FFI-RAPPORT

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a general and robust methodology

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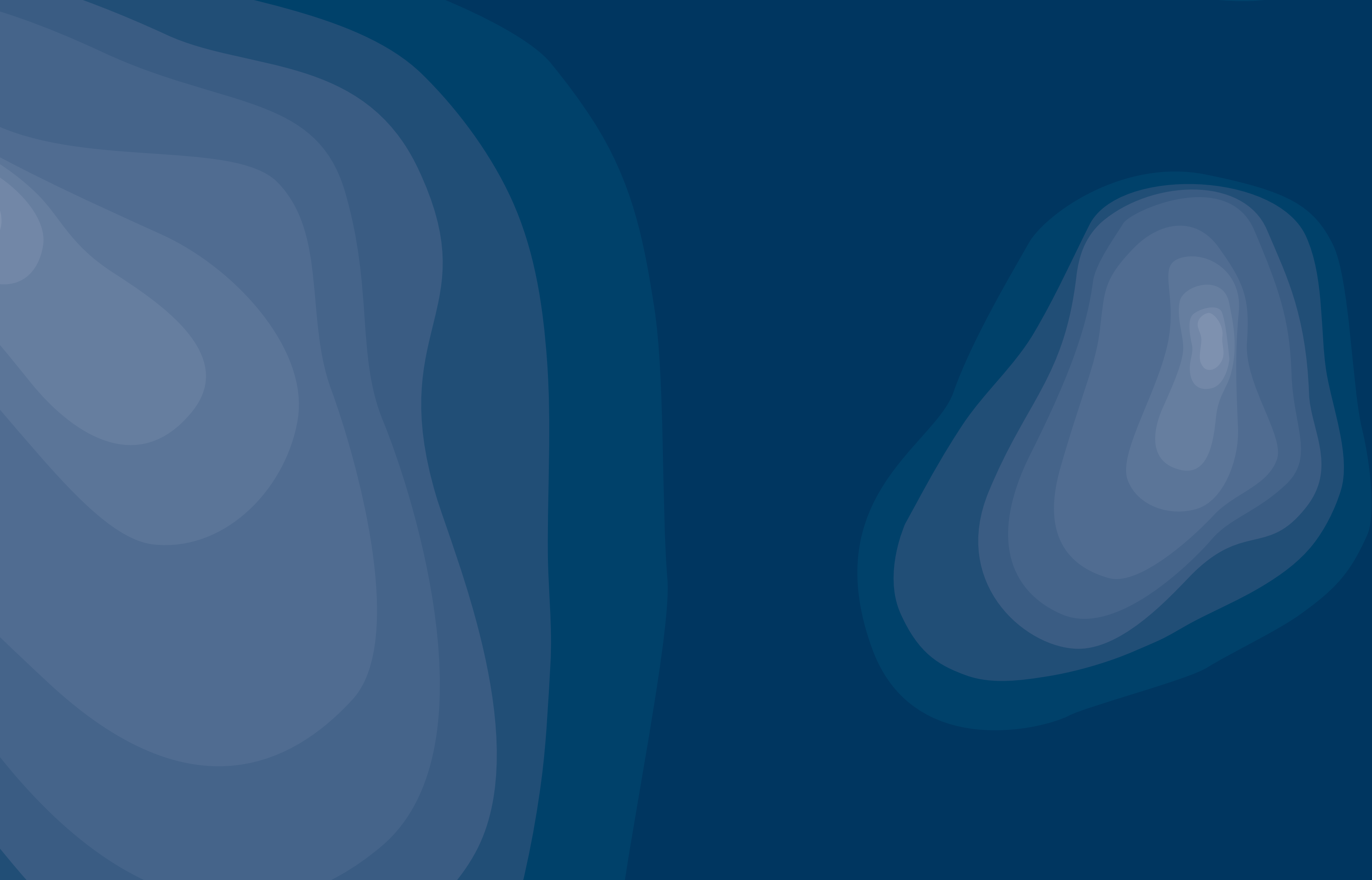

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(U) Summary

The present report details appropriate methodology and choice of parameters for the conversion of graphical information-system data into computational meshes suitable for computational fluid dynamics (CFD) simulations. The work is presented in the context of FFI Project 1394 (UNOS), which concerns the development of high-quality operational hazmat dispersion models for use in urban environments. However, the guidelines and workflow reported herein are relevant to any case in which CFD simulations of a geographical area is of interest. Moreover, the methodology presented is general, enabling robust and quick generation of CFD meshes of any area of Norway, usually within a day or two of work.

(U) Sammendrag

I denne rapporten redegjøres det for passende metodikk og parametervalg for konvertering av kartdata til beregningsnett (*mesh*) egnet for beregningsorientert fluiddynamikk (CFD). Arbeidet presenteres i sammenheng med FFI-prosjekt 1394 (UNOS), som omhandler utvikling av operative spredningsmodeller av høy kvalitet for bruk i urbane områder. Det må imidlertid presiseres at metodikken som presenteres er generell og kan brukes til å generere et CFD-beregningsnett for ethvert geografisk område i Norge på en robust og rask måte, vanligvis i løpet av èn til to dagers arbeid.

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Preface

FFI Project 1394 is partly a collaboration with the Naval Research Laboratory (NRL) in Washington, D.C, in the United States. In particular, NRL is responsible for development and maintenance of the front-end software, CT-Analyst®, as well as production of the Nomografs™ required for that software to work. Further details are supplied in the report.

Abbreviations

The following abbreviations are introduced and used in the text:

AOI	area of interest
CFD	computational fluid dynamics
DEM	digital elevation model
FKB	felles kartdatabase (*common map database*)
GIS	geographic information system
IED	improvised explosive device
LES	large-eddy simulation
NRL	Naval Research Laboratory
RANS	Reynolds-averaged Navier-Stokes
STL	stereolithography, a 3D-model format
UTM	Universal Transverse Mercator

PART I

Hazmat dispersion modeling for urban environments

1 Background

In the context of urban safety, outdoor air dispersion of hazardous materials (hazmats) comprises a potential threat to public health. Whether the release of a chemical, biological or radiological agent is accidental (e.g. from an industrial incident) or intentional (e.g. from a terrorist attack), the agent is ultimately dispersed by means of turbulent winds for distances which may range up to several kilometers or more.

The National Strategy for CBRNE-preparedness in Norway (Ministry of Justice and Public Security, Ministry of Health and Care Services, Ministry of Defence, 2016) as well as a recent White Paper to Parliament on societal security (Ministry of Justice and Public Security, 2016) state that improved chemical emergency preparedness is a governmental priority.

Atmospheric dispersion modeling commonly range from near-field modeling comprising only up to a few hundred meters to meteorological models which can predict dispersion over entire continents (cf. e.g. Miller and Hively (1987); Vardoulakis et al. (2003); Holmes and Morawska (2006)).

The application of dispersion models to predict hazmat dispersion in urban areas has a range of uses: It can have a preventative effect as an aid in decision-making (i.e., risk-management) related to e.g. city planning, transportation routes, or resource allocation. Furthermore, it may play a part in emergency preparations through e.g. personnel training or consequence analyses. Dispersion models can also be used as a tool for air quality predictions related to city pollution management.

In the event of an actual emergency, an easily accessible and fast model could be used operationally and yield useful information about contaminant areas, danger zones, evacuation routes, etc.

Finally, dispersion models can be employed after the occurrence of a hazmat incident. For example, dispersion models may help determine the location and size of the hazmat source, if unknown (co-called “backtracking”). In the case of an explosive source, some models can be used to estimate where bomb residue can most easily be found.

Hazmat dispersion through air is significantly different in urban areas compared to that in unpopulated landscapes. The buildings of a city instigate additional turbulence and mixing; at street level, effects such as street channeling or building-induced vortex shedding can change the mean wind direction completely from the overall meteorological conditions, cf. e.g. Pal (2001), p. 346, or Fernando (2012).

2 Dispersion modeling

The dispersion models which presently exist can be classified into three groups.

The first class of models represents the simplest and fastest modeling procedure, also known as “operational dispersion modeling”. It is easily employed by operatives in the field or by use of pencil and ruler on a map. Given a hazmat dispersion source and a mean wind direction, an area defined by a circle or a triangle is defined as the danger zone, within which people might be exposed to the dispersed contaminant. If the wind velocity is small or the area is highly affected by urban geometry, a circular region with its center at the source location is typically used. Otherwise, a triangle is used, and one corner of the triangle is placed at the source location.

The diameter of the circular danger zone and the angle and size of the triangular danger zone can vary from model to model[1], but the pros and cons of such models are the same: While fast and easily employable, they are inaccurate and uncertain. At best, the danger zone is much larger than necessary, possibly resulting in exaggerated evacuation, and at worst, the danger zone is too small, possibly resulting in injuries or loss of life. The models do not incorporate any effects of topography or buildings.

So-called Gaussian puff models represent a more sophisticated class of models, in which the level of complexity varies greatly (cf. eg. Holmes and Morawska, 2006). The simplest puff models are almost at the level of the operational models, whereas the more complex varieties can incorporate variations in geometry and meteorology, to some extent. Common to all puff models is the use of model parameters which are tuned according to the case in question. Given a dispersion scenario, a typical puff model may compute a prediction within a few minutes, but the time required differs significantly depending on the complexity and spatial extent of the scenario.

The most complex class of models incorporate computational fluid dynamics (CFD), in which equations representing the physics of fluid flow are solved. Typically, CFD solvers aim to generate solutions which satisfy momentum and mass conservation at all points within a specified geometry. By solving additional equations governing the dispersion of hazardous materials, reliable dispersion predictions can be obtained. Consult e.g. Versteeg and Malalasekera (1995) for an introduction to CFD. Due to increasing computational resources, CFD has become a popular tool for reasonably accurate dispersion modeling in recent years (Lien and Yee, 2004; Coirier et al., 2005; Lien et al., 2006; Santiago et al., 2007; Lateb et al., 2016).

Needless to say, the CFD-based approach is the most time-consuming of the three kinds of dispersion modeling. Additionally, it also usually requires more user experience, as well as information about the flow conditions at the boundaries of the domain of interest. However, also within the class of CFD models, the complexity varies from two-dimensional turbulence-averaging models to highly accurate models which give three-dimensional time-varying predictions of the dispersion. Nevertheless, for urban areas, CFD models generally provide significantly better predictions of street-level hazmat concentrations than do Gaussian puff models (Pullen et al., 2005).

It is important to note that experimental work also plays a large role in the development of dispersion models. Both wind-tunnel modeling and large-scale field trials are important tools

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[1] In Norway, the Norwegian Defence uses 90° (personal communication, Lt. Col. P.-I. Ohrstrand, Norwegian Army, 2016), whereas the Fire Dept. uses 60° (personal communication, J. K. Kristiansen, Oslo Fire Dept., 2016).

for validating and improving the dispersion models, as well as for observing and understanding certain features of the dispersion itself. The comparison of experimentally obtained measurements and computationally derived values from a dispersion model is not always trivial. For example, uncertainties about experimental conditions, scaling issues, or even principally different underlying assumptions may complicate the comparison (Obasaju and Robins, 1998; Hertwig et al., 2017).

2.1 Dispersion modeling at FFI

Dispersion modeling within the CFD framework has been carried out at the Norwegian Defence Research Establishment (FFI) in many different contexts, both military and civilian, over the previous decade (Wingstedt et al., 2012; Fossum and Petterson Reif, 2012; Fossum et al., 2012; Gjesdal et al., 2013; Vik et al., 2015; Aalbergsjø and Vik, 2016; Endregard et al., 2016; Wingstedt et al., 2017; Osnes et al., 2017). Applications range from simple Reynolds-averaged Navier-Stokes (RANS) models of passive, neutral gas dispersion in closed geometries to outdoor dispersion of dense gases in stratified environments and dispersion from improvised explosive devices (IEDs).

The CFD-based dispersion methodology presently used at FFI utilizes RANS or, more often, large-eddy simulation (LES) turbulence models, implemented in a finite-volume solver. FFI currently operates a cluster of more than 1000 CPUs, suitable for performing high-fidelity dispersion simulations for relatively large areas.

The main rationale for using CFD instead of the faster, less complex classes of dispersion models is essentially that the turbulence present in almost all real-life air flows directly affects the mixing and dispersion of hazardous materials, often significantly. Turbulence, in turn, depends strongly on the geometry of the problem. Thus, to correctly capture one of the most important physical phenomena affecting hazmat dispersion, CFD is required. Further reading on the topic of turbulence and turbulent dispersion can be found in e.g. Tennekes and Lumley (1972); Durbin and Petterson Reif (2011).

Commonly, most high-quality CFD dispersion simulations take time and require a lot of computational resources. In some cases, only a few hours are required, but for larger areas with more geometry, days, weeks, or even months might be needed. Hence, CFD-based dispersion models are usually used for planning, design and training purposes or to shed more light on prototypical dispersion processes. It has not generally been possible to use CFD in an operational context, e.g. as a dispersion tool used for crisis management during a hazmat incident.

3 FFI Project 1394 (UNOS)

FFI Project 1394 (“Utvikling av nestegenerasjons operative spredningsmodelleringsverktøy”, “*Development of next-generation operational dispersion modeling tools”*, UNOS), is motivated by the desire to combine the high-fidelity physical modeling approach of CFD with a fast-response, easy-to-use dispersion modeling tool based on the use of precalculated data.

The central idea of the project is that by precomputing extensive CFD simulations for a desired geographical area, the results can be used as a “look-up table” by suitable computer software. That is, one can use the precomputed CFD data to make quick, yet accurate, dispersion predictions. In Project 1394, a demonstration version of such a dispersion modeling tool will be created for a central part of Oslo. Similar software has already been created for other urban areas by our collaborator on this project, the Naval Research Laboratory (NRL) in Washington, D.C. (cf. e.g. Boris et al., 2004; Patnaik and Boris, 2007).

> By using high-quality precomputed wind fields from CFD simulations, dispersion predictions can be calculated quickly and accurately for a predefined area of interest via streamfunctions.

It is clear that to make the dispersion tool outlined above, several steps are required, as outlined in the following:

1. **Area of interest** Firstly, the area of interest (AOI) must be decided upon. Depending on the intended end-user base of the tool, the area could contain important hazmat transit areas, such as docks, train stations and loading terminals, or potential terrorist targets, for example symbolic buildings, highly populated city centers, or important infrastructure. One could also choose an AOI centered around an important industrial site or defence installation. In the demonstration version developed in Project 1394, an area of downtown Oslo roughly enclosed by the road Ring 3, approximately 100 km^2, is chosen.
2. **Creating a 3D model** Given an AOI, geographic information system (GIS) data is used to generate a 3D model of the urban geometry. The GIS data needs to be processed in a particular way in order to yield a 3D model suitable for computational meshing and subsequent simulation. In particular, the model should be topologically coherent (i.e., be “airtight”) and have an appropriate level of detail.
3. **Creating a computational mesh** Once a topologically sound 3D model of sufficient quality has been created, the model must be discretized into a computational mesh. This entails subdividing the model into millions of smaller, geometrically simpler shapes, such as tetrahedrons.
4. **Computational parameters** The system of equations which represents the physics of the air flow within the AOI is implemented in suitable computer software, as is all relevant information regarding wind conditions at the boundaries of the AOI. Other parameters, such as temperature, gravity or surface roughness may be specified if relevant.
5. **Simulation** Once the code and the chosen set of parameters are ready, 18 simulations will be performed for each chosen weather regime. These simulations will cover the entire 360° wind

rose in 20° intervals, yielding enough data in total to enable interpolation to any arbitrary prevailing wind direction. High-Reynolds number flow implies that wind speeds can also be scaled linearly based on the simulation results.

6. **Post-processing, including validation** The results of the simulations must be post-processed to condense the information into a format suitable for the resulting dispersion model. During this process, the results will also be checked for errors and validated against appropriate reference data.
7. **Create front-end computer program** As a final step, the front-end graphical user interface which is used for dispersion modeling is compiled. GIS data is combined with a dispersion model relying on the CFD simulation data, so that accurate and instantaneous results are displayed directly on a map over the AOI.

In the subsequent parts of the report, only steps 1–3 will be discussed. These steps constitute practical knowledge that could also be of use in other applications. The computational methodology related to steps 4–6 will be treated in a separate report. Analysis of results pertaining to the flow simulations will, if time permits, be published as peer-reviewed academic papers.

The work flow outlined above is a collaboration between FFI and NRL. In particular, steps 1 and 2 will be completed by FFI, whereas step 7 will be accomplished by NRL. Steps 3–5 are conducted both at FFI and NRL, and step 6 will be a collaborative effort.

In addition to the creation of a dispersion modeling tool for Oslo, Project 1394 includes collaborative research on extensions of the software. Among others, modeling of dense gas dispersion and thermal plume evolution, as well as inclusion of spatially and temporally varying meteorological data from forecast models, will be considered.

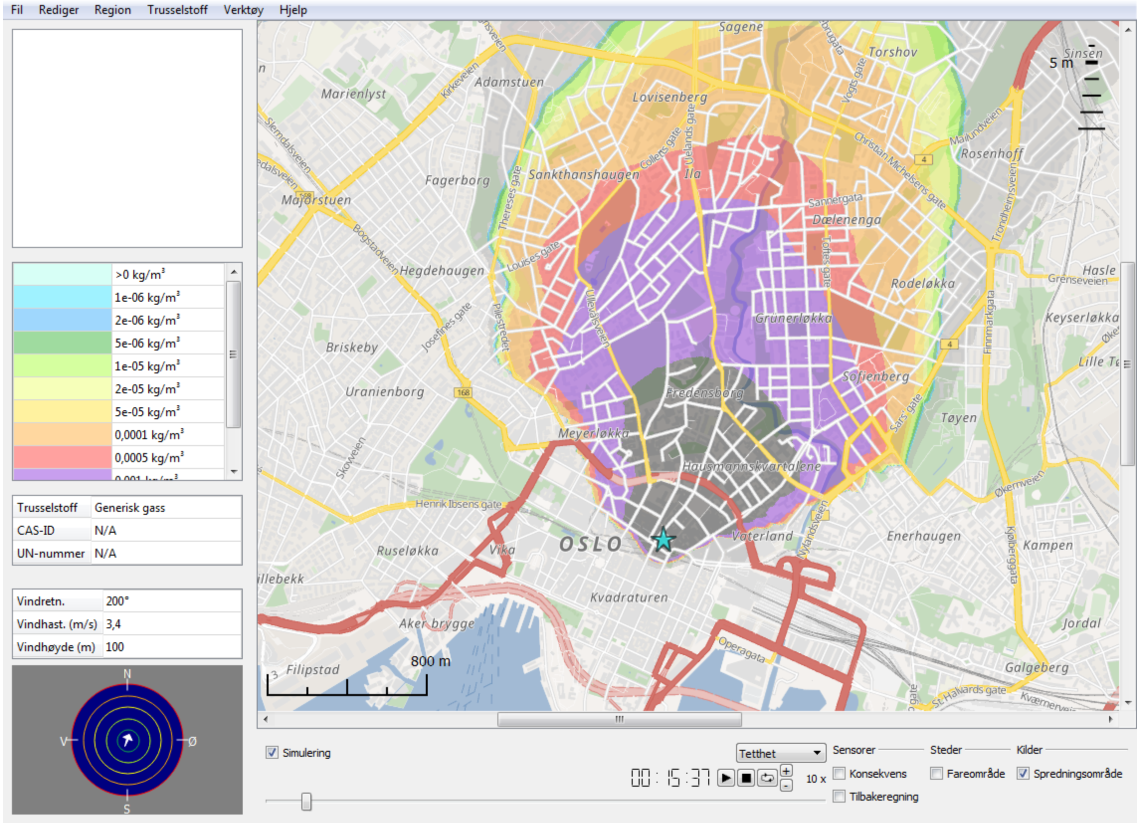
Before moving on to the next part, which is concerned with GIS and CAD modeling exclusively, a brief summary of NRL's dispersion modeling tool, CT-Analyst, is provided for context. The following thus pertains to step 7 in the work flow given above.

3.1 CT-Analyst®

NRL is developing software, called CT-Analyst®, that can utilize comprehensive databases consisting of massive amounts of CFD simulation data condensed to statistics relevant for dispersion. A front-end graphical user interface, also created at NRL, is then used to interpret the statistical datasets in a GIS context. Thus, end-users will be able to quickly and easily predict and visualize hazmat dispersion on a map, given specified meteorological conditions. The system responds instantaneously and is easy to understand and use without knowledge of fluid mechanics.

The essential feature of CT-Analyst® is how the enormous CFD database is processed to enable quick dispersion predictions. By first calculating a weighted vertical average of the three-dimensional temporally averaged flow field, a plane of mean and root-mean-square velocities are obtained for each simulated wind direction. This information is then used to generate streamfunctions, so-called Nomografs™ for left and right plume edges. Within CT-Analyst® , a source's plume edge is then rapidly determined by following the streamline that passes through the source. No knowledge of the source strength or type is needed to predict the hazard area. Combined with key data from CFD-modeled plumes, concentration within the plume, as well as plume arrival times, can also be predicted in CT-Analyst® . By interpolating between simulated wind directions, any arbitrary wind direction (and speed) can be chosen. Thus, results from accurate CFD models are used to obtain realistic local wind conditions in urban environments, which in turn are used for dispersion predictions via plume-edge streamfunctions.

A screenshot of a preliminary test version of CT-Analyst® for Oslo is given in Figure 3.1. The final version may differ somewhat from the screenshot. More information on CT-Analyst can be found in e.g. Boris et al. (2004); Patnaik and Boris (2007); Boris et al. (2011).



🟦	>0 kg/m³
🟦	1e-06 kg/m³
🟦	2e-06 kg/m³
🟩	5e-06 kg/m³
🟩	1e-05 kg/m³
🟨	2e-05 kg/m³
🟨	5e-05 kg/m³
🟧	0,0001 kg/m³
🟥	0,0005 kg/m³
🟪	0,001 kg/m³

Trusselstoff	Generisk gass
CAS-ID	N/A
UN-nummer	N/A

Vindretn.	200°
Vindhast. (m/s)	3,4
Vindhøyde (m)	100

☑ Simulering

00 : 15 : 37

10 x

☐ Konsekvens

☐ Tilbakeregning

☐ Fareområde

☑ Spredningsområde

Figure 3.1 *A screenshot of a preliminary test version of CT-Analyst® Oslo. The colors represent different concentration values of a generic gas.*

PART II

Creating computational meshes from geographical information-system (GIS) data

4 Obtaining GIS data for the area of interest

As part of a national collaborative consortium, *Norge Digitalt*[2], FFI has access to detailed GIS data of Norway. Among others, these data contain digital elevation models (DEM) of the terrain and extensive information about buildings and other structures. Additionally, data on vegetation, land use, waterways, etc. is also available.

The DEM data used for this project is the “standard” Norwegian DEM data, which is resolved at ten meters horizontally. The horizontal resolution leads to up to 3 m standard deviation in the vertical elevation, depending on the terrain and production date of the GIS data. The building data is retrieved from the so-called “felles kartdatabase” (FKB) data for Oslo and is processed as outlined shortly. For all practical purposes, the building data can be regarded as exact.

The actual AOI used for the demonstration version is chosen based on the following criteria:

- It should contain both residential and commercial districts.
- It should contain downtown Oslo.
- It should contain at least one cargo terminal (preferably one port and one train station).
- If known in advance, it should contain areas used in national emergency response exercises.

As a result of these considerations, the area within the road Ring 3 will be used, as well as parts of adjacent areas. Figure 4.1 illustrates the area chosen for the demonstration version of CT-Analyst® Oslo. The area will measure about 150 m^2, and the Universal Transverse Mercator (UTM) coordinates (WGS84, zone 32N) of the lower left and upper right corners are, respectively,

$$\begin{aligned} \text{Lower left:} \qquad & (591700, 6638400) \\ \text{Upper right:} \qquad & (606200, 6649400) \end{aligned} \tag{4.1}$$

It should be noted that the area chosen for the demonstration version can be expanded later without having to recompute the bulk of the original area. Similarly, if significant local changes occur within the existing area, e.g. due to large reconstruction projects in the city, areas affected by the change can be recomputed separately and “patched” onto the larger existing area.

In the following, the workflow for generating suitable computational meshes from GIS data will be described, along with certain details related to appropriate parameter choices and approximations. While the workflow and parameters given have been developed and chosen to enable efficient processing of the large AOI used for the demonstration version, smaller geographical subsets may be used as examples throughout the text. In other words, the process described can be used for any AOI in Norway[3].

Once the AOI is chosen, the relevant GIS data can be downloaded from the *Norge Digitalt* web portal. The GIS data files are separated into terrain data (DEM, in the form of TIFF raster files), building data (FKB, in the form of vector Shapefiles), waterways (FKB) and vegetation (FKB), among others. Each of these datasets must be clipped to the coordinates given above.[4] The free, open-source GIS package GDAL can be used for this purpose by means of its tools `ogr2ogr` (for clipping FKB data) and `gdal_translate` (for clipping DEM data).

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[2] `https://www.geonorge.no/Geodataarbeid/geografisk-infrastruktur/Norge-digitalt/`

[3] However, different levels of approximation may be used for differently sized AOIs.

[4] If the AOI covers several counties, the county datasets must also be merged.

Figure 4.1 *The area of interest chosen for the demonstration version of CT-Analyst® Oslo, shown in Google Earth. The dimensions of the area are 14.5 × 11 km*^{2}.

5 Processing the GIS data

Once the GIS data for the chosen AOI has been downloaded and clipped, GIS software is used to clean and simplify the data. It is, however, imperative that the clean-and-simplify procedure is as automatic as possible. For an area as large as Oslo, manual GIS tweaking on a per-building basis is at best impractical and expensive. More likely, it is essentially impossible within a reasonable timeframe.

In Project 1394, ESRI's ArcGIS for Desktop 10.4 is used. ArcGIS is a powerful software which contains many useful tools. For the procedure developed in the present project, the Integrate, Itersect, and Dissolve capabilities are the most important tools, as well as the ability to manipulate data attribute fields. Via a semi-automatic process combining these features with other suitable script-based tools, it is possible to generate a "CFD-friendly" 3D model of any area in Norway in less than a day's work. This is a direct result of Project 1394.

The vector GIS data available from *Norge Digitalt* is incredibly detailed and contains far more information than is required for a CFD mesh. Among others, it contains information related to chimneys, stairways, patios, work sheds, skylights, and so forth. Furthermore, these data are not well-connected in a topological sense. For example, the vector polylines describing the edges of a roof seldom comprise one nice rectangle. Rather, several line segments, which may not perfectly align (horizontally or vertically), are used. This is due to the way the GIS data has been collected, and it represents a major challenge for using the GIS data to construct a topologically well-connected 3D model.

Unfortunately, the ideal way to reduce the comprehensive GIS data to a level suitable for 3D CFD meshing is not obvious; figure 5.1 exemplifies the original and resulting GIS data following appropriate simplification. Nevertheless, the goal is a GIS dataset which adheres to the criteria discussed in the following.

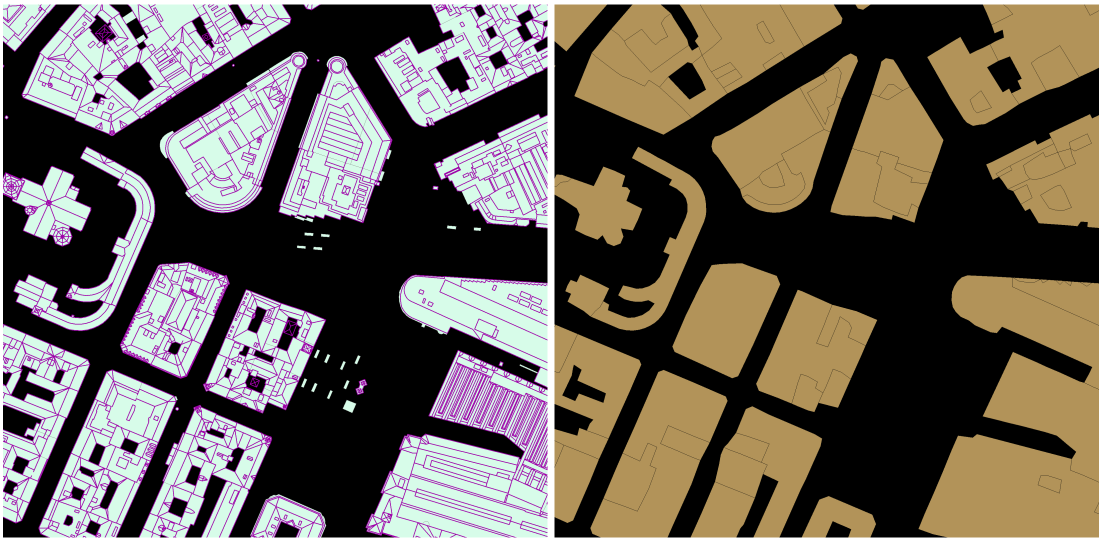

Figure 5.1 *GIS data for Oslo before (left) and after (right) suitable data processing.*

5.1 Criteria for suitable GIS data

Whereas city planners, architects, and gaming developers need their 3D models to look as "nice" and realistic as possible, without too much concern that their models may have tiny flaws no one can see, the criteria for CFD simulations are quite different. The primary goal in the latter case is not a visually appealing model. In fact, textures and minor geometrical details are irrelevant in the context of large-scale urban CFD modeling. Instead, the topology is the most important factor.

5.1.1 Topology

A 3D model used for CFD meshing must be topologically well-connected. That is, the 3D surface consisting of terrain and buildings must be "airtight". No holes, leaks, overlaps, or glitches can be present. In terms of GIS data, this means that

- no building polygons should overlap each other,
- all polygons must be perfectly closed loops, and
- very small distances between adjacent vertices should be removed.

The notion of "very small" distances refers to distances less than the intended CFD mesh resolution, which presently implies distances of less than approximately 1 m. The removal of such distances generally entails merging of multiple adjacent vertices.

5.1.2 Level of detail

Another critical issue is the level of detail of the GIS data. While the ideal might be to have as much detail as possible, the final level of detail of the CFD mesh should be kept in mind. Details much finer than the intended mesh resolution are unnecessary, and may, in some cases, lead to difficulties in generating the mesh.

From a fluid dynamical viewpoint, fine GIS details, such as small patios, stairwells, or carports, compare with many non-permanent urban-environment features like cars, trash cans or signal lights. The absence of such small-scale objects in the CFD mesh are negligible for the large-scale fluid flow field and consequently also for hazmat dispersion over long ($\gtrsim$ 500 m) distances.

5.1.3 Vertical variations

The vertical variations of the terrain is given by the accuracy of the DEM rater data, and need not be modified.

The building heights stored in the GIS vector data should be processed slightly, so as to minimize unnecessary meshing complications. Again, the intended CFD mesh resolution serves as a guide; by approximating all building heights to the nearest N meter, many adjacent buildings – sometimes entire blocks – can be merged into one, so as to simplify the subsequent 3D modeling and meshing process. The value of N could be constant or vary with height[5]. As an example, with $N = 5$, all building heights are rounded off to the nearest 5 meter, resulting in buildings with heights of 0, 5, 10, 15, . . . m only. This can in turn lead to fewer building objects in the 3D model and a better-conditioned CFD mesh.

The official Norwegian GIS data (from *Norge Digitalt*) comprises several different vector datasets for buildings: The most important is the polygon dataset which contains the footprints of all buildings. The building height is stored as an attribute of each individual polygon. However, many buildings contain smaller elevated parts, such as towers or partly raised landings. Such elevations can be fluid dynamically relevant (if large) and are rarely contained in the polygon dataset.

In addition to the polygon GIS data, a polyline dataset exist. This dataset is enormous and contains a number of different lines to describe building roofs and fronts. By processing the dataset correctly, most of the important building elevations can be recovered and combined with the footprints from the polygon dataset. The elevations should then be subjected to the same rounding-off and combination procedure as described for the ordinary building polygons. Thus, a resulting merged GIS dataset can be created, containing all relevant buildings and elevations with their corresponding (approximate) heights.

It should be noted that the GIS processing described in the above leads to buildings exclusively with flat roofs. This is an acceptable approximation for the present purpose of dispersion modeling.

5.1.4 Accuracy

While the level of detail of the GIS data should not be exaggerated, the accuracy should obviously be as high a possible. In essence, this means that whereas certain polygon vertices may be removed to reduce the level of detail, all remaining vertices should retain their original coordinates. If two vertices are merged, the resulting vertex should represent the two original vertices as closely as possible.

Similarly, although building heights may be approximated to the nearest N meter, the original value used to determine round-off values should be as accurate as possible. Accuracy in this regard implies both data reliability (which is considered very high in the case of the Norwegian official GIS data) and numerical accuracy (in terms of significant figures).

5.2 Converting to a 3D model

There are several tools for converting GIS data into a 3D model. In the present case, a robust tool is desired rather than a sophisticated one.

5.2.1 Raster data

The DEM raster data for the terrain is converted from its native TIFF format to the 3D standard format STL (STereoLithography) by means of a code written at FFI during Project 1394. The

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[5] N as a function of height can be a good idea since CFD mesh resolution commonly varies with height.

output is thus a 2D surface in 3D space which describes the topography of the chosen AOI. The UTM coordinates of the AOI are retained in the STL output file.

5.2.2 Vector data

The GIS vector data for the buildings are exported as Shapefile data. An open-source `Node.js` script[6] then converts this Shapefile into STL sets of surfaces, based on the building heights stored in the Shapefile. The STL surfaces comprise the roofs of the buildings – which correspond to the polygons in the GIS data – and the building side walls – constructed from the polygon boundaries.

5.2.3 Preparations

Once the GIS data has been converted to STL files, the STL data is merged and processed in appropriate CAD software. In Project 1394, the ANSYS tool ICEM CFD 16.2 is used. The modifications to the raw STL data consist mainly of topology feature extractions and clean-up, such as generating intersection curves between different surfaces, and the construction of a closed volumetric domain, usually a rectangular (or rather, hexahedral) box. The bottom of the domain box comprises the terrain and buildings, whereas the sides of the box commonly represent the north, south, east, and west boundaries of the computational domain. The height of the top of the box determines the vertical extent of the computational domain (and thus the CFD mesh).

Figure 5.2 illustrates the desired level of detail of the 3D model generated from processed GIS data.

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[6] `https://github.com/dougmccune/shp2stl`

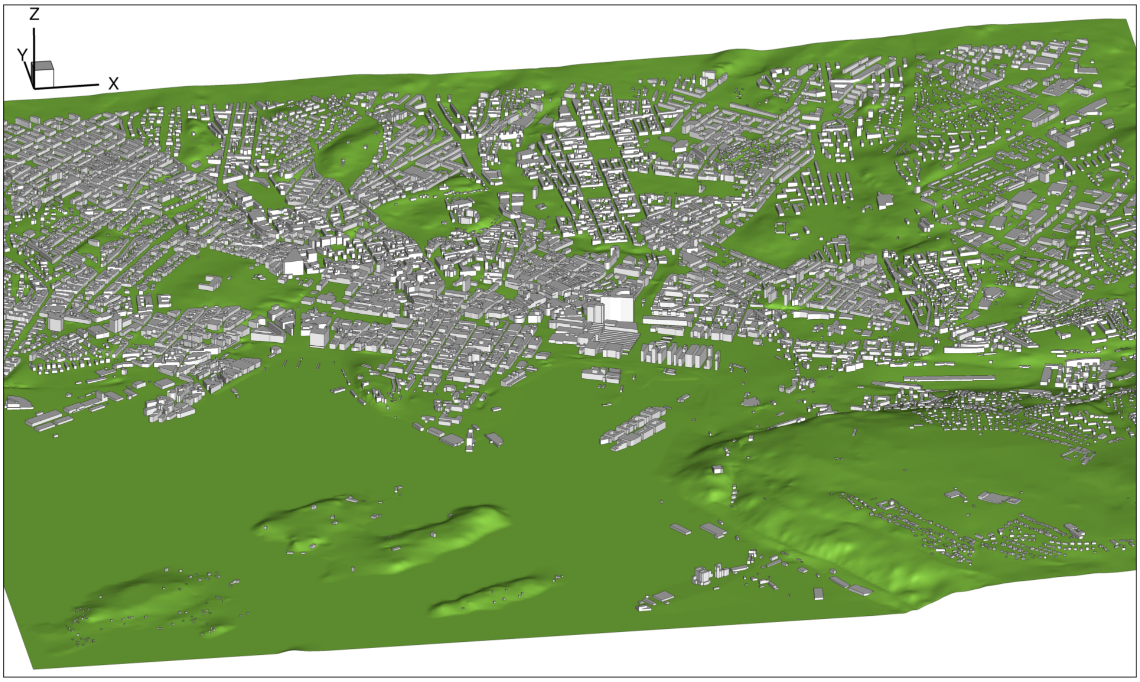

Figure 5.2 *A northward view of a 5×5 km^2 subset of the Oslo geometry (preliminary version), illustrating the level of detail and scope of the desired 3D geometry. In this example, building heights are rounded to N = 5 m.*

6 Creating the computational mesh

Once a suitable 3D model is ready, it needs to be *discretized*, i.e. divided into a large number of small, geometrically simple shapes. These shapes comprise what we call the computational mesh. For complex geometries, meshes commonly consist mainly of tetrahedral elements, as such meshes are easier to generate more reliably. This is also the case in Project 1394.

After testing a number of meshing strategies in several kinds of software, the ANSYS tool Fluent Meshing (v17.1) has been chosen for Project 1394, due to its robustness and speed. By importing 3D-model files from ICEM CFD, further mesh parameters (such as sizing) can be specified in Fluent Meshing before the mesh is generated. As long as the imported data is topologically sound (as discussed earlier), the meshing algorithm reliably produces meshes of high quality.

In the case of tetrahedral CFD meshes, the main quality criteria are topological connectedness, well-posed elements, suitable element sizes, and appropriate size transitions. Usually, the first requirement is satisfied if the input geometry is topologically sound and the mesh element sizes are not too large. ‘Well-posed elements” typically means that the aspect ratios and angles of the elements are not too small or too large. Very obtuse or acute angles should be avoided. Mesh sizing is perhaps the most difficult parameter choice; a balance must be found between computational tractability and resolution of important details. The last mesh requirement implies that there should be no abrupt changes in element size. For example, further away from geometrical details or boundary layer regions, the mesh size should gradually increase.

The mesh parameters chosen in Project 1394 can be outlined as follows.

- Near the ground (open regions), the mesh element sizes range from 3 to 6 m.
- Near buildings (urban regions), the mesh element sizes range from 3 to 12 m.
- Moving away from the ground or building surfaces, the element size grows geometrically with a ratio of 1.1.
- The computational mesh has a vertical extent of 1 km.

With the above meshing parameters, the mesh generally contains approximately 400,000 computational nodes[7] per km^2 area to be modeled. It should be noted, however, that this number is strongly dependent on building size and density.

An example of the resulting (surface) mesh is shown in Figure 6.1. This figure also highlights the level of detail of the geometry; it should be evident that the level of detail matches the mesh resolution appropriately, as desired.

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[7] Computational mesh nodes correspond to vertices of the computational mesh elements.

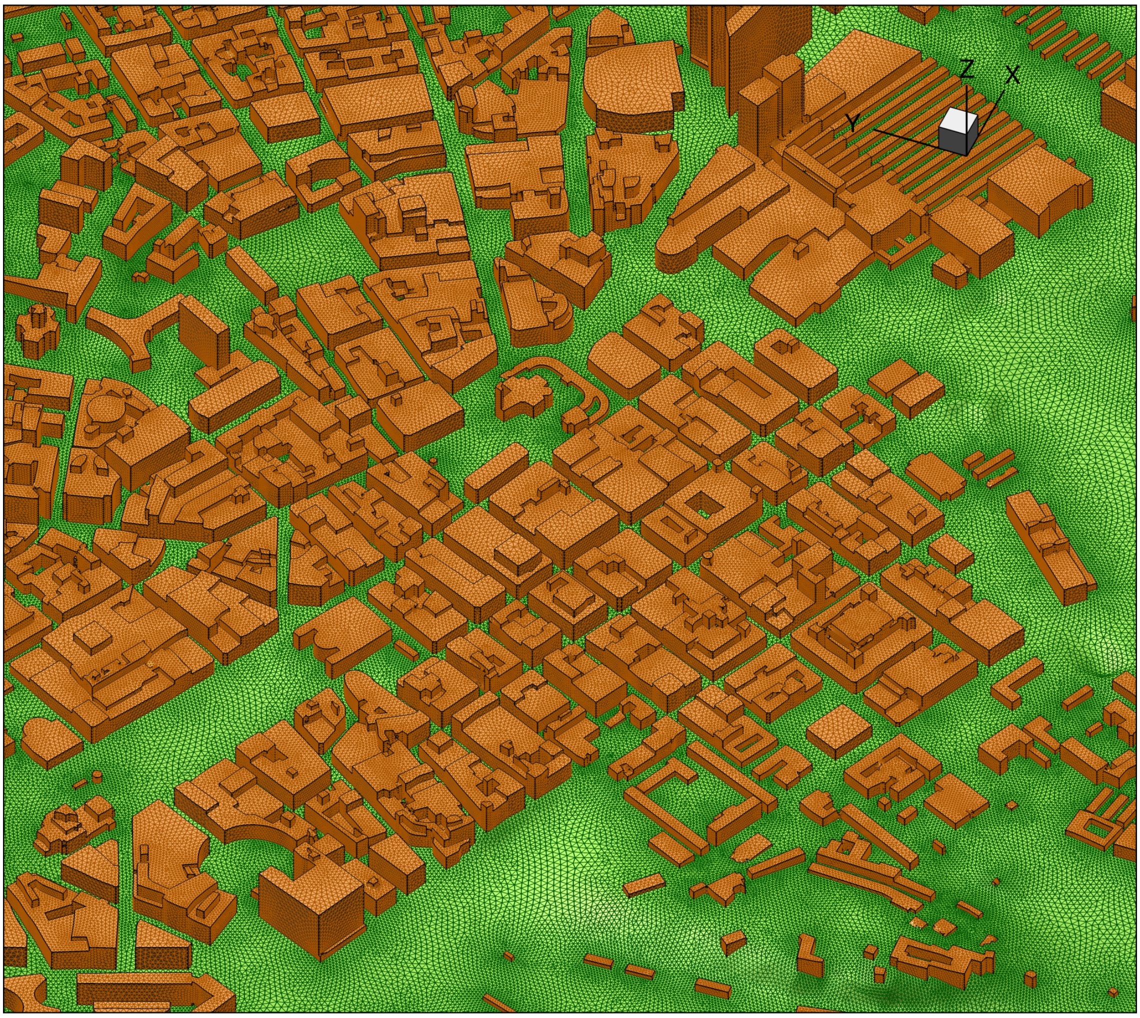

Figure 6.1 *A northeastward view of a small part of the Oslo mesh (preliminary version). Oslo Central Station can be seen in the upper right corner.*

PART III

Concluding remarks

7 Future work

Once a suitable mesh is ready for a selected AOI, the next step will be CFD flow simulations (cf. Section 3). The setup of the simulations, as well as interpretation and postprocessing of the simulation results, are the next main steps in Project 1394. The final milestone is of course the dispersion tool, CT-Analyst.

At present, numerous preliminary simulations have already been performed, and all necessary functionality have been implemented in the CFD simulation code. Shortly, all 18 wind directions (neutral stability conditions) will be simulated for a chosen AOI. The estimated time frame for the computations per se is approximately 6–12 months, depending on the availability of computational resources.

Figure 7.1 illustrates an example result of a simulation of the wind field in Oslo. Such local mean wind data is used as a basis for the dispersion tool in Project 1394.

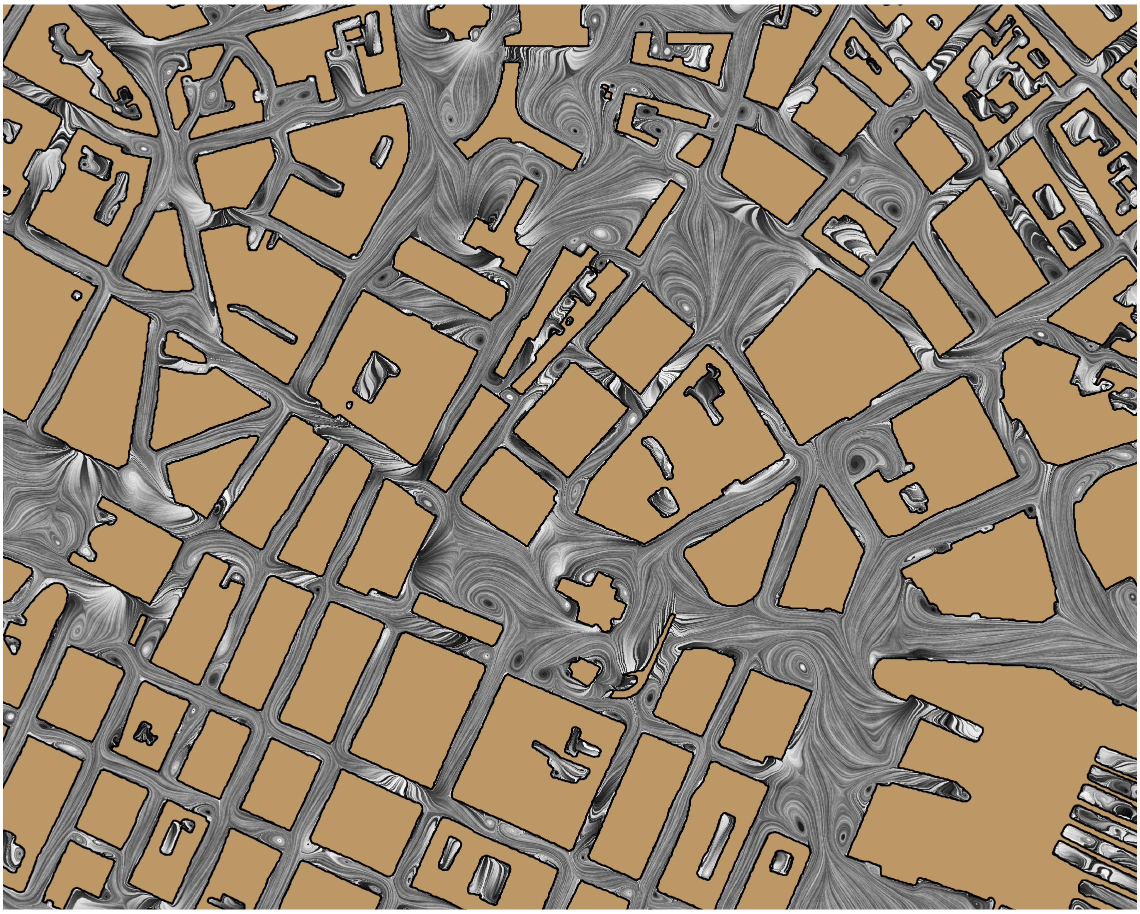

Figure 7.1 *The simulated local mean wind field in the streets of Oslo (at height 4 m) when the prevailing (global) wind is from the south. The wind field is illustrated via the line integral convolution technique.*

7.1 Rivers and oceans

GIS data for river and ocean surfaces is readily available. As of yet, this data has not been utilized. Small rivers (which include all rivers in Oslo) affect hazmat dispersion insignificantly on the scales considered here.

Ocean surfaces – such as the Oslo fjord – can generally also be neglected, provided that two conditions are fulfilled. Firstly, the temperature difference between the water surface and the air should be sufficiently small so that strong stratification is avoided. Secondly, the dispersion tool which performs the actual dispersion should have a lower bound on its local lateral dispersion, so that a minimum plume angle is guaranteed, even above non-urban “terrain” such as water surfaces. This ensures that dispersion in such areas will not be underestimated. Such a constraint is already implemented in CT-Analyst®.

The first condition is, at present, assumed to be true. Future plans in Project 1394 include research on effects of stratification. More specifically, it will be investigated to what extent urban dispersion (on the kilometer scale) is affected by stratification. If the effect of stratification is shown to be significant, a follow-up question is how large a temperature difference is needed to attain relevant levels of stratification and how often such stratification levels occur in Oslo. For now, effects of stratification is not considered.

The second condition warrants more research as well; it is beneficial to investigate how small the minimum lateral dispersion needs to be above oceans to ensure conservative dispersion predictions. This is a complex question, in which both surface roughness, wave kinematics and boundary-layer structure should be considered, and it may be outside the scope of Project 13934. For now, a lower bound is chosen that ensures that the dispersion predictions err on the side of caution.

7.2 Vegetation

So far, vegetation – such as forestry – has not been discussed in this report, even if it constitutes part of the GIS data. However, the GIS data for vegetation is not treated in direct relation to the geometry and meshing process. Rather, it is preprocessed seperately so that it can be imported directly into the CFD simulations. As such, vegetation will be treated in more detail in a subsequent Project 1394 report. That said, a few key issues related to vegetation will be mentioned here.

Firstly, although the CFD simulation software can handle a range of vegetation, through different kinds of models (such as wall roughness, momentum sinks, geometrical models), only forest canopies will be considered in Project 1394. Other kinds of vegetation, such as single trees and small thickets, grasslands, grain fields or bushland is irrelevant for urban dispersion models, given that the areas of such kinds of vegetation will be small and/or have negligible effect relative to surrounding buildings.

Secondly, the technical ability to include forest canopies in the simulations does not imply that the knowledge about the forest canopies in the AOI is adequate. For the Norwegian GIS data, there simply is not enough empirical data about forestry to make the models very reliable. As an example, only rough distinctions between coniferous and deciduous forests are made. Furthermore, information about tree height is completely absent. This necessarily leads to numerous rather uncertain assumptions about the forest canopies which are modeled.

Fortunately, a final point worth making is that preliminary simulations indicate that the presence of typical forest canopies in and near urban areas have little effect on the dispersion of hazmats when compared to the effect of buildings and topography. Moreover, during winter, the effect of forest canopies will be significantly less than in the summer.

In conclusion, while the ability to model forests has been implemented in the software, the empirical data is lacking, and there might not be strong reason to include effects of forests in any case.

8 Concluding remarks

A methodology to transform available GIS data into an appropriate high-quality CFD mesh has been given. Examples of parameter choices suitable for dispersion modeling in large urban areas have also been provided, in the context of Project 1394. This FFI project aims to produce a quick and accurate dispersion tool in collaboration with NRL, and the workflow detailed in the present report is a direct result of the project.

Aside from its use for dispersion modeling, the workflow that has been described can be useful for general 3D modeling of urban areas, as well as for CFD simulations of local wind, pollution, or accoustics. The methodology can in principle be used for areas ranging from approximately 50 m to almost indefinite size[8], by choosing appropriate workflow parameters.

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[8] However, for areas $\gtrsim 50 \times 50$ km^2, computational resources may be a severe limitation.

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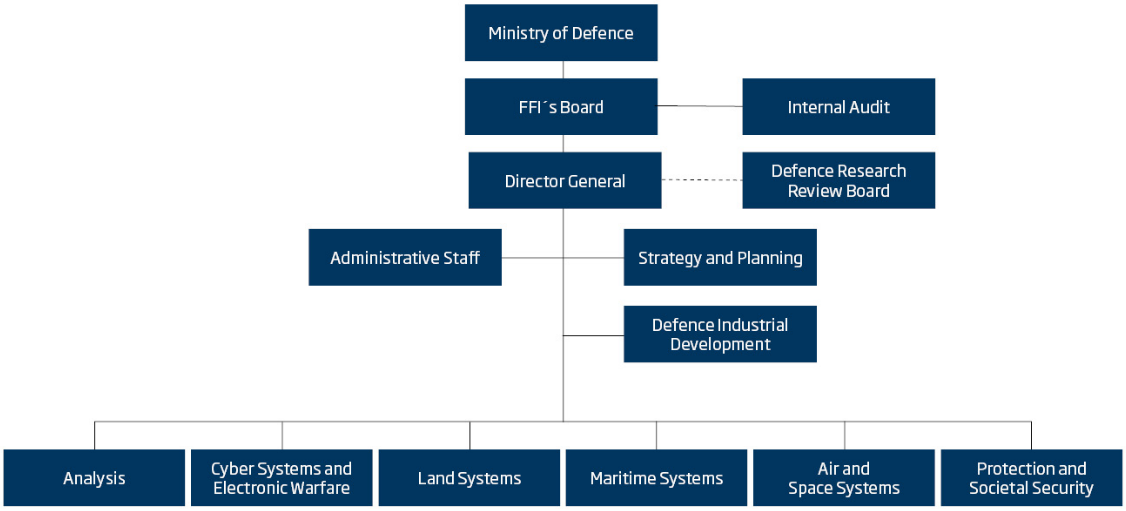

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