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Boundary Conditions for Water Tightness Testing Based on Pareto-Front Analysis

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ABSTRACT

The predominant boundary conditions for evaluating watertightness of a wall are pressure difference across and water spray rate on the wall. However, the relation between these key climatic effects as defined in standards or actual weathering conditions remain, as yet, undefined. A comprehensive calculation method to define correct boundary conditions based on extreme value analysis of wind and rain events has been developed, however, the method relies, to an extent, on the statistical independence of these events. Hence, the calculation of the return period for wind-driven rain loads on buildings has up to now required unverified and perhaps uncertain assumptions concerning the co-occurrence of wind and rain events; this necessarily affects the calculation of results for wind-driven loads. In this paper a new methodology is presented that was developed to derive boundary conditions for watertightness testing based on Pareto-front analysis of meteorological data. The method takes into account actual combinations of rain and wind without making assumptions regarding the co-occurrence of wind and rain events, and thereby allows calculating realistic boundary conditions for different return periods. This method was developed based on only one climate database, and necessarily should be validated for a broader range of climates and return periods. As well, the Pareto-based methodology only offers information for the specific averaging period of a given climate database. The conversion to shorter time periods for both wind and rain again introduces assumptions on the co-occurrence of extremes.

Keywords: boundary conditions, meteorological data, Pareto-front analysis, rain, wall, watertightness, wind

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Introduction

Many of the standards and codes related to watertightness testing of building components in use today were prepared several decades ago and have not taken into consideration the significant research efforts over recent years on quantifying wind pressure loads, wind driven rain (WDR) and wetting intensities on buildings and facades: probably these studies might add information to adjust or optimize the existing test methods. Furthermore, apart from the testing methodology, different types of performance criteria have been established in different countries. Depending on the specific standard and country, these criteria take into account parameters affecting climatic loads on building facades including, e.g. building height, location, shielding, location on the building, building geometry, return period, building typology. Irrespective of the broad spectrum of research on this topic, little information is available concerning the scientific basis for watertightness test methods.

Existing watertightness test methods can be categorized into four distinct classes: static, cyclic, dynamic, and wind tunnel testing (these categories are further described in a subsequent section). Within watertightness test methods a pass-fail criterion for performance assessment is typically specified; e.g., a test specimen typically fails when water infiltrates past a specific boundary. Consequently, it is of significant importance that the test conditions be representative of real meteorological conditions to which a test specimen will be subjected during its lifetime. In the four classes of watertightness testing methods different types of performance requirements are stated, each with a specific set of boundary conditions. The degree to which boundary conditions specified in existing watertightness test methods coincide with actual weather conditions has not yet been studied in depth.

Ideally, a reliable test protocol would require a range of different test sequences to assess the susceptibility of a test specimen to different types of weather conditions. On one hand there is a difficult balance between establishing test conditions to assess the performance of a component over its service life, and those conditions that can practically be achieved in a test facility. On the other hand there is also a balance between creating a test method that comes close to simulate realistic boundary conditions and a test method that is practical and thus economically viable in a laboratory setting.

Most publications related to watertightness performance assessment focus on the fundamental physics of WDR based on physical measurements and computer simulations. In some cases the research results are demonstrated by specific case-studies or a general methodology is developed to calculate the WDR on a specific building. However, the relation between the calculated wind loads, WDR and a testing methodology is in most cases not made explicit. Sahal and Lacasse (2008) developed a very useful methodology for calculating water penetration test parameters of wall assemblies, based on the work of Mayo (1998a, 1998b, 1998c) as well as that undertaken at the NRC-IRC (Cornick et al. 2002) which itself was based on the methodology of Choi (1998), and research by Straube and Burnett (2000). An extension of the methodology and application was presented by Cornick and Lacasse (2009). However, although this methodology is useful and consistent, it does not allow integrating additional information generated by simulations of wind loads and WDR or on-site testing, and it can only be used if a certain set of climatic data is available.

In this paper a review of watertightness test standards is offered as a basis for determining the current level of practice in industry and whether these indeed offer realistic boundary conditions to assess the performance of wall systems and components. Thereafter is provided a summary of a proposed method developed by Cornick and Lacasse (2009) to determine boundary conditions for watertightness testing. Given that this method presumes the independence of the occurrence of wind and rain events, a brief overview of literature on their co-occurrence is then offered. Following which a further elaboration on the suggested methodology is presented and an approach for its use is given as well as an example of its application to development of boundary test conditions for a 30m building located in a coastal setting in Belgium.

Watertightness test standards

The first three test methodologies provided in standards, that is static, cyclic and dynamic pressure methods, use a similar approach: wind and rain are decoupled and treated independently. Wind effects are represented by pressure differences generated by a fan, and rain is provided by means of a water spray system in front of the test specimen. Conversely, the fourth test method, which is based on an integrated approach in a wind tunnel, and for which water is not sprayed directly on the test specimen itself contrary to that presented in the previous test methods. In this instance, rain drops are released in the air stream that flows over the test element to simulate raindrop trajectories.

An extensive overview of static, cyclic and dynamic watertightness test standards was presented by Sahal and Lacasse (2008), where the test conditions of 14 test methods were discussed elaborately. These standards typically prescribe a uniform static water spray rate: 2.0L/min-m² in Europe; and 3.4L min-m² in North America.

Test standards using static pressure methods

Most static watertightness test standards require a static pressure difference for a period of time (in the range 5 to 15 minutes), which is stepwise augmented to assess the performance level of a component (e.g. EN 1027:2000 – see figure 1; CWCT, 2006). Classification is done based on the pressure difference achieved without water ingress, and the classes correspond to a pressure difference in the range 0 to 1200Pa. The required level of performance for a component in a specific building is typically incorporated in National guidelines for each country. It should be noted that some tests (e.g. E514:2009) only require one pressure difference level throughout the whole test, and only allow a pass-fail evaluation.

Test standards using cyclic pressure methods

Test standards in which cyclic tests are prescribed within the test protocol are undertaken by subjecting the test specimen to rapid pressure pulses; the pressure fluctuation of these pulses is typically either a rectangular function or a sine-wave function (Figure 2). The duration of one pulse varies depending on that given in the standard (range 2s – 15s) and these pulses are repeated for a period of 10 minutes (EN 12865:2001, ASTM E2268:2004, ISO 15821:2007). The pressure levels and their corresponding lower and upper limits of pressure for a pulse are also provided in the standards. A lower limit of zero is only set in the EN 12865:2001. A practical advantage of a zero value for the lower limit is that this simplifies the test apparatus. On the other hand, EN 12865:2001 is also the only standard that incorporates a stepwise approach for performance assessment, similar to most static test standards. The applied range of upper limit pressure differences is similar to those of the static tests.

Test standards using dynamic pressure methods

Contrary to the cyclic tests where the pressure fluctuation is carefully prescribed, the dynamic test protocols use an axial flow fan, installed close enough to the test specimen to generate a turbulent flow field. AAMA 501.1:2005 describes a test setup with a standard water spray rack, but with a fan up to 4.1m diameter such as an aircraft propeller (figure 3). The standard describes a calibration protocol to measure the peak gust wind velocities at the surface of the specimen, corresponding to industry standard test pressures in the range 300 – 720Pa. ENV 13050:2001 specifies a combination of cyclical testing (5s pulses) and an axial fan in a 600mm diameter rigid duct that is moved upwards along the sample (figure 4). Furthermore, rain is simulated by a single spray nozzle on top of the axial fan. Only one publication was found on standardized dynamic testing, which does not allow concluding whether the AAMA 501.1 test with aero-engine is sufficiently reproducible.

The fourth type of testing is basically designed for roof coverings of pitched roofs, but the methodology can be applied to any building component. FprEN 15601:2009 describes a test protocol where the interior side of the specimen is depressurized, with a fan system capable of generating a horizontal or inclined wind flow over the test specimen. Contrary to the other test standards, here water droplets are introduced into a high velocity air stream far enough from the test specimen which allows the droplets to achieve the required velocity prior to impact. Consequently this is the most realistic effect of the actual weather conditions that may act over a wall or roof element. Next to that, a test sequence consists of sub-tests, which represent different types of weather conditions (e.g. low wind speed with high rainfall rate). Note that the standard provides 5 examples of different test configurations for the same test, and it is stated explicitly that the test results depend on the specific test setup. Finally, the document FprEN 15601:2009 has the status of technical document: the final vote of the draft was unsuccesfull because of the implicit low reproducibility of the test results.

In reviewing the different test methods presented above, it can be stated that in these standards the water spray rate is held constant, the pressure difference is varied, and of the first three types of tests, the interaction of rain and wind is simplified by spraying water from close range onto the test specimen. In none of these standards is information provided on droplet velocity. Consequently, one needs to assess whether the degree of wind, rain and the interaction between wind and rain is of importance to the results of watertightness testing. It has been clearly established that pressure difference is one of the most important parameters to test the watertightness of building components (Lacasse et al. 2003, 2009; Van Den Bossche et al., 2008, 2009a, 2009b;

Mayo 1998a, 1998b, 1998c; Chew, 2001). The effect of the intensity of water spray rate on the results of watertightness testing of building components is an ambiguous situation. According to Sacré (1984), the spray rate will not be a determining factor as to whether or not a component is watertight, but it will indeed affect the quantity of water that enters into the construction once infiltration is established. The latter assumption was confirmed for, e.g., curtain walls (Mayo, 1998c), hardboard sidings (Sahal and Lacasse, 2005) and masonry brick walls (Selvarajah and Johnston, 1995). The amount of water deposited onto the test specimen can thus have a significant effect in constructions where the drainage capacity determines the performance. Whether or not the raindrop trajectories have a significant effect is currently unclear. The only publication known to the authors on the effect of droplet velocity has offered inconclusive information regarding the importance of raindrop trajectories on watertightness (Maerker, 1983).

The different test methods are listed according to their supposed ability to produce realistic boundary conditions that relate to actual extreme weather conditions. However, a higher degree of complexity for testing in turn brings about an increase in the cost of testing, and perhaps the repeatability and reproducibility of test conditions are likewise problematic. Although interesting and very promising research on new dynamic test methods has been published (Kopp et al., 2010; Bitsuamlak et al., 2009; Salzano et al., 2010), these have typically focus on hurricane risk mitigation, and it remains to be determined whether these test methodologies are too complex to be viable for routine testing of building components. At present, the most practical and efficient test method that could incorporate realistic boundary conditions is perhaps a combination of static and cyclic testing. Both introduce a different kind of performance requirement of the test specimen that might induce different types of failure.

For every test method one needs to define the boundary conditions for testing. If we consider static testing, only the water spray rate, pressure difference and test duration are necessary. For cyclic testing, information is required to define the pulses; specifically, lower and upper pressure limits, and pulse duration (i.e. frequency). These dynamic testing protocols should generate pressure fluctuations on the surface of the sample that correspond to typical turbulence effects on a building.

The test conditions for static and cyclical testing are currently insufficiently documented in relation to meteorological conditions; as a result, this has tended to induce arbitrary choices in respect to the required performance levels in watertightness testing.

Calculation of boundary conditions for watertightness testing

Cornick and Lacasse (2009) have extended the test protocols by Sahal and Lacasse (2008), Cornick and Lacasse (2005) and Choi (1998). This methodology only offers information on defining the boundary conditions for static testing. The design of a watertightness test protocol can be summarized as follows:

Step 1 – Collection of historical climate data hourly wind speed and hourly horizontal rainfall intensity.

Step 2 – Calculation of Wind Driven Rain (WDR: rainfall intensity on a vertical surface of a building [mm/h]) using the method recommended by Straube and Burnett (2005) for every data point:

Step 6 – Modify the loads for the RAF: the WDR was calculated based on a RAF = 1, which corresponds to e.g. a top corner position of a building according to Straube and Burnett (2005).

Step 7 – Modify the loads for the wind speed, taking into account surroundings and height. This can be calculated with the standard formulas in wind codes: power law in ASCE 7-95, logarithmic in the Eurocode (EN 1991-1-4:2005).

Step 8 – Calculate the rainfall intensity for shorter periods using following equation (Linsley et al, 1975):

Pareto-front analysis

Cornick and Lacasse (2009) already stressed the importance of assumptions concerning the co-occurrence of rain and wind, or WDR and DRWP. The validity of their assumption of statistical independence is uncertain, but no evident alternative was then apparent. Information from the previously provided brief review on the co-occurrence of wind and rain wind clearly shows that peak wind speeds do not necessarily coincide with peak rainfall intensities. However, no general guidelines have yet been derived to calculate coinciding extreme events, as these seem to be very sensitive to the geographical location and local weather systems. Therefore, a new methodology is developed to derive boundary conditions for watertightness testing based on Pareto-front analysis of meteorological data.

Pareto-analysis is a concept derived from economics, where Pareto efficiency is defined by solutions which are optimized to every parameter without a decrease in efficiency for other parameters. In engineering it is typically used in multi-criteria optimization, where there are multiple, potentially dependent and conflicting objectives. The collection of Pareto points (Pareto-optimal solutions) thus captures the available trade-offs between the different objectives. The calculation of boundary conditions for watertightness testing is an ideal situation to apply Pareto-analysis, as the relative weight of the criteria (wind and rain) cannot be defined.

Assuming that a large amount of data is available (e.g. 30 years of hourly data for rain and wind; 10 years of 10 min data), it is possible to use Pareto front analysis to determine watertightness test parameters. The approach is straightforward: (i) every single point with coordinates X and Y of the data (assume X: wind speed at time *i*; Y: rainfall intensity at time *i*) is plotted on an Euclidian plane; for watertightness testing the values of interest are only the outer extreme points of the cloud of points that are plotted (ii) given interest of the two parameters of wind and rain, the set of maximum values is thus partially ordered and the line connecting every Pareto maximum in the data set is called the Pareto-front (Zitzler et al., 2008). (iii) verify that for every point on the Pareto-front there is no other point with a higher value for one parameter, without simultaneously causing a lower value for the other parameter.

Once the Pareto front has been determined for the data points for wind speed and rainfall intensity; every point along that front defines a unique combination of wind and rain that occurred only once over the period covered in the weather database. Hence, for instance where 30 years of data have been analyzed, the point defines a combination with a probability of yearly occurrence of 1/30. Every Pareto-optimal point thus offers an extreme combination of wind and rain: there is not a single other point with both higher wind speed and higher rainfall intensity. Consequently, we can consider the group of extreme combinations as a closed subset of data that defines a specific climate. If one would then delete this subset of data from the original database, and thereafter construct the Pareto front with the remaining data, the reconstructed Pareto front would then define a new subset of data with extreme combinations of wind and rain with a probability to occur twice in 30 years. If now, both the first and second subset of Pareto points is deleted from the original database, a third Pareto front would then define the combination with a return period of three times in 30 years, or once in 10 years; thus removal of the 6th and 30th Pareto front would correspond to return periods of 5 and 1 year respectively. This way it is possible to determine extreme combinations of wind speed and rainfall intensity for specific return periods by omitting the typical problem of statistical analysis of the correlation between wind and rain. Note that the extreme wind velocities and rainfall intensities are only valid for the specific location of the recording weather station, and is limited to the specific averaging period of the data. In most cases the weather station will be located in an open field surrounding, and the data will need to be adapted to be used for other locations.

Pareto-front analysis of wind and rain intensity data for Uccle, Belgium

The development of the Pareto-front analysis was undertaken for Uccle, Belgium. Uccle is located just south of Brussels, Belgium. Ten years of weather data from Uccle were used for this study, for the period between 01/01/2000 and 01/01/2011. The wind speed was measured at a height of 30m, and the 10-minute values were the average of continuous high-frequency measurements in that period. The horizontal rainfall intensity was measured with an all-weather precipitation gauge that uses weight-based technology to measure rainfall, snow or hail. Like most regions in North-western Europe, Belgium has a maritime temperate climate: it is rainy, humid and cloudy, and has mild winters and cool summers (Köppen-Geiger classification Cfb). The measurements do not differentiate in respect to the type of precipitation, so there is an error in the analysis for days with snow fall (15 on average), and hail (no statistical data available, but relatively rare).

The wind data were collected at 30m height, and according to Cabooter et al. (2006), Uccle is located in a zone with a continuous urban fabric with an aerodynamic roughness length of 1.0m, terrain category IV in the Eurocode. Based on standard conversion formulas in the Eurocode, the wind velocities were converted to a reference wind speed at 10m height in open terrain (evidently, the difference in turbulence intensity can be disregarded because the average turbulent component over a 10 minute period is zero). The weather station is the only one in Belgium that could provide measurements with a resolution of 10 minutes for a period of 10 years. Figure 5 shows a plot of the 10-minute averaged wind speeds and rainfall intensities in Uccle for a period of 10 years. The first 10 Pareto-fronts were constructed, and the Pareto-points are plotted in red. Statistical analysis of the 10 subsets of Pareto-points revealed that an exponential function provided the best fit to the data:

now plotted against the return period, a linear relation can be found (see Figure 6). This allows determining additional curves that correspond to chosen return periods. For Uccle, the Pareto lines can thus be calculated as follows:

example, the performance of an operable window with EPDM gaskets may depend on the time constant of the relaxation of the gasket when the sash is subjected to wind loads (Van Den Bossche et al., 2008). Obviously, short frequencies are potentially accompanied by high wind loads and high WDR intensities due to small averaging periods. The longer the period, the more moderate the boundary conditions of the test will be. Ideally, a test sequence should cover the whole range of frequencies of the wind spectrum, but this is not feasible for full-scale components from a practical point of view. Consequently, a limited number of frequencies should be selected for the test protocol. These frequencies could correspond to, e.g. 3 second, 1 minute, 10 minutes, 1 hour and 12 hours, depending on the type of failure mechanisms of the specific component. Once the typical behavior of a component is determined, a more narrow range of frequencies can be selected to which to subject the component. In absence of specific information on failure behavior of façade systems and components, separate test protocols might be developed for face sealed wall systems, drained wall systems and mass buffering wall systems. There is currently however insufficient data on failure mechanisms that take into account sensitivity to WDR intensity, DRWP as well as different frequencies for a range of building components.

As an example of how this approach might be implemented in practice, a test protocol was calculated for supposed 30 m high building located on the Belgian coast, based on the Pareto front for a return period of 10 years (see Figure 8). On the Pareto curve three points were selected: extreme WDR with low DRWP, moderate WDR with moderate DRWP, and low WDR and extreme DRWP. For each point on the Pareto curve, 3 frequencies were evaluated, corresponding to the 10 min, 1 min and 3 s events. The effect of the frequency was evaluated with the Eurocode for wind speeds, and equation 3 for rainfall intensity. Note that for the 3 s rainfall intensities the 1 min intensity was used as the equation was never validated for periods shorter than 1 min (e.g. Sumner, 1978). The lower and upper limit for the cyclic testing was also calculated based on the turbulence intensity formulations provided in the Eurocode. As a conservative approach, it was assumed that for the calculation for the shorter time periods that peak wind speeds and peak rainfall intensities coincided.

Discussion and Conclusions

The watertightness of building envelope systems can be evaluated with a range of different test methodologies be these based on static, cyclical, or dynamic methods, or indeed based on wind tunnel testing. The predominant boundary conditions for evaluating watertightness are pressure difference and water spray rate. However, the relation between these boundary conditions as specified in test standards is typically undefined. Cornick and Lacasse (2009) presented a comprehensive calculation method to define correct boundary conditions based on extreme value analysis of extreme rain and wind events. In absence of general principles on the co-occurrence of wind and rain, and based on only a moderate correlation of WDR and DRWP the authors assumed statistical independence to calculate the return period of extreme combinations of rain and wind. The Pareto-front analysis presented in this paper is a methodology that takes into account actual combinations of rain and wind without assumptions on co-occurrence, and allows calculating realistic boundary conditions for different return periods.

Climate analysis shows that high rainfall intensities typically do not coincide with high wind speeds, and peak values are significantly lower for longer averaging periods. Therefore realistic boundary conditions should take these effects into account. The methodology consists of 4 steps. In the first, the relevant range of boundary conditions for the test must be determined; this is based on knowledge of the failure mechanisms of the building component. For example, brick masonry walls would require a different test protocol than curtain walls. Secondly, the DRWP and WDR are calculated for a given climate database, e.g. 10 years of 10-minute averaged values. In the third step the Pareto points are determined for the DRWP and WDR data points and thus define a subset of unique combinations of extreme DRWP and WDR that occur once in the period covered by the database. A one-parameter exponential function can then be fitted through the Pareto points thereby defining a Pareto front. By deleting the subset from the original database and again calculating the Pareto points for the new database, a new subset of extreme values is defined, recurring twice in that period, thus cutting the return period in half. In a similar fashion, additional iterations can be made that provide shorter return periods with corresponding exponentially defined Pareto fronts. The method when applied to the climate database for Uccle, Belgium, revealed that the single parameter that defines the exponential Pareto fronts was linearly correlated to the return period. This correlation renders it possible to formulate a simple exponential equation to calculate WDR intensity based on wind speed and return period. Finally, the fourth step allows calculating realistic boundary conditions for watertightness testing based on the exponential function for a specific climate location.

Notwithstanding the apparent practical advantages for determining WDR loads offered with this method, there are limitations to its use and further improvements need to be developed. This method was established based with only one climate database, and should be validated for a broader range of climates and return periods. The linearity of the coefficient for Pareto fit a_i needs further investigation for different climate types and over longer return periods. As well, the methodology presented above only offers information for the specific averaging period of a given climate database. The conversion to shorter time periods for both wind and rain again introduces assumptions on the co-occurrence of extremes.

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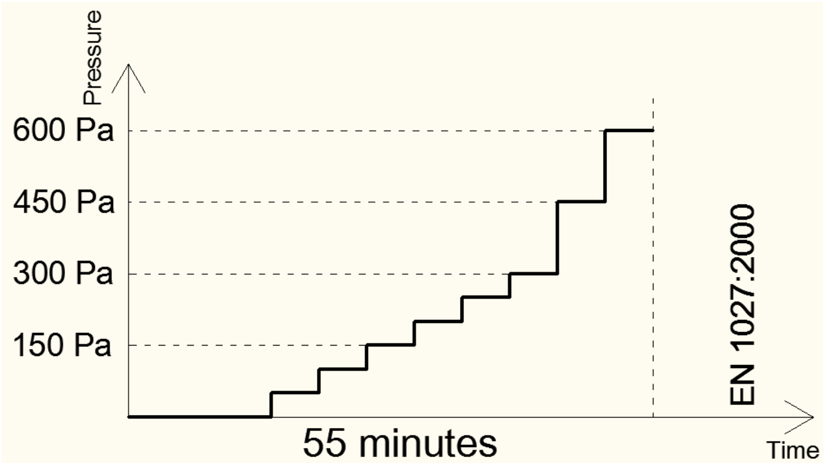

Figure 1. Pressure differences according to EN 1027:2000 static test protocol.

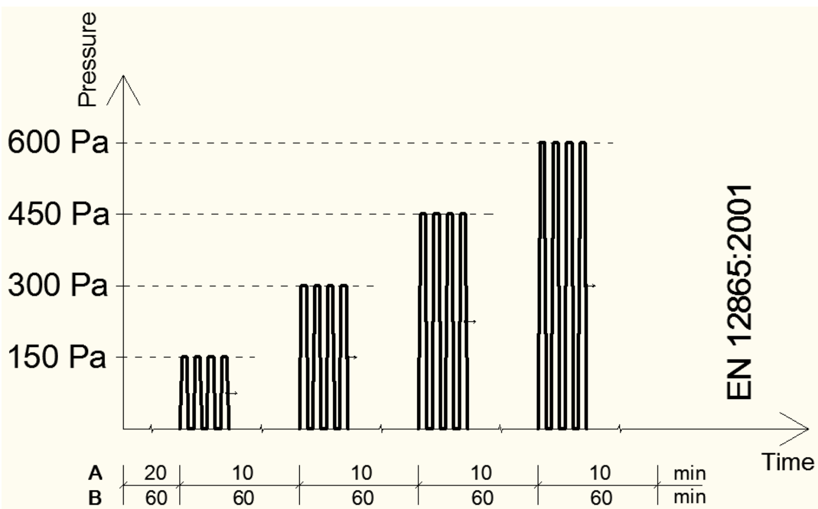

Figure 2. Cyclical testing according to EN 12865:2001 with 5 s pulses.

Figure 3. Dynamic test with aero-engine (AAMA 501.1:2004)

Figure 4. Dynamic testing with axial fan and mounted spray nozzle (ENV 13050:2000)

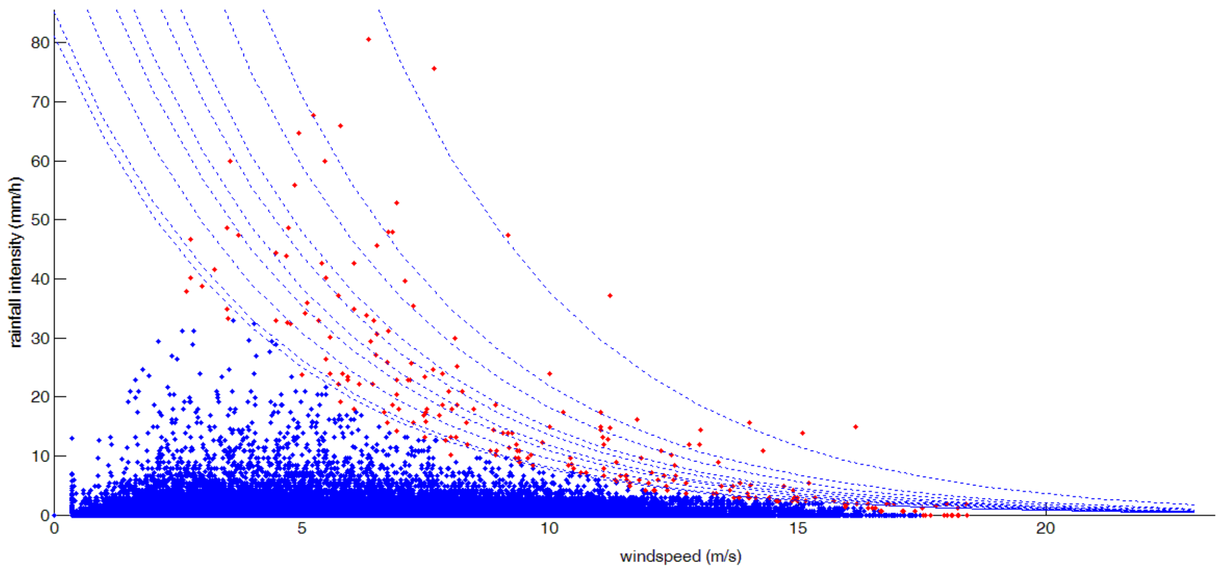

Figure 5. Pareto-front analysis of wind speed and horizontal rainfall of 10 min data for Uccle (2000-2010)

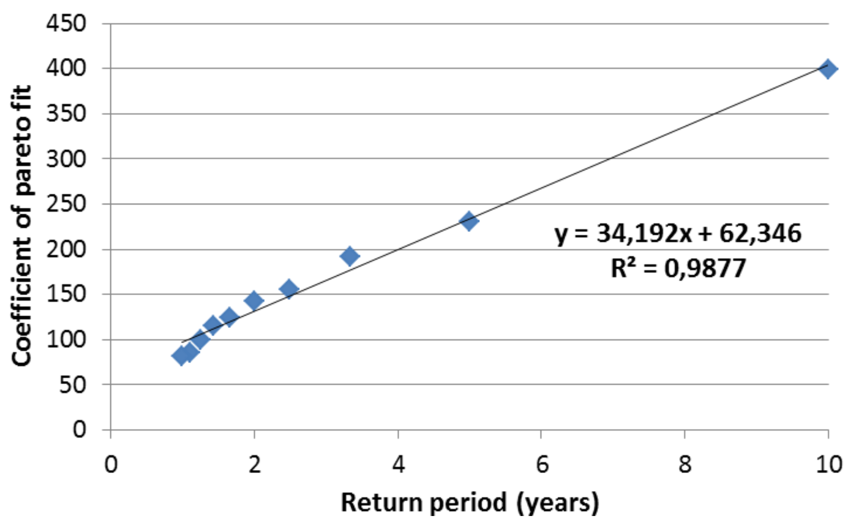

Figure 6. For the data of Uccle, the coefficients of Pareto fit show a linear correlation with the return period.

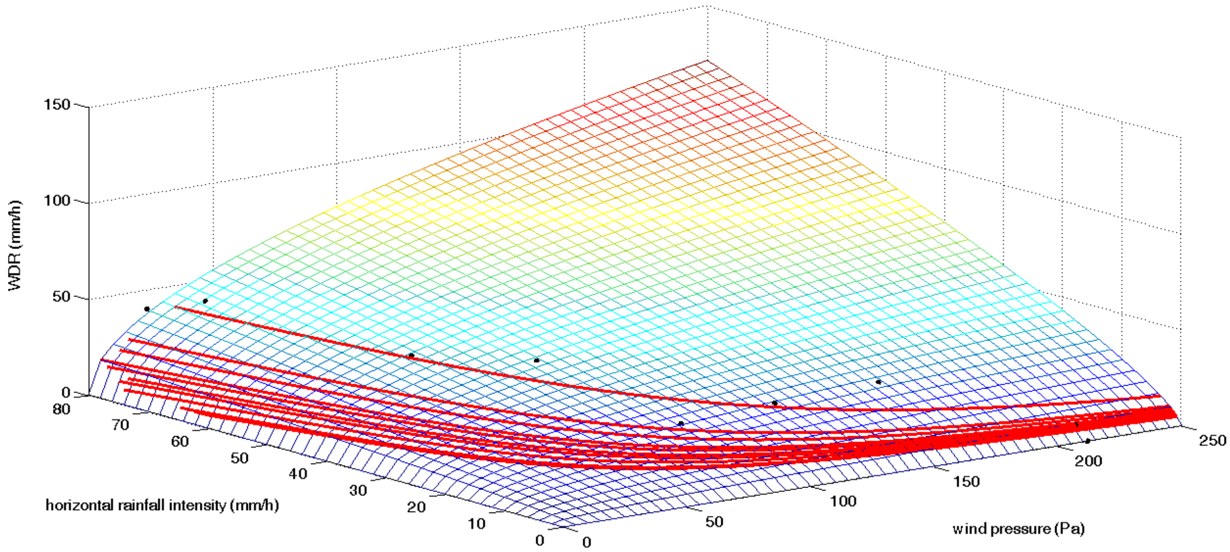

Figure 7. WDR intensity can be calculated based on wind pressure and horizontal rainfall intensity.

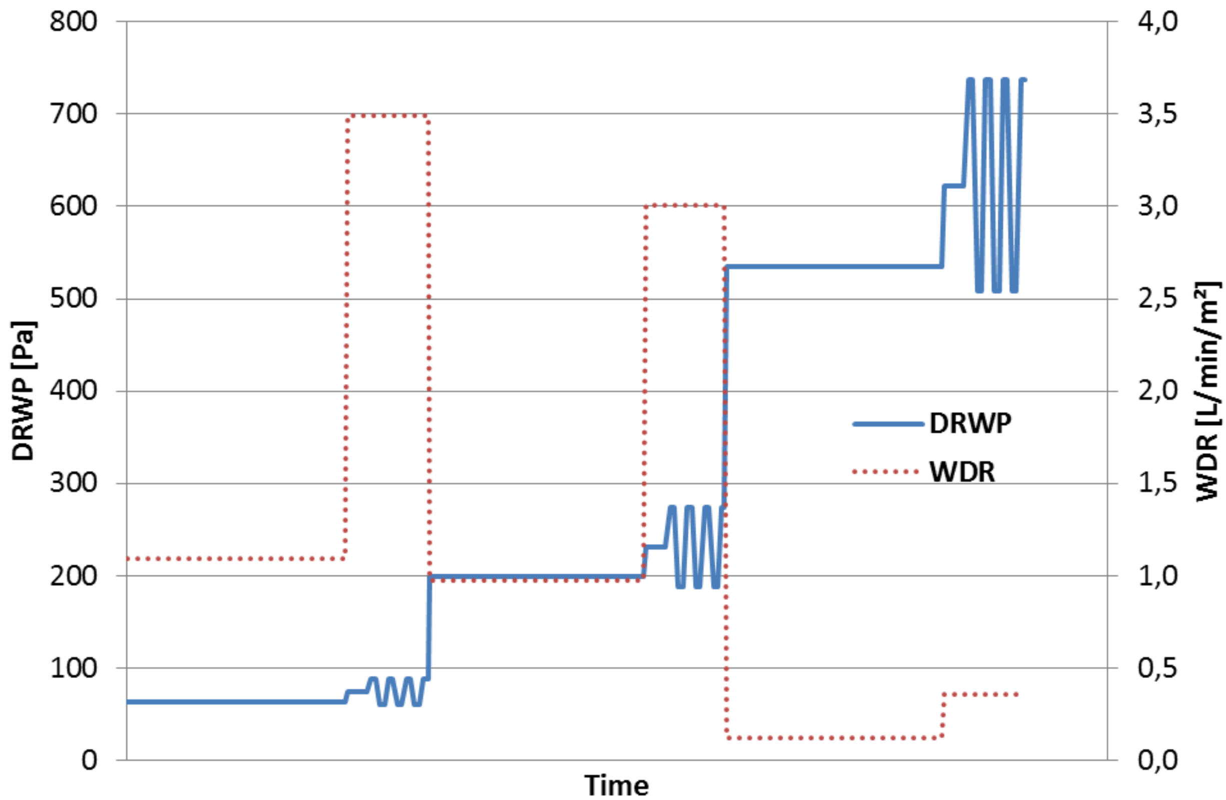

Figure 8. Example test protocol based on Pareto analysis, for three points on the Pareto-curve and three time periods.