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Data Requirements for WAsP, CFD & WRF

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Abstract (max. 2000 char.):

Flow model uncertainty is often caused by the models inability to correctly describe the wind flow. However, another important and often overlooked source of error is the topographical input data used for the flow modelling; these must be sufficiently detailed and accurate to obtain accurate results. This report reviews the requirements of WAsP, WAsP CFD and WRF on the topographical input data to obtain accurate results.

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Chapter 1

Introduction

This report concludes deliverable D2.1 - "Report: requirements for new inputs to flow models" of the Innowind project. The report consists of a literature review and a user survey and highlights the requirements on topographical data (orography and land-cover) for micro- and mesoscale models (WAsP, WAsP CFD and WRF). The report starts with a short introduction of the flow models investigated (Section 1). In Section 2 the effect of model configuration is discussed as this influences the data requirements. Section 3 analyses the orographic (terrain elevation) requirements while section 4 analyses land-cover. Section 5 gives a summary of all the findings while the appendix contains a user-survey analysis (in Danish) and a description of the roughness classification used by WAsP.

Flow models

Micro-scale models like the Wind Atlas Analysis and Application Program (WAsP) Troen and Lundtang Petersen (1989) have been used for 30 years to estimate wind resources at one location based on wind measurements at a different location. To replace expensive wind measurements, wind engineers have in the recent decade started to use mesoscale models like the Weather Research and Forecasting Model (WRF) (Skamarock 2008) to estimate the wind data. For complex terrains like steep hills or forested areas, the standard WAsP model may lead to less accurate estimates. A new generation of micro-scale models based on CFD (Computational Fluid Dynamics) are, therefore, being adopted by the wind industry. WAsP CFD (1995),(1994),(1992) will be used as representative for these models in this report.

The user-survey (see Appendix) was posted on the WAsP and WindPRO LinkedIn pages and investigated the use of flow models. 21 micro-scale users and 11 mesoscale users answered the survey. Only 1/3 of the users (8 micro-scale users and 4 meso-scale users) specified the model they use, but these all used WAsP and WRF. The survey showed that 3/8 of the micro-scale modellers also use CFD-based models. If the survey is representative for the target user group, then we can get an estimate of the relative number of model users:

- WAsP: 50% (21 users)
- WRF: 30% (11 users)
- CFD: 20% (8 users)

Using flow models

WAsP and WAsP CFD is used by the wind industry specifically to estimate the average wind climate. WRF is a multipurpose research model with different purposes and therefore different input requirement.To reduce the number of investigations, this report specifically investigates the requirements of data for flow models when the application is wind resource assessment.

Having defined the flow models and their application, the accuracy of model predictions mainly depend on three aspects (Santos-Alamillos et al. 2015):

1. Model configuration
2. Orography representation
3. Land-cover representation (particularly roughness)

To make accurate model predictions, the three aspects cannot be considered isolated; the roughness length, for instance, depends on the model configuration. The Bolund blind comparison (A. Bechmann et al. 2011) is an example of how similar micro-scale models can give very different results even with "fixed" topographical input data. Each flow modeller often has a subjective view of the ideal model configuration and consequently about data requirements. It is therefore difficult to make conclusions on data requirements without considering the specific model configuration.

The following sections deal with each of the three aspects.

Chapter 2

Model configuration

The lower boundary or the ground surface is the only physical boundary for atmospheric models, and the surface irregularity is traditionally described statistically using a roughness length. At times, extra care can be given to forested areas descriping it them in more details. Here we give a short description of how the surface is modelled in WRF, WASP and CFD and we end up with five different model configurations that each have different data requirements.

Surface-model

WAsP, CFD and WRF characterize the frictional effects caused by the obstacle-elements of the surface, ranging in scale from sand grains and grass to trees and buildings, using the aerodynamic roughness length, z_0. Close to an obstacle-element, the flow is perturbed uniquely based on the obstacle geometry, with distance. However, the exact geometry of each obstacle loses its importance, and the rough surface can be described adequately in a statistical sense using the roughness length.

The roughness length can be defined as the constant that results from the derivation of the logarithmic wind profile:

$U(z) = \frac{u_*}{\kappa} \ln \frac{z}{z_0}$,

where U is the mean wind speed, z the height above the ground, κ is the von Kármán constant and u_* the friction velocity. The logarithmic relation is derived by assuming that the terrain is flat, have a uniform distribution of obstacle-elements and by assuming the wind to be neutrally buoyant. The logarithmic profile is a surface model that relate the surface stress to the wind speed, and it is used so much that it is often called the “log-law”. The “log-law” is, however, only a good surface model when the assumptions of uniformity are kept or when there is the adequate distance to the individual obstacle elements.

In general, a surface model needs to account for all subgrid-scale stresses in a flow model. *Stress* refers to the transfer of energy and *subgrid* refers to scales smaller than the flow model resolution. Micro-scale models (WAsP and CFD) usually only consider the momentum fluxes generated by the neutrally buoyant flow. This is an adequate simplification for high wind speed situations at typical wind turbine heights. With this simplification WAsP and CFD can use the log-law as a surface model and fully describe the surface with a roughness length.

The surface model of WRF is more complex and needs additional surface information of, e.g. the soil moisture and temperature to properly forecast the complex processes of the atmospheric boundary layer.To simplify WRF modelling, the many land surface parameters are grouped under "Land-Use" (LU) or Land-Cover (LC) classes. The WRF model comes with 24 LC classes from the U.S. Geological Survey (USGS), but many different LC datasets exist. Even though the many parameters needed to describe the surface for WRF are grouped under LC classes, the roughness length is still the most important parameter for accurate estimation of the wind speeds relevant for wind turbines. It is the standard of WRF, WAsP and CFD to use the log-law as basis for their surface-modelling and rely on the roughness length to describe the surface roughness. Throughout the report, we call these standard model configurations for

- WRF-rough
- WAsP-rough
- CFD-rough

Forest-model

The roughness length used in the log-law is only a good description of the rough surface when roughness elements are small and uniformly distributed. Close to an obstacle-element, like a building or a shelter, the flow is perturbed uniquely based on the geometry of the obstacle. Due to its relativly high model resolution, WAsP can model "nearby" obstacles in extra detail using a dedicated obstacle model. For modern wind turbines, forests are often more of a concern than individual obstacles, and while the roughness length (if properly chosen) can be a good description far from and within forests, the flow close to the forest edge may not be reproduced well by the log-law. It can, therefore, be meaningful to include dedicated forest models.

Since CFD, WAsP and WRF are operating with different spatial resolutions, some obstacle-elements or forest details can be resolved by CFD and WAsP but not by WRF. WRF is operating with a coarse resolution, and every obstacle element is treated statistically by the roughness length. For micro-scale models, the forests can be resolved and simulated with a dedicated forest model. However, all the unresolved roughness elements still need to be modelled using roughness length. Therefore, the roughness length needs to be reduced when a forest-model is active, but the roughness model is always active

> The aerodynamic roughness length is not a physical quantity but a model parameter that depends on the specific model configuration used. The roughness value should be reduced when a forest model is active.

One way to improve modelling of forests in WAsP is to include a zero plane displacement height, d into the log-law:

$U(z) = \frac{u_*}{\kappa} \ln \frac{z-d}{z_{02}}$,

where d is the height above the ground at which the wind is zero, i.e. the height by which the forest has displaced the wind. d is often chosen by the user as $2/3$ of the average forest height but with additional knowledge about the vertical distribution of forest density (see "Forest parametrisation"), a more accurate algorithm for choosing d and z_{02} can be used.

When modelling forest with CFD the drag force exerted by the trees can be directly inserted into the numerically solved Navier-Stokes (RANS) equations. The volume force can be written as,

$F = -C_d U^2 PAD(x, y, z)$

where C_d is a drag coefficient of the trees and PAD is the Plant Area Density (PAD). The PAD must be specified at all positions within the forest and describes the local density of the forest (see "Forest parametrisation").

There is today no forest model in WAsP and WAsP CFD, but they can be implemented if the required input data is available. To investigate the data requirements for the micro-scales model using a forest model, we add two model configurations:

- WAsP-forest
- CFD-forest

Model requirements

To investigate the requirements for inputs to flow-models, we have specified that the model application is wind resource assessment and selected two micro-scale models (WAsP and WAsP CFD) and one meso-scale model (WRF).

Since the requirements to the topographical (orography and land-cover) input depend not only on the model but also on how the model is configured by the user, we have further defined five model configurations. Models can be configured in many ways but to limit this study, a "standard roughness"-configuration and a “forest”-configuration have been selected. The five model configurations and the model input needed are given in Table 1.

Table 2.1: Data required for the five model configurations. Terrain elevation z, roughness length z_0, the displacement height d, and plant area density PAD. The roughness length should be changed from the “standard” (z_0) for the forest configurations. The surface model of WRF requires many additional parameters not given here.

Model Configuration	Orography model	Surface model	Forest model
WRF-rough	$z(x, y)$	$z_0(x, y)$	-
WAsP-rough	$z(x, y)$	$z_0(x, y)$	-
WAsP-forest	$z(x, y)$	$z_{02}(x, y)$	$d(x, y)$
CFD-rough	$z(x, y)$	$z_0(x, y)$	-
CFD-forest	$z(x, y)$	$z_{03}(x, y)$	$PAD(x, y, z)$

Chapter 3

Orography representation

Current practice

Orographic elements such as hills, valleys, cliffs, escarpments and ridges influence the wind. Near the summit or crest of these features the wind will accelerate while near the foot, and in valleys, it will decelerate.

The orography (terrain elevation) must in WAsP be specified as a digital height contour or vector map, containing the (x, y)-coordinates and altitudes of the map contour lines. The map is usually made by transformation of a digital elevation model (DEM) with spot heights in nodes of a regular grid. The 3 arc-second (90 meters) resolution elevation data from the Shuttle Radar Topography Mission (SRTM), is accessible from within WAsP and is often used, after manual inspection, to establish the required height contour map.

Below, we will mainly investigate the orography requirements from the perspective of WAsP and WAsP CFD, since these are more restrictive than for WRF.

Spatial size and resolution

Mortensen and Petersen (1998) studied the effect of the digital height contour map for seven complex and mountainous terrains in Portugal and France using WAsP. The study focused on different aspects of the height contour map and also investigated the effect of the resolution of the underlying DEM. The study concluded that an adequate height contour map covers an area of at least 10 by 10 km^2 and have height contours intervals of less than 20 m. It was also found that the grid size of the DEM should be less than 50 m. For a later study, Mortensen et al. (2014) used larger elevation maps that covered 40 by 40 km^2

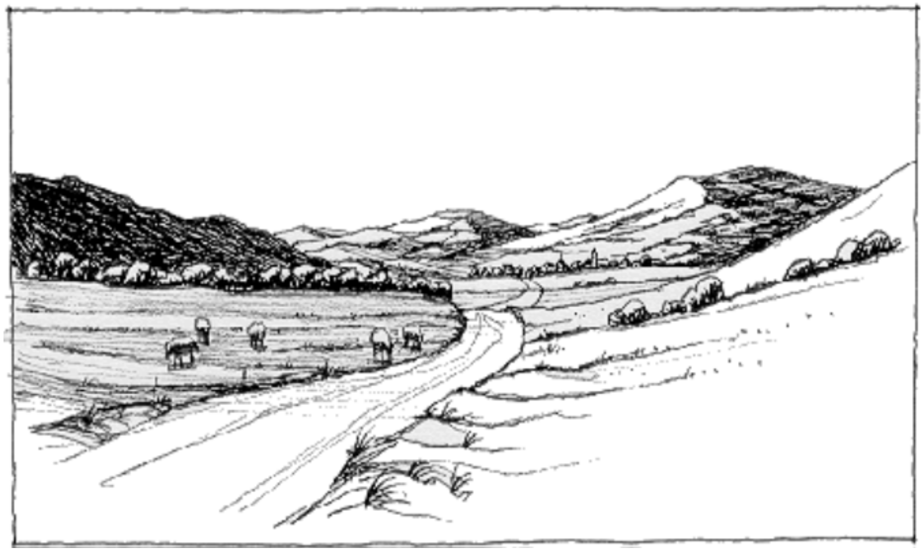

Figure 3.1: Illustration of orography (elevation) from the European Wind Atlas

with 20- or 10-m height contours and with detailed 5-m contours in an area of 10x10 km^2 close to the met. station to minimise uncertainty.

A. Bechmann (2016) investigated the effect of the resolution of WAsP CFD. For this study, a very high-resolution elevation contour map was used, and it was transformed to different resolution CFD grids. This study illustrates how data requirements depends on model configuration; if a flow model is coarsely resolved, increased data resolution does not affect on model results. A. Bechmann (2016) found that if proper (high-order) numerical techniques are used, a CFD grid resolution of 20 m is adequate; the improvements in going to 10 m were hard to quantify. If low-order discretisation schemes are used for the CFD, then higher CFD resolution can be used to achieve comparable results. However, this is a computationally expensive approach and therefore not recommended.

In complex terrain with steep slopes flow phenomena like recirculation can occur that generates regions of high turbulence. CFD captures these phenomena but not by WAsP. CFD includes a turbulence model that can advect turbulence far downstream from the source. CFD will therefore generally need a larger elevation map than required by WAsP.

A. Bechmann (2017) (see appendix) found that WAsP micro-scale users are asking for high resolution, high-quality terrain maps. All WAsP users are today relying on the SRTM data, but often combine it with other data sources. We assume that the WAsP users are using the 3 arc-second (~90 meters) resolution version of the SRTM built into WAsP and not the 1 arc-second (~30 meters) version released more recently.

Santos-Alamillos et al. (2013) study the effect of WRF resolution (1, 3 and 9 km) for four complex sites in southern Spain. For the complex sites even the high resolution WRF simulation (1 km) cannot represent the orography of the terrain accurately and consequently, the wind speed predictions are biased. This problem is not caused by the DEM input but by the coarse WRF model resolution tends to smoothen the terrain and consequently decrease the terrain drag.

As described above, the resolution and required extend of elevation maps depend on the terrain steepness (RIX) and the model being used. WAsP has been designed for only moderately complex terrain and while CFD can handle any steepness of terrain its main application is the complex sites. The orography requirements in the table are therefore based on the model's main applications (WAsP = simple, CFD = complex) and are similar to the recommended value used in WAsP courses.

Table 3.1: requirements to the digital elevation model (DEM) for the five model configurations. There are no requirements for WRF-rough as the resolution of WRF is much coarser then the DEM datasets.

Model	DEM Resolution	DEM Extend
WRF-rough	-	-
WAsP-rough	50 m	15 km $(30 * 30\ km^2)$
WAsP-forest	50 m	15 km $(30 * 30\ km^2)$
CFD-rough	20 m	20 km $(40 * 40\ km^2)$
CFD-forest	20 m	20 km $(40 * 40\ km^2)$

Accuracy and uncertainty

L.-E. Boudreault et al. (2012), demonstrates that DSM models differ when it comes to interpretation of terrain elevation in forested areas. Coarsely resolved satellite measurements are shown to have difficulties in determining the true ground elevation compared to high-resolution aerial Lidar scans. The effect of having the terrain elevation offset by a tree-height fraction has not been investigated but is probably small for wind resource assessment. Close to the faulty elevation-change the wind will be affected but at heights much lower than the wind turbine hub-height. With distance, the effect gets smaller. A misinterpretation of the ground elevation can, however, lead to an underestimation of tree heights and consequently of the forest roughness causing uncertainties in the wind resource assessment (see next Section)

Several data products based on the Shuttle Radar Topography Mission are freely available including a 1 arc-second (~30 meters) resolution version with global coverage. This dataset is continuously being quality improved and should full-fill most users requirements to a global DEM dataset.

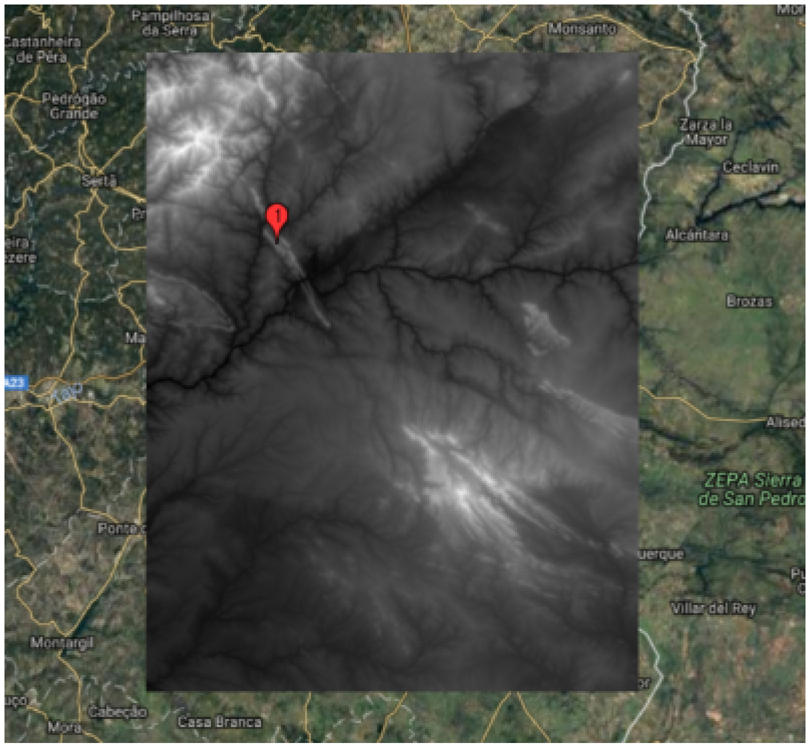

Figure 3.2: 1 arc-second (~30 meter) resolution SRTM elevation map of the Perdigão site. The GeoTIFF file (and other formats) can be downloaded from earthexplorer.usgs.gov

Chapter 4

Land-Cover representation

Current practice in WAsP and CFD

Mortensen et al. (2014) describe how the land cover around each met station was determined for the WASA (Wind Atlas for South Africa) project for use in WAsP. The process consists of site inspection trips where ground truth observations are compared to Google Earth satellite imagery. For the site inspections, it is important to inspect typical land cover types of the whole area (40x40 km) surrounding the mast. The land cover in the immediate proximity of the mast, say 2x2 km, is not relevant for the measured wind conditions. By having roughness evaluations for different types of land cover, a roughness map can manually be digitized in a GIS software by comparing with satellite imagery and coastlines, lakes and rivers can as an example be derived from the SRTM Water Body Dataset. The result is a roughness map specified as roughness change contour lines (roughness lengths on each side of the line) that can be used in WAsP and WAsP CFD.

The roughness map for WAsP and WAsP CFD can contain any value of roughness length. However, Troen and Lundtang Petersen (1989) gives five typical roughness classes (see Appendix B). Each roughness class has an exemplary illustration of a corresponding terrain (figure 4.1) and gives the relation to a commonly used roughness length. The five roughness classes are:

- Class 0: Water areas (z0 = 0 m)
- Class 1: Open areas with few windbreaks (z0 = 0.03 m)
- Class 2: Farmland with closed appearance (z0 = 0.10 m)
- Class 3: Urban districts with many windbreaks (z0 = 0.40 m)
- Class 4: Tall/sparse forest (z0 = 1.50 m)

The illustrations are useful as a reference for non-experts and help to reduce the bias from person to person. Since a traditional WAsP user (WAsP-rough)

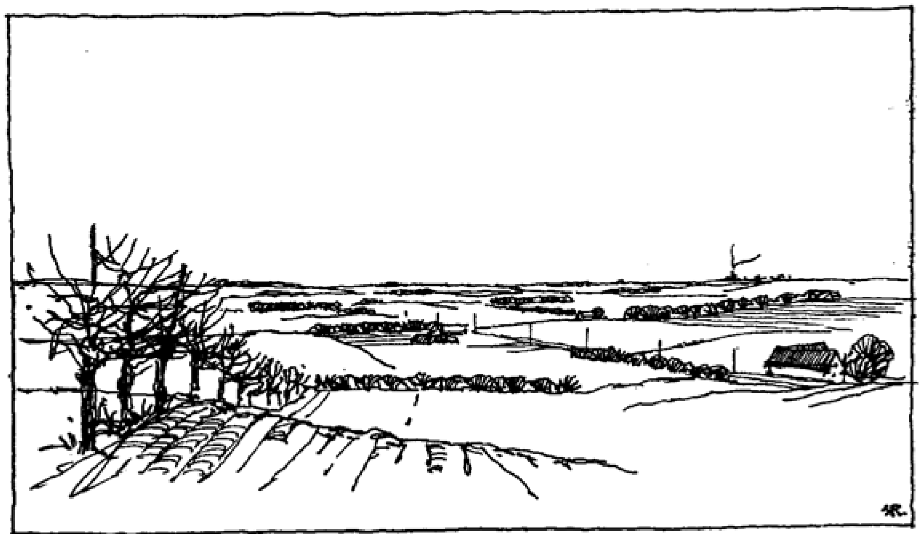

Figure 4.1: Illustration and description of terrain corresponding to roughness class 2 ($z_0 = 10m$) of the European Wind Atlas

only needs to consider roughness length, he quickly gets experience in evaluating different sources. An experienced user can combine roughness maps, land-cover datasets, photos, and site-visits into a single coherent high-resolution roughness map. This is confirmed by the user-survey (see appendix A), who found that the average WAsP user combines about three different datasets.

A downside of the described approach is that the process is difficult to track and therefore is user dependent. Also, the generated roughness map (z_0) is not directly usable for the WAsP-forest (z_{02}) and CFD-forest configurations (z_{03}) (see Table 2.1).

To not dismiss the many years of experience that current WAsP and CFD users have in evaluating the "standard" roughness length (z_0) it must be a requirement that the WAsP-forest and the CFD-forest configurations can still use standard roughness as input. To achieve this, new land-cover maps must retain the roughness length but have information about the vertical structure of the forest added (see "Forest parametrisation"), this will ensure that new forest land-cover map can be translated to any model configuration.

> New land-cover dataset should contain information about the vertical structure of forests (h, PAI and z_m) and the roughness length (z_0) to ensure that all model configurations can use the dataset.

Table 4.1: The table shows how a new "Forest" land-cover type can be translated to any model configuration

Model Configuration	Land-Cover description	Translated model parameters
WRF-rough	z_0	z_0
WAsP-rough	z_0	z_0
WAsP-forest	z_0+"Forest"	$z_{02}+d$
CFD-rough	z_0	z_0
CFD-forest	z_0+"Forest"	$z_{03}+PAD$

Current practice in WRF

Contrary to the WAsP and WAsP CFD (rough configuration) user who only inputs the roughness length, the WRF user needs many additional parameters due to its complicated surface model. To simplify WRF modelling, the many land surface parameters are therefore grouped under Land-Cover (LC) classes. The WRF model comes with 24 LC classes from the U.S. Geological Survey (USGS), but many different LC datasets exist. Each class has a description like "Grassland" or "Mixed forest" and it is the responsibility of the WRF-user to inspect, e.g. using satellite imagery, that the classifications are correct and up to date.

A downside of using LC classes is that the important model parameters, like the roughness length, is somewhat "hidden" and the user may unconsciously use inappropriate values. Also, it is not trivial to use alternate LC datasets as the alternate classes need to be matched/converted to the 24 USGS classes built into WRF. This process consists of:

1. changing the geographic projections of the new dataset
2. converting the new LC classes to the 24 USGS classes
3. write the resulting LC map to a specific binary file format

The complicated conversion is highlighted in the user-survey (A. Bechmann 2017) where WRF-users prioritise "new data prepared specifically for wind energy". Despite the complicated conversion, most modellers in the user-survey used the CORINE dataset. However, WRF-users do not combine different datasets as the WAsP-user do.

Table 4.1 shows the USGS LC-classes and the roughness length values used by Sertel, Robock, and Ormeci (2010) and Santos-Alamillos et al. (2015). Santos-Alamillos et al. (2015) describe in detail how he reclassifies the 44 classes of the 100-m resolution CORINE map into the 24 USGS classes and determines the minimum and maximum roughness length (the variation through the year) used for each class.

Table 4.2: USGS 24-category Land Use Categories and the roughness length (z_0) used by Sertel, Robock, and Ormeci (2010) and Santos-Alamillos et al. (2015) (z_{0min}, z_{0max})

LU Class	Land Use Description	z_0	z_{0min}	z_{0max}
1	Urban and Built-up Land	1.00	0.50	0.50
2	Dryland Cropland and Pasture	0.07	0.05	0.15
3	Irr. Cropland and Pasture	0.07	0.02	0.10
4	Mixed Dryland/Irr. Cropland	0.07	0.05	0.15
5	Cropland/Grassland Mosaic	0.07	0.05	0.14
6	Cropland/Woodland Mosaic	0.15	0.20	0.20
7	Grassland	0.08	0.10	0.12
8	Shrubland	0.03	0.01	0.05
9	Mixed Shrubland/Grassland	0.05	0.01	0.06
10	Savanna	0.86	0.15	0.15
11	Deciduous Broadleaf Forest	0.80	0.50	0.50
12	Deciduous Needleleaf Forest	0.85	0.50	0.50
13	Evergreen Broadleaf	2.65	0.50	0.50
14	Evergreen Needleleaf	1.09	0.50	0.50
15	Mixed Forest	0.80	0.20	0.50
16	Water Bodies	0.00	0.0001	0.0001
17	Herbaceous Wetland	0.04	0.20	0.20
18	Wooden Wetland	0.05	0.40	0.40
19	Barren/Sparsely Vegetated	0.01	0.01	0.01
20	Herbaceous Tundra	0.04	0.10	0.10
21	Wooded Tundra	0.06	0.30	0.30
22	Mixed Tundra	0.05	0.15	0.15
23	Bare Ground Tundra	0.03	0.05	0.10
24	Snow or Ice	0.001	0.001	0.001

Forest parametrisation

The vertical distribution of foliage affects the frictional forces of forests. The vertical distribution is often described by the Plant Area Density, $PAD(x, y, z)$, that represents the area of leaves, branches and stems opposing the wind (L.-É. Boudreault et al. (2015)). The PAD can be used by the CFD-forest model configuration (for the forested areas only). However, the three-dimensional description is extensive and difficult to measure. Sogachev et al. (2017) therefore describe a way to parametrise the PAD so that it can be used for both roughness-length and canopy-drag flow models. Only three parameters are needed to describe the vertical structure:

- Tree Height, h

- Plant Area Index, PAI
- The Height of Maximal Plant Density, z_m

From these parameters, the PAD can be reconstructed for use by for the forest configurations or an accurate roughness length can be estimated for the roughness configurations. Sogachev et al. (2017) additionally show that PAI and z_m can be estimated from traditional forestry relationships when the tree-type is known.

> The forest density can be described by three parameters (h, PAI, z_m) that can be estimated from measurements or knowledge of tree-type.

Roughness accuracy and uncertainty

Roughness characterisation via assignment of z_0 by wind engineers based on onsite inspection can be considered standard industry practice for WAsP and CFD but automatic translations of LC maps to roughness values, like done for WRF, is becoming more common.

No matter if the roughness values are determined by wind engineers or by land cover translations both methods are uncertain (see table 4.2). Kelly and Ejsing Jørgensen (2017) investigate how the uncertainty in roughness length relate to uncertainty in predicted wind speeds when using WAsP and also investigates the uncertainty in z_0 when derived from measurements or by wind engineers. Kelly and Ejsing Jørgensen (2017) asked a group of wind resource assessment experts to individually evaluate the roughness length of two land surface types, forest ($z_0 = 1.3\ m \pm 2.0\ m$) and grass ($z_0 = 4.1\ cm \pm 5.7\ cm$), based on photographs.

For the study, the standard deviations of the estimated roughness were more than 100% for both surface types. When deriving z_0 from wind measurements, similar uncertainties was found. The paper (2017) gives examples that show that a 100% roughness uncertainty at both measurement and prediction site can lead to $5 - 20\%$ error on the estimated Annual Energy Production (AEP), depending on the roughness at observation and prediction site.

A simple method of reducing the uncertainty when characterising roughness could be to take the average of three independent estimates. Kelly and Ejsing Jørgensen (2017) shows that this can reduce the standard deviation of the z_0 by 50% and reduces the AEP error to about $3 - 10\%$.

Another approach to reducing uncertainty is to estimate the roughness length based on measured forest parameters, e.g. the forest height. As a crude approximation, the roughness length of a forest can be estimated as $z_0 = h/10$ (this does not include the vertical distribution described in “Forest parametrisation”). Using this, the uncertainty in roughness length can be expressed as uncertainty in tree height, and it becomes clear that even modest measuring accuracies will greatly reduce uncertainties. If the three height can be measured with an accuracy of $\sigma_h = \pm h/3$, it would greatly increase precision compared to most wind engineers intuitive estimates.

> When wind engineers evaluate roughness length, it should be standard practice to collect several independent evaluations to reduce uncertainty. However, evaluating roughness based on measured forest parameters such as tree height will have the most profound effect on reducing the uncertainty

For new land cover data, an explicitly recommended translation to roughness is important. This is backed up by the Meso-scale modellers (A. Bechmann 2017) who states that data should be prepared specifically wind Energy. Consequently, the modellers are not only asking for quality land cover datasets but also a method on how to use them in the models.

Temporal resolution

The Corine Land Cover (CLC) was used by nearly all of the Meso- and Micro-scale modellers of the user-survey (2017) and can be considered the reference land cover mapping at the European scale. The CLC resolves features larger than 25 ha (160 x 160 m). While this, according to the user-survey, is an adequate resolution for the Meso-scale modellers, the micro-scale modeller wishes for more detail (as described in Chapter 3).

In addition to the spatial resolution, Inglada et al. (2017) highlight that timeliness of the land-cover also needs to be considered. Inglada et al. (2017) explain that even though the CLC has the reference year 2012, it was not made available before the year 2015.

The importance of using an up to date LC dataset is also described by Cheng et al. (2013) who compares three different LC datasets (USGS, MODIS and one from the National Central University of Taiwan) for the Taiwan area and performs WRF simulations for each dataset. The study finds that the datasets have quite different representations of the LC and consequently different roughness lengths and wind speed predictions. The different representations were also due to the different reference years of the datasets (1992 USGS, 1999 MODIS and 2007 NCU) that therefore did not fully capture the urbanisation and deforestation that had occurred in Taiwan.

Sertel, Robock, and Ormeci (2010) made a similar WRF comparison for a region in Turkey using the USGS land cover dataset (1992) and a land cover dataset derived from new Landsat satellite images (2001-2005). Sertel, Robock, and Ormeci (2010) found that the USGS data was not representative and therefore had misclassifications for urban and forested areas.

> The land-cover changes continuously with time as a result of processes such as urbanisation, deforestation and tree growth. Therefore, a

land-cover dataset can become rapidly outdated. It should be updated regularly ($<$ every three years).

Appendix A

Analyse af InnoWind user survey

Baggrund

I dette dokumemt analyseres resultaterne af InnoWinds bruger undersøgelse.[1] Analysen er del af deliverable D2.1 “Report on the requirements for new inputs to flow models.[2] Formålet med analysen er at belyse brugen og eventuelle mangler ved eksisterende topografi dataset til mikro- og meso-skala modeller.

Brugerundersøgelsen består af et spørgeskema, der var åbent fra d. 1-23 Juni 2017. Spørgeskemaet blev bl.a. annonceret på EMD’s og WAsP’s LinkedIn profil og henvender sig dermed primært til allerede eksisterende WAsP og WindPRO brugere hovedsageligt fra Europa. Omkring 600 personer så opslaget på EMD’s LinkedIn profil og i alt 33 har besvaret spørgeskemaet.

Fra spørgsmål 1 i spørgeskemaet kan man læse, at størstedelen, godt 60% af de 33 brugere der har svaret (20 brugere), skriver at de benytter flow modeller til “Wind Energy development”, mens 21% (7 brugere) benytter dem til “Research”. De resterende brugere enten “develop flow models” (9%) eller er en blanding af de tre andre uu typer.

Herunder kommer først en opsummerende konklusion for hele spørgeskemaet, der bygger på analyser af alle spørgsmål. Gennemgangen af de enkelte meso- og mikro-skala spørgsmål kommer efter konklusionen.

[1] Badger M. et al: InnoWind user survey - land surface input for flow modelling in connection with wind energy, SurveyMonkey, Accessed 2017-06-26

[2] Badger M. et al: Projektplan – InnoWind, 2017-01-27

Survey Konklusion:

Baseret på **meso-skala** spørgsmålene konkluderes at:

Der er brug for et pålideligt, kvalitets meso-skala land-cover kort med global dækning der kan bruges i WRF. Dokumentation af "korrekt" brug af kortet til vind energi og gøre kortet let anvendeligt i WRF er vigtig for at styrke kortets udbredelse, og muligvis gøre det til den nye "standard"

"Høj kvalitet" for meso-skala :

- *Reliable*
- *Good quality roughness lines*
- *(well-defined) land-sea discontinuities*
- *Better accuracy*

Baseret på **mikro-skala** spørgsmålene konkluderes at:

Der er brug for mikro-skala land-cover kort der har høj opløsning i både tid og rum. Kortet må gerne indeholde detaljeret info om land-cover (f.eks. om træhøjder og lokale lægivere) og skal være tilgængeligt i et standard GIS format. WAsP er udbredt og kan fungere som løftestang for kortet udbredelse

"Høj kvalitet" for mikro-skala:

- *High resolution, high resolution, high resolution*
- *Detailed roughness, vegetation height*
- *Height of forest*
- *Roughness with better handling of like windBreaks and more forest info, like height*

Umiddelbart er kvalitets kravene til et meso- og et mikro-skala dataset modstridene. Meso modellerne ønsker et pålideligt gennemtestet datasæt med en velbeskreven WRF anvendelse, hvorimod mikro-modellerne ønsker et meget detaljeret dataset som let kan kombineres med anden information. Det er derfor vigtigt at målgruppen for de nye dataset bliver skarpt defineret, så de ikke falder mellem to stole

Meso-skala spørgsmål:

Q2 Do you have experience in running a mesoscale flow model?
26 ud af 33 har besvaret. 42% (11 brugere) har kendskab til meso-skala modeller. 4 personer uddyber hvilken meso-skala model de benytter; alle bruger WRF. Vi havde nok det indtryk inden undersøgelsen at langt de fleste meso-skale modellører benytter WRF, spørgeskemaet underbygger dette.

WRF benyttes af næsten alle spurgte meso-skala modellører

Q3 How would you characterize your use of land surface input for mesoscale modelling?
24 ud af 33 har besvaret. 9 har bevaret at spørgsmålet er irrelevant. Der er altså 15 tilbage der har udtalt sig om hvordan de benytter data til meso-modeller selv om der kun er 11 der har erfaring med meso-modeller. De 3 svar muligheder bliver valgt ca. lige meget ("I use default": 6, "I customize": 4, "depends, case to case": 5). Det er svært at drage klare konklusioner af dette; men der er altså en betydelig gruppe, der vælger "default" datasets.

En betydelig gruppe af Meso-skala modelløren bruger "standard/default" data

Q4 What type of orography information do you use for mesoscale modelling?

24 ud af 33 har besvaret. 10 brugere (42%) besvarede "not relevant" til brugen af orografi data. Hovedvægten af de resterende svar er enten på "defaults" 25% eller "SRTM" 38% . De andre svar muligheder er alle små. Ligesom med mikro-skala modellerne (Q9) har SRTM en dominerende rolle, og det på trods af at WRF kommer med sit eget datasæt. Man kan også læse at hver meso-skala modellør kun benytter ét dataset (SRTM eller default). Det er i kontrast til mikro-skala modellørerne der selv mixer et orografi dataset baseret på SRTM samt andre datakilder. Det tyder på at meso-skala modelløren er godt tilfreds med de orografi data de tilbydes i dag?

Meso-skala modellører er sandsynligvis tilfredse med de orografi data de har til rådighed i dag (SRTM eller default)

Q5 What type of roughness / land-cover information do you use for mesoscale modelling?
24 ud af 33 har besvaret. 10 brugere (42%) besvarede "not relevant". Ifølge spørgeskemaet benytter de fleste brugere (38%) sig af CORINE land cover data til meso-skala modellering. Det er lidt overraskende, at flere bruger CORINE end "defaults" (USGS) (17%) eller MODIS (13%) da disse to dataset følger med WRF. Det er ikke trivielt at konvertere CORINE til WRF: 1. projektionen skal ændres, 2. land-cover klassificeringen skal konverteres til WRF og 3. filen skal skrives i bineært format.

Brugen af det globale dataset "GlobCover" er ikke overvældene. Dette kan skyldes at kvaliteten ikke på højde med CORINE og at spørgeskemaet primært er besvaret af Europæiske brugere (CORINE dækker kun Europa). Generelt er der stor spredning i brugen af land-cover data til meso-skala modeller; der er altså ikke en tydelig dominans, som vi så med orografi data. Et kvalitets dataset, som CORINE, men med globalt dækning kunne måske derfor være efterspurgt.

Meso-skala modellører mangler sandsynligvis et kvalitets land-cover dataset med globalt dække. De konverterer (sikkert med besvær) CORINE til WRF

Q6 On a scale of 1-5 (with 5 being the most important), what should

we improve regarding mesoscale land surface input?
15 ud af 33 har besvaret. Dette spørgsmål spørger direkte brugeren hvad vi skal forbedre med hensyn til meso-skala data på en skala fra 1 til 5 (middelscore i parentes): "Ease of use"(2,8), "Data Quality" (4,1) og "Prepare data specifically for wind energy" (4,0). Brugerne fortæller altså at de gerne have kvalitets data dedikeret til vind energi.

Meso-skala modellørerne ønsker sig et kvalitets dataset specifikt designet til vind energi

Q12 / Meso-skala comments
Her er nogle bruger kommentarer tilknyttet meso-skala data:

- Reliable land cover data outside of europe
- Good quality roughness lines for use in energy resource other than Corine that only covers Europe
- Well better accuracy is important
- Discontinuities land-sea
- Find out why Meso scale models overpredict wind speeds more the more inland (e.g. 20% South Germany,10% mid Germany, 5% North GErmany, 3,5% Denmark) - is it due to wrong roughness input, or other model problems

Mikro-skala spørgsmål:

Q7 Do you have experience in running a microscale flow model?
23 ud af 33 har besvaret. 91% (21 brugere) har altså kendskab til mikro-skala modeller - det er en højere %-del end det tilsvarende spørgsmål for meso-modellerne. 8 personer uddyber hvilken model de benytter. Alle bruger WAsP, hvilket næppe kommer som en overraskelse, da det er den bruger gruppe vi har målrettet spørgeskemaet. 3 bruger CFD (WAsP CFD og andet CFD).

Næsten alle brugere i survey er WAsP brugere

Q8 How would you characterize your use of land surface input for microscale modelling?
23 ud af 33 har besvaret. Kun 1 har bevaret at spørgsmålet er irrelevant. De 3 svar muligheder blev besvaret efter følgende fordeling ("I use default": 18%, "I customize": 59%, "depends, case to case": 59%). Mikro-skala modelløren tilpasser altså i høj grad de eksisterende land surface dataset. Dette er i kontrast til meso-skala modelløren, hvor en stor gruppe benytter "defaults"

Mikro-skala modelløren bruger ikke kun "standard/default" data. Han må ofte manuelt tilpasse eksisterende data

Q9 What type of orography information do you use for microscale modelling?

22 ud af 33 har besvaret. Hovedvægten af mikro brugerne (91%) benytter sig af SRTM orografi data. Det ligner altså umiddelbart mønstret fra meso-skala modellerne. Imidlertid, kan man se, at mikro-skala modelløren også bruger supplerende datakilder, hvilket er i kontrast til meso-modelløren. Mikro-skala modeløren kombinerer SRTM dataene (Ved ikke om det er standard 90 m opløsning SRTM eller det nyere 30 m opløste) med højopløste lokale kort (41%), lidar-scanninger (32%) og nationale højde modeller (32%). Der findes altså ikke et "default" orografi kort for mikro-skala modellører, som der gør for meso-skala. *Mikro-skala modellører mangler højtopløst orografi data; de sammensætter selv fra mange datakilder*

Q10 What type of roughness information do you typically use for microscale modelling?
22 ud af 33 har besvaret. I kontrast til meso-skala modelløren benytter hver micro-scala modellør sig af mange forskellige land-cover dataset. I gennemsnit benytter hver mikro-skala modellør sig af 2,6 forskellige landcover dataset, hvorimod meso-skala folket kun benytter 1,6. Meso-skala modellører som gruppe bruger mange forskellige dataset; men hver enkelt modellør har sit eget favorit dataset. Hver enkelt mikro-skala modellør benytter sig derimod af mange dataset.

De fleste mikro-modellører benytter CORINE (77%); men mange benytter sig også af GlobCover (32%) - %-forskellen skyldes nok at vi spørger Europæiske brugere. Udover at bruge landcover databaser digitalisere næsten alle mikro-skala brugerne selv ruhedsdata manuelt (73%). Dette skyldes sandsynligvis, at eksisterende database ikke har den nødvendige opløsning, samt at ændringer i landcover over tid (skove der vokser/fældes, huse der bygges osv.) i forhold til etablerede databaser har stor indflydelse på mikro-skala vind forholdene

Mikro-skala modellører har i dag ikke en ruhedsdatabase i den høje rummelige og tidslige opløsning de behøver. De skal derfor kunne evne at sammensætte data fra mange forskellige kilder manuelt

Q11 On a scale of 1-5 (with 5 being the most important), what should we improve regarding microscale land surface input?
19 ud af 33 har besvaret. Dette spørgsmål spørger direkte brugeren hvad vi skal forbedre med hensyn til mikro-skala data på en skala fra 1 til 5 (middelscore i parentes): "Ease of use"(3), "Data Quality" (4,3) og "Prepare data specifically for wind energy" (3,3). Brugerne fortæller altså meget tydeligt at vi skal fokusere på kvalitets data med høj opløsning

Mikro-skala modellørerne ønsker sig et højopløst kvalitets dataset

Q12 / Mikroskala comments
Her er nogle bruger kommentarer tilknyttet mikro-skala data:

- "It is normally provided to me" (the land surface input)
- "High resolution", "High resolution", "High resolution"
- "Roughness length values to be assigned to land cover types"
- "Height of forest"

- “Roughness with better handling of like windBreaks and more forest info, like height”
- “Detailed roughness, vegetation height”
- “I would like roughness data for microscale modelling”

Appendix B

WAsP Roughness Classification

This appendix gives an overview of the WAsP roughness classification. The classification was originally defined by Troen and Lundtang Petersen (1989) but has since been updated with an additional class (Class 4).

The Wind Atlas Analysis and Application Program (WAsP) is a software program for the calculation of wind climates for energy yield assessment of wind turbines. WAsP needs as input a terrain description of the area surrounding the site of interest, which includes:

- roughness length map
- terrain elevation map
- nearby sheltering obstacles such as buildings and wind breaks

The roughness map can contain any value of roughness length; it is thus not restricted to the 5 roughness classes given below. Each roughness class has an exemplary illustration of a corresponding terrain and gives the relation to a commonly used roughness length. The five roughness classes are:

- Class 0: Water areas (z0 = 0.0002 m)
- Class 1: Open areas with few windbreaks (z0 = 0.03 m)
- Class 2: Farmland with closed appearance (z0 = 0.10 m)
- Class 3: Urban districts with many windbreaks (z0 = 0.40 m)
- Class 4: Tall/sparse forest (z0 = 1.50 m)

Class 4 was included after the publication of the European Wind atlas (1989). For wind turbines placed in proximity of forests a more detailed forest description than provided by a roughness length may be considered e.g. by inclusion of a forest displacement height or the vertical PAD (Plant Area Density) distribution.

Figure B.1 gives an overview of typical roughness lengths and the five roughenss classes are illustrated on Figure ??-B.2.

Land cover and roughness length

z_0 [m]	Terrain surface characteristics (land cover)	Roughness Class	WAsP z_0 [m]
1.0-3.0		**4** (1.5 m)	1.5
1.0-3.0	tall/sparse forest +)		> 1
1.0	City		1.0
0.8	low/dense forest		0.8
0.5	suburbs		0.5
0.4	shelter belts	**3** (0.4 m)	0.4
0.2	many trees and/or bushes		0.2
0.1	farmland with closed appearance	**2** (0.1 m)	0.1
0.05	farmland with open appearance		0.05
0.03	farmland with very few buildings/trees	**1** (0.03 m)	0.03
0.02	airport areas with some buildings and trees		0.02
0.01	airport runway areas		0.01
0.008	mown grass		0.008
0.005	bare soil (smooth)		0.005
0.001	snow surfaces (smooth) *)		0.003
0.0003	sand surfaces (smooth) *)		0.003
0.0002	(used for water surfaces in the Atlas)	**0** (0.0002 m)	0
0.0001	water areas (lakes, fjords, open sea)		0

+) Consider displacement height effects

*) Roughness lengths < 0.003 m will be interpreted as a water surface

Figure B.1: Roughness length, surface characteristics and roughness class

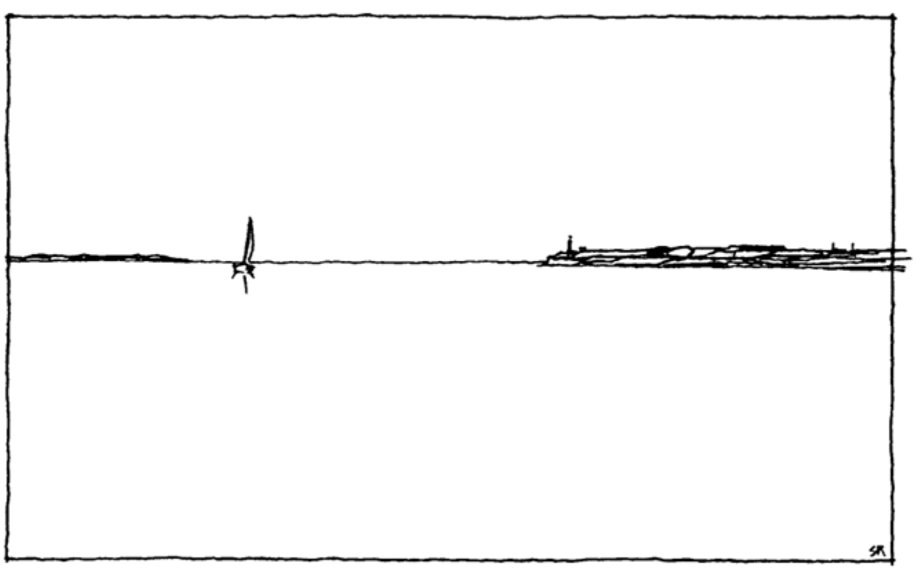

Figure 1.2: Example of terrain corresponding to roughness class 0: water areas (z_0 = 0.0002 m). This class comprises the sea, fjords, and lakes.

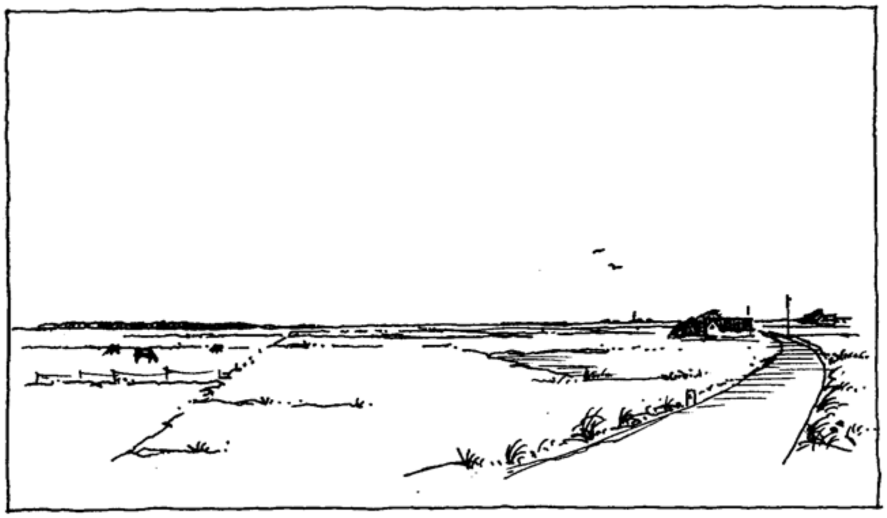

Figure 1.3: Example of terrain corresponding to roughness class 1: open areas with few windbreaks (z_0 = 0.03 m). *The terrain appears to be very open and is flat or gently undulating. Single farms and stands of trees and bushes can be found.*

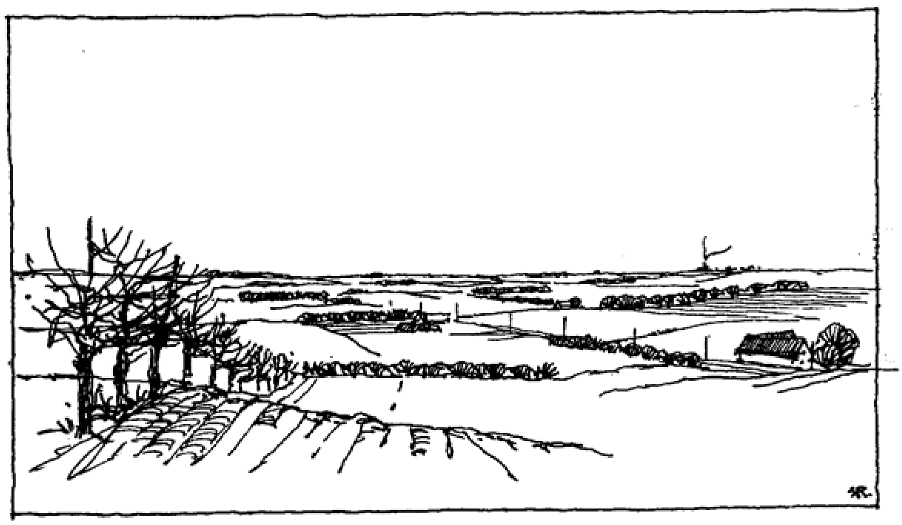

Figure 1.4: Example of terrain corresponding to roughness class 2: farm land with windbreaks, the mean separation of which exceeds 1000 m, and some scattered built-up areas (z_0 = 0.10 m). *The terrain is characterized by large open areas between the many windbreaks, giving the landscape an open appearance. The terrain may be flat or undulating. There are many trees and buildings.*

Figure 1.5: Example of terrain corresponding to roughness class 3: urban districts, forests, and farm land with many windbreaks ($z_0 = 0.40$ m). The farm land is characterized by the many closely spaced windbreaks, the average separation being a few hundred metres. Forest and urban areas also belong to this class.

Example of a terrain corresponding to roughness class 4: tall forests. The tree density may vary from sparse to dense. Roughness lengths of forests may – depending on tree height and stand density – typically range from 1 to 3 m.

Figure B.2:

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