist</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>2</td>
<td>4/12/25</td>
<td>90/5/5</td>
<td>350/0/10</td>
<td>25/50/25</td>
<td>dlc31_wsp04_wdir350: 0.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.9 0.02/Nfiles</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>dlc31_wsp12_wdir000: 0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.05 0.02/Nfiles</td>
</tr>
<tr>
<td>31</td>
<td>50</td>
<td>4/12/25</td>
<td>#1000/#50/#50</td>
<td>0</td>
<td>100</td>
<td>dlc31_wsp04_wdir000: 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1000-len(file)/$S_{PR_YEAR}$/Nfiles</td>
</tr>
</tbody>
</table>

Note that the dlc probability is ignored as it comes after “#1000” read from right to left.
2. The Sensors sheet

The Sensors sheet defines the desired sensors for the analysis.

<table>
<thead>
<tr>
<th>Column name (case insensitive)</th>
<th>Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Name of postprocessing sensor.</td>
<td>“Power”</td>
</tr>
<tr>
<td></td>
<td>The names must be unique.</td>
<td>“MxBR”</td>
</tr>
<tr>
<td></td>
<td>It is recommended to choose a short and descriptive name</td>
<td></td>
</tr>
<tr>
<td>Nr</td>
<td>Sensor number in result files. Note that a certain sensor, e.g. Power, must have the same channel number, e.g. 90, in all results files.</td>
<td>“90”</td>
</tr>
<tr>
<td></td>
<td>More sensors can be combined into a single postprocessing sensor, e.g. the blade root moments of the three blades</td>
<td>“(26,32,38)”</td>
</tr>
<tr>
<td>Description (optional)</td>
<td>Description of the sensor</td>
<td>“Electrical power”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“Blade root flap”</td>
</tr>
<tr>
<td>Unit (optional)</td>
<td>Unit of sensor</td>
<td>“W”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“kNm”</td>
</tr>
<tr>
<td>Statistic (optional)</td>
<td>Defines which sensors to include in the statistic table and plots, see section 6. A nonempty field includes the sensor in the statistic table</td>
<td>“”: Exclude</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“x”: Include</td>
</tr>
<tr>
<td>Feature</td>
<td>Description</td>
<td>Values</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-----------------------------</td>
</tr>
</tbody>
</table>
| Ultimate (optional) | Defines which sensors to include in the extreme table and plots, see section 6. A nonempty field includes the sensor in the extreme table and plots, while an empty field excludes the sensor | “” : Exclude  
“x” : Include |
| Fatigue (optional) | Defines which sensors to include in the fatigue table and plots, see section 6. A nonempty field includes the sensor in the fatigue table and plots, while an empty field excludes the sensor | “” : Exclude  
“x” : Include |
| M (optional)     | Wöhler slope coefficient for fatigue analysis                               | “4”  
“10” |
| NeqL (optional)  | Lifetime equivalent load number for fatigue analysis                         | “1E+7”  
“1000000” |
| ExtremeLoad      | Defines which sensors to include in the extreme load table, see section 6.  
A nonempty field includes the sensor in the extreme load table, while an empty field excludes the sensor.  
The corresponding “Nr”-field must contain 6 numbers specifying the Fx, Fy, Fz, Mx, My, Mz sensor numbers | “” : Exclude  
“x” : Include |
3. The Variables sheet

The Variables sheet defines variables required for the post processing as well as custom variables used in the DLC sheet.

The first column specifies the name of the variables and the second column their values.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>res_path</td>
<td>Path to the folder that contains the result files or subfolders with result files</td>
<td>“res”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“iec_res”</td>
</tr>
<tr>
<td>no_bins</td>
<td>Number of bins for fatigue analysis</td>
<td>“46”</td>
</tr>
<tr>
<td>m_list</td>
<td>List of Wöhler slope coefficients for the fatigue analysis. A eqloadxx sensor will be added to the statistic files for each value in the list</td>
<td>“3,4,6,8,10,12” (default)</td>
</tr>
<tr>
<td>res_folder</td>
<td>Name pattern for result subfolders. If “%s” in the res_folder value, then “%s” will be replaced with the dlc group id</td>
<td>“”: No sub folder (default)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“DLC%s_IEC61400-1ed3”</td>
</tr>
<tr>
<td>Vref</td>
<td>Reference wind speed of the wind class</td>
<td>“50”</td>
</tr>
<tr>
<td>X</td>
<td>Custom variables used at the DLC sheet, e.g. ‘Vin’</td>
<td>“10”</td>
</tr>
</tbody>
</table>
4. Statistic files

4. Generating statistic files

From Pdap statistic files are generated via the “Make sensor statistic files” (menu – DLC – Make sensor statistic files).

This function opens a dialog requesting the DLC input file (workbook) and generate a statistic file for each post processing sensor, see figure below.

The statistic files are saved in the folder: <res_path>/stat/<sensor name>.h5

The files can be loaded, viewed and plot via Pdap.

5. Naming convention

When generating the statistic files via the menu, the default parameters are used (use scripting to apply with custom parameters). This means that the result files must obey to the following standard naming convention to be found by the fatigue analysis function:

Filename: dlcxxx_wsp00_wdir000*.sel

dlc: group id, e.g.: 11, 22b
wsp: wind speed [m/s]
wdir: wind direction % 360 [deg]

Examples of valid filenames:
dlc11_wsp04_wdir350_s1001.sel
dlc22b_wsp04_wdir000.sel
6. Contents of statistic files

The statistic files contain the following attributes

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>filename</td>
<td>Filename of result file. Combined with description, the full path is obtain. Special “file” unit, see select dataset plot</td>
</tr>
<tr>
<td>name</td>
<td>Case id</td>
</tr>
<tr>
<td>Dlc</td>
<td>Dlc group id</td>
</tr>
<tr>
<td>wsp</td>
<td>Wind speed</td>
</tr>
<tr>
<td>wdir</td>
<td>Wind direction</td>
</tr>
<tr>
<td>min</td>
<td>Minimum value</td>
</tr>
<tr>
<td>mean</td>
<td>Mean value*</td>
</tr>
<tr>
<td>max</td>
<td>Maximum value</td>
</tr>
<tr>
<td>std</td>
<td>Standard deviation**</td>
</tr>
<tr>
<td>weight</td>
<td>Weight of case, see weight calculation example</td>
</tr>
<tr>
<td>eqload</td>
<td>Short term equivalent load, i.e. range of 1Hz signal that results in equivalent load</td>
</tr>
<tr>
<td>Neq</td>
<td>Equivalent load number, i.e. number of 1Hz cycles (duration of simulation in cycles)</td>
</tr>
</tbody>
</table>

* For sensors measured in degrees or radians (lowercase(unit) = “deg” or “rad”) the mean is calculated by:

\[
\text{mean}(x) = \text{atan2} (\text{mean} (\sin(x)), \text{mean} (\cos(x)))
\]

** For sensors measured in degrees or radians (lowercase(unit) = “deg” or “rad”) the std is calculated by:

\[
\text{std}(x) = \sqrt{1 - \text{mean}(\sin(x))^2 + \text{mean}(\cos(x))^2}
\]

7. Select dataset plot
The special “file” unit of the filename attribute enables the “Select dataset plot” option (right click on sensor – Plot – Select dataset plot).

In this plot the file name is seen next to the cursor position in the right side of the cell toolbar and the dataset (result file) represented by a dot, can be opened by right-clicking the dot, see figure below.

5. Fatigue analysis

8. Short term equivalent load, stel

\[ stel = \left( \frac{\sum n_i S_i^m}{N_{eq}} \right)^{1/m} \]

Where

\( n_i \): Number of cycles with range \( S_i \)

\( m \): Wöhler slope

\( N_{eq} \): Length of simulation in seconds

9. Life time equivalent load

\[ Life \, time \, equivalent \, load = \left( \frac{\sum stel^m \cdot N_{eq} \cdot weight}{N_{eq}L} \right)^{1/m} \]

Where
**stel**: Short term equivalent load, see above

**m**: Wöhler slope

**Neq**: Length of simulation in seconds

**weight**: See below

**NeqL**: Lifetime equivalent load number as defined in the “Sensor” sheet

**Weight calculation**

The weight specifies how many times a result file should be included in 20 years of operation.

Example 1: dlc11_wsp04_wdir000_s1001

First calculate the probability of the case:

\[
P(\text{case}) = P(\text{dlc11}) \cdot P(\text{wsp}) \cdot P(\text{wdir}) = 0.975 \cdot 0.213 \cdot 0.5 = 0.105
\]

As

\[
P(\text{wsp}) = e^{-\left(\frac{\text{wsp} + \text{step}}{2}\right)^2} - e^{-\left(\frac{\text{wsp} - \text{step}}{2}\right)^2} = e^{-\left(\frac{\text{wsp} - \text{step}}{2\cdot0.2\cdot10}\right)^2} - e^{-\left(\frac{\text{wsp} + \text{step}}{2\cdot0.2\cdot10}\right)^2}
\]

\[
= 0.967 - 0.754 = .215
\]

Then the number of hours in 20 years of this case

\[
\text{Hours(\text{case})} = P(\text{case}) \cdot \frac{\text{hours}}{\text{20year}} = 0.105 \cdot 20 \cdot 365 \cdot 24 = 18194
\]

And finally the weight of each file is calculated based on the length of the file (=600s) and the number of files for this case (=2), i.e. same dlc, wsp and wdir, but different seed.

\[
\text{Weight(\text{case})} = \text{hours} \cdot \frac{\text{3600sec/hour}}{\text{len(\text{case})} \cdot \text{files pr \text{ case}}} = 18194 \cdot \frac{3600}{600 \cdot 2} = 55181
\]
6. Report elements
From the generated statistic files some standard report elements, see sections below, can be generated.

The report elements can be generated separately (menu – DLC – Report element – xxx) or all together (menu – DLC – Full standard report).

Sensor table
The sensor table gives an overview of the postprocessing sensors, including names, units and descriptions

<table>
<thead>
<tr>
<th>Nr</th>
<th>Name</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>MxTB</td>
<td>kNm</td>
<td>Tower bottom fore-aft</td>
</tr>
<tr>
<td>(26,32,38)</td>
<td>MxBR</td>
<td>kNm</td>
<td>Blade root flap</td>
</tr>
<tr>
<td>90</td>
<td>Power</td>
<td>W</td>
<td>Electrical power</td>
</tr>
<tr>
<td>(23,24,25,20,21,22)</td>
<td>TT</td>
<td></td>
<td>Tower top</td>
</tr>
</tbody>
</table>

10. Statistic table
The statistic table shows the minimum, mean and maximum values

<table>
<thead>
<tr>
<th>Name</th>
<th>Min</th>
<th>Mean</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>-1.92E-02</td>
<td>7.91E-02</td>
<td>1.26E+00</td>
</tr>
</tbody>
</table>

Statistic plots
The statistic plots show the min, mean, max and std(separate plot) of each result file as function of wind speed

![Statistic plots graph]
**Extreme table**
The extreme table shows the minimum and maximum values including partial safety factor found in any ultimate analysis files as well as the id of the file where the value is found.

Ultimate analysis files are the result files of the dlc groups that have a “U” in the “Load” column of the DLC sheet.

<table>
<thead>
<tr>
<th>Name</th>
<th>Min incl. psf</th>
<th>Max incl. psf</th>
<th>DLC min</th>
<th>DLC max</th>
</tr>
</thead>
<tbody>
<tr>
<td>MxTB</td>
<td>-8.36E+04</td>
<td>1.26E+05</td>
<td>14_wsp10_wdir000</td>
<td>14_wsp10_wdir000</td>
</tr>
<tr>
<td>MxBR</td>
<td>-2.07E+04</td>
<td>1.56E+04</td>
<td>14_wsp10_wdir000</td>
<td>14_wsp10_wdir000</td>
</tr>
</tbody>
</table>

**Extreme plots**
The extreme plots consist of different plots showing extreme values including partial safety factor of the ultimate analysis files.

The first shows the min, mean and max values of all result files as function of wind speed.

Then two bar charts shows the 10 most extreme values and the id of the corresponding result files
Finally two pages shows the maximum and minimum values respectively. In this case the dlc main group, i.e. 1x, 2x, ... are shown in individual plot and dlc sub groups, e.g. 11, 14, ... are marked with different colors.

**Fatigue table**
The fatigue table shows the Life time equivalent load and the corresponding m and Neq values.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Life time equivalent load</th>
<th>m</th>
<th>neq</th>
</tr>
</thead>
<tbody>
<tr>
<td>MxTB</td>
<td>5.488E+04</td>
<td>4</td>
<td>1E+07</td>
</tr>
<tr>
<td>Mx8R</td>
<td>1.341E+04</td>
<td>10</td>
<td>1E+07</td>
</tr>
</tbody>
</table>

**Fatigue plot**
The fatigue plot consist of three different plots. The first is a pie chart showing the amount of damage in percent caused by each dlc group included in the fatigue analysis, i.e. groups that have a “F” in the “Load” cell in the DLC sheet.
The next plot shows the short term equivalent load of each result file as function of wind speed. DLC groups are separated by colors.

The last plot shows the amount of damage caused by each DLC group for each wind speed.

**Extreme load table**
The extreme load table shows the minimum and maximum loads (forces and moments) as well as the id of the result file in which the load occurs. In addition the values of the other sensors of the observation where the extreme occurs are listed.

<table>
<thead>
<tr>
<th>Loadcase</th>
<th>Loadcase</th>
<th>SF</th>
<th>Fx</th>
<th>Fy</th>
<th>Fz</th>
<th>Fres</th>
<th>Mx</th>
<th>My</th>
<th>Mz</th>
<th>Mres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>dlc11_wsp04_wdir350_s5001</td>
<td>1</td>
<td>+3.4E+02</td>
<td>+4.3E+01</td>
<td>+3.5E+03</td>
<td>+1.5E+02</td>
<td>+8.8E+02</td>
<td>+8.1E+02</td>
<td>+3.8E+02</td>
<td>+1.4E+02</td>
</tr>
<tr>
<td>Min</td>
<td>dlc14_wsp10_wdir000</td>
<td>1</td>
<td>-1.7E+02</td>
<td>-3.4E+02</td>
<td>+3.4E+03</td>
<td>+1.3E+03</td>
<td>+4.2E+03</td>
<td>+4.5E+03</td>
<td>+4.4E+03</td>
<td>+6.6E+03</td>
</tr>
<tr>
<td>Max</td>
<td>dlc11_wsp12_wdir350_s5005</td>
<td>1</td>
<td>+2.8E+00</td>
<td>+1.2E+03</td>
<td>+3.5E+03</td>
<td>+1.2E+03</td>
<td>+7.0E+02</td>
<td>+4.0E+03</td>
<td>+1.5E+01</td>
<td>+4.1E+03</td>
</tr>
<tr>
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References

DTU Wind Energy is a department of the Technical University of Denmark with a unique integration of research, education, innovation and public/private sector consulting in the field of wind energy. Our activities develop new opportunities and technology for the global and Danish exploitation of wind energy. Research focuses on key technical-scientific fields, which are central for the development, innovation and use of wind energy and provides the basis for advanced education at the education.

We have more than 240 staff members of which approximately 60 are PhD students. Research is conducted within nine research programmes organized into three main topics: Wind energy systems, Wind turbine technology and Basics for wind energy.