ASSESSMENT OF THE AIR QUALITY AT THE APRON OF COPENHAGEN AIRPORT KASTRUP IN RELATION TO THE WORKING ENVIRONMENT

Technical Report from DCE – Danish Centre for Environment and Energy No. 15 2012

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Data sheet

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Abstract: In the period 2009-2011 DCE - Danish Centre for Environment and Energy, Aarhus University assessed the air quality on the apron of Copenhagen Airport, Kastrup, in relation to the working environment. The assessment was prepared for Copenhagen Airports A/S and included measurements of pollutants on the apron, emission inventories for Copenhagen Airport, Kastrup, and model calculations of the air pollution based on the inventories. The measurements included nitrogen oxides, the mass of particles with diameter less than 2.5 µm ($PM_{2.5}$), particle number and selected organic pollutants, including polycyclic aromatic hydrocarbons. The concentrations of the majority of the species were in the same range or lower than typically measured on H.C. Andersens Boulevard in Copenhagen, that is one of the streets with most traffic in the capital of Denmark. However, the particle number at the apron were 2-3 times higher than at H.C. Andersens Boulevard. The two most important sources to air pollution at the apron were handling vehicles, the airplanes main engine and Auxiliary Power Units (APU). The present report is a translation of DCE Technical Report no. 5, 2011.

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Contents

Summary

This report presents results from an assessment of air pollution at the apron[1] of Copenhagen Airport in relation to the working environment. The Assessment has been carried out during the period 2009 to 2011 by DCE - Danish Centre for Environment and Energy, Aarhus University (DCE) for Copenhagen Airports A/S. The present report is a translation of the original Danish version of the report (Ellermann et al., 2011).

The aim of the assessment was to investigate the air pollution at the apron and to identify sources of air pollution. The study focuses on the working environment. Therefore, the emphasis is on air pollution at the apron, with focus on the areas where the staff is mainly present during the working hours.

The assessment includes air pollutants, which are suspected to cause problems regarding the working environment at the apron. These are the following: Nitrogen oxides (NO and NO_2), sulfur dioxide (SO_2), the mass of particles with diameter below 2.5 µm ($PM_{2.5}$), particle number[2] and their size distribution, particulate elemental carbon (soot), polycyclic aromatic hydrocarbons (PAH) and selected volatile organic compounds (VOC).

The assessment is based on a combination of measurements, compilation of an emission inventory and model calculations. The main elements are:

- Measurements of NO_X and $PM_{2.5}$ at the apron close to Gate B4 (Station B4 hereafter). Measurements of these compounds on the outskirts of Copenhagen Airport (Station East and West) are also included in the study. These measurements are performed by DCE for Copenhagen Airports A/S in connection with the monitoring of air quality at Copenhagen Airport.
- Measurements of particle number (6 – 700 nm in diameter)[3] and particle size at Station B4 and Stations East and West.
- Measurement campaign on the spatial distribution of air pollution at the apron.
- Measurement campaign on organic compounds, including PAH, selected VOC, particulate organic carbon and elemental carbon (soot).
- Measurement campaign on particle number and SO_2 and Station B4.
- Compilation of an emission inventory on the sources at the airport. The inventory includes emissions of NO_X, $PM_{2.5}$, VOC, carbon monoxide (CO) and total fuel consumption (jet fuel, diesel, etc.).

[1] The apron is the part of the airport where the airplanes are parked near the gates.
[2] In this report the expression "particle number" is used as a short expression for the concentration of the number of particles per volume (particles per cm^3)
[3] Ultrafine particles (diameter below 100 nm) typically accounts for 75-95% of the particle number with diameter between 6 and 700 nm.

- Modeling of air pollution levels and source contributions. The model calculations include only NO_2, NO_X and $PM_{2.5}$. Model calculations for the apron itself are performed with a spatial resolution of 5 m x 5 m in order to better address the location of sources relative to the working areas and to assess the impact of buildings on the wind flow and dispersion of air pollution.

The study has led to the following main conclusions:

The concentrations of NO_X and SO_2 on the apron are below the levels at H.C. Andersens Boulevard (HCAB) measured in connection with the Danish air quality monitoring. HCAB is one of the busiest streets in Copenhagen (approximately 60,000 vehicles per day). Concentrations are also below the EU air quality limit values for these two compounds.

Measurements of VOC's include organic substances that are partly found in the background air and partly expected to origin from sources at the apron (vehicles and aircraft), and which can cause adverse health effects. The measured VOC concentrations are in the same range or lower than typically found in urban background air in Copenhagen. N-octane and trimethyl benzene, which are related to jet fuel, are at a level of 2-6 times the levels measured in urban background, however the concentrations are still low. VOC's are not routinely measured at HCAB, and therefore cannot be compared to the levels at a busy street. Only benzene is measured at HCAB. Measured benzene concentrations at the apron are below the levels at HCAB as well as the EU limit value.

Measurements also include aldehydes, which may cause sensory irritation of the eyes, nose and throat. Aldehydes are produced during combustion of jet fuel. The average concentrations (8 hour time-integrated measurements) of aldehydes at the apron are significantly below the levels expected to cause irritation. However, the peak concentrations for shorter time periods are unknown.

The study included a number of aspects on particle pollution in the airport. The results show that the particle number was about two to three times higher at the apron compared to HCAB. 85-90% of the particle numbers consist of particles with a diameter 6 – 40 nm. This particle fraction accounts for the difference between the particle number at the apron and HCAB. The ultrafine particles originate from combustion of jet fuel and diesel at the apron. At the outskirts of the airport, the particle number is about 20 – 40 % lower than at HCAB.

The larger particles with diameters up to 2.5 μm are measured by mass and called $PM_{2.5}$. The $PM_{2.5}$ level at the apron is approximately equivalent to HCAB while the $PM_{2.5}$ level at Station East and West are intermediate the levels measured at HCAB and urban background in Copenhagen. These particles originate mainly from sources outside the airport.

The particle-bound PAH concentration at the apron is about one third or less of the concentrations measured at HCAB. PAH concentrations are furthermore below the levels measured at the apron at the Leonardo Da Vinci Airport in Rome (Cavallo et al., 2006). The EU has established a limit value for benzo(a)pyrene (1 ng/m^3), which is considered as repre-

sentative for the carcinogenic PAH. The limit value is not exceeded in the 4-week measurement campaign.

Measurements also included elemental carbon (EC, also known as soot) in the particles. Levels at the airport are slightly less than half of the levels measured at HCAB. On the other hand, the amount of particulate organic carbon (OC) is comparable to HCAB, indicating that there must be a source of these substances on or near to the airport. This has not been studied in detail.

A geographically detailed emission inventory was compiled for NO_X, $PM_{2.5}$, VOC and CO. The uncertainty of the inventory is relatively high due to the many hundreds of different air pollution sources at the apron.

For NO_X and $PM_{2.5}$, the greatest share of emissions originates from handling vehicles[4], followed by the aircraft's APU (auxiliary power units), aircraft main engines and the smallest proportion from traffic at the apron. For VOC and CO the emissions are dominated by contributions from the aircraft main engines.

Furthermore, the emission inventory indicates that up to half of the particle emissions from aircraft main engines are due to the high sulfur content of about 900 ppm in the jet fuel. The combustion of sulfate-rich fuels leads to the formation of sulfur-containing ultrafine particles. Measurements of sulfur dioxide also indicate a linkage between sulfur and the large particle number.

Model calculations have shown higher concentrations of NO_X at the apron compared to the measurements. A detailed comparison between model results and measurements indicate that the most likely reason for this difference is that the emission inventory results in too high emissions at the apron. Thus it is desirable to review the basic input data behind the emission inventory. Unfortunately, this has not been possible within the framework of this study. Instead, the model results have been adjusted empirically on the basis of the measurements. In this way the model calculations can be used to determine the spatial distribution of pollution and the relative source contributions.

The calculations show that NO_x at the apron originate primarily from background (44%) and handling (41%) with smaller contributions from the APU (7%), main engines (7%) and traffic at the apron (1%). The numbers refer to Station B4, which is located at Gate B4.

Model calculations show that $PM_{2.5}$ at the apron comes primarily from background (91%) with smaller contributions from handling (5.5%), APU (3.4%), main engines (0.4%) and traffic at the apron (0.1%).

Model calculations show that the apron is the location, where the airport staff is most likely exposed to elevated levels of NO_X and $PM_{2.5}$.

As mentioned above, the project did not include an emission inventory for particle numbers. It has therefore not been possible to make a proper assessment of the sources of particle number on the basis of model calcu-

[4] Handling is the service in and around the aircrafts, which occurs at arrival and departure.

lations. However, it is expected that handling, APU and main engines are the major sources for particle number while the background plays a minor role. Measures taken to reduce the high particle number at the apron should involve reduction measures for all the expected major sources.

In summary it can be concluded that the concentrations at the apron for the majority of the investigated air pollutants (NO_X, $PM_{2.5}$, PAH, VOC, particulate organic and elemental carbon) are below the levels measured at HCAB. Furthermore, at the apron there are no measured excedances of the air quality limit values for those air pollutants where limit values exist.

The particle number is the only deviation from this picture, since the levels measured at the apron is about two to three times higher than at HCAB. There is no air quality limit value for particle number.

Preface

This report is prepared for Copenhagen Airports A/S by the DCE - Danish Center for Environment and Energy, Aarhus University (DCE). This report presents results from an assessment of the air quality at the apron of Copenhagen Airport Kastrup in relation to the working environment, based on measurements, emissions inventories and model calculations of atmospheric pollutants from 2009 to 2011. The present report is a translation of the original Danish version of the report (Ellermann et al., 2011). As an implication of the organizational change in Aarhus University, DCE has per July 1st, 2011 taken over the responsibilities and tasks on advising from the former National Environmental Research Institute (NERI). The staff at Copenhagen Airports A/S is acknowledged for their cooperation within the assessment.

1 Introduction

This report presents the results from an assessment on air pollution at Copenhagen Airport with emphasis on the apron in relation to the working environment. Measurements, emission inventories and model calculations were conducted in period 2009 - 2011 by DCE - Danish Centre for Environment and Energy, Aarhus University for Copenhagen Airports A/S.

The main objectives are:

- Quantification of atmospheric pollutants at the apron of Copenhagen Airport, Kastrup based on emission inventories, measurements and model calculations.
- Quantification of sources to air pollution at the apron.
- Evaluation of the effect of environmental intervention at the apron, within the available resources.
- Comparison of pollutant concentrations at the apron with measured concentrations in a busy street in Copenhagen, Denmark (H.C. Andersens Boulevard, HCAB) and the urban background of Copenhagen (H.C. Ørsteds Instituttet, HCOE).

The assessment concerns only air quality and not associated health issues.

The assessment covers atmospheric pollutants emitted from sources at the apron, which have the potential to cause health effect amongst the staff working at the apron. These pollutants are:

- Nitrogen oxides (NO and NO_2)
- Sulfur dioxide (SO_2)
- Mass of particles with diameter smaller than 2.5 μm ($PM_{2.5}$)
- Number and size distribution of particles with diameter in the range 6-700 nm.
- Elemental carbon (soot).
- Polycyclic aromatic hydrocarbons (PAH)
- Selected Volatile Organic Compounds (VOC), including benzene and toluene.

These atmospheric pollutants were selected for the assessment, since they are generally associated with health effects. Their relevance is furthermore supported during communication from M.D. Niels Ebbehøj, Bispebjerg Hospital), who mention the health effects associated with these species.

Originally, the assessment included 7 subprojects:

1. **Particle and NO_X measurements at the apron.** A measurement station will be installed at the apron, close to a handling area, where high concentrations of NO_X and particles are expected. The station will be equipped with monitors, which automatically measure NO_X and $PM_{2.5}$ in the period September 2009 - January 31st 2010. Particle number and size distribution, including ultrafine particles, will be measured during autumn 2010. All measurement data will have a time resolution of 30 minutes, and the results will be compared to measurements in the Danish Air Quality Monitoring Program (NOVANA).

2. **Additional measurements at background stations East and West**. Particles ($PM_{2.5}$) and NO_x are already monitored at the background stations East and West by DCE for Copenhagen Airports A/S (Figure 2.1). Sources to ultrafine particles are evaluated by comparison of the background measurements on the outskirts of Copenhagen Airport with those at the apron. The measurements are conducted during autumn 2010 in parallel with subproject 1.

3. **Measurement campaign on organic compounds, including PAH, particulate carbon and VOC at the apron.** Samples are collected for analysis of PAH's, particulate elemental and organic carbon, and selected VOC's during a 4-week measurement campaign. The concentrations of the pollutants are compared to a busy street and urban background measurements within the Danish Air Quality Monitoring Program.

4. **Horizontal variation of atmospheric pollutants at the apron.** In the forth subproject, 15-20 samplers for $PM_{2.5}$, NO_2 and benzene are placed over the apron in order to map the horizontal variation of these pollutants during a 5-week measurement campaign. The subproject will provide information about possible *hot spots*, and reveal the representativity of the measurement station at the apron (subproject 1). Furthermore, the subproject serves to validate the quality of the model calculations.

5. **Emission Inventories.** Emissions from the individual sources at the apron will be prepared for the various activities, i.e. various vehicles and aircraft. Furthermore, emissions from aircrafts during taxiing, takeoff and landing. Emission inventories will be used for the evaluation of sources to atmospheric pollutants and as input to the model calculations in subprojects 6-7.

6. **Model calculation of atmospheric air pollutions from other parts of the airport and Copenhagen.** Transport of air pollution to the apron from other sources at the airport (outside the apron area), and from Copenhagen city and regional background, are modeled using the model "OML-Multi". Individual sources at the airport and their contribution to the total air pollution measured at the apron, are evaluated from these results. The calculated contributions from these other sources serve as input for model calculations of air pollution at the apron (subproject 7).

7. **Model calculation of the air pollution at the apron.** Advanced model calculations in this subproject are based on Computational Fluid Dynamics (CFD) modeling with a high spatial resolution of 5 m x 5 m. The applied model offers detailed calculations of airflows around buildings at the apron, and takes into account dispersion from local sources under local meteorological conditions. The results focus on the local air pollution levels associated with handling of aircrafts, and provide information about the horizontal variation at the apron, which serves to identify possible locations of elevated air pollution levels.

Subsequently, the assessment was following extended to include a continuation of the measurements at the apron throughout 2011. In addition, ultrafine particles were measured at Station West in addition to $PM_{2.5}$ and NO_X, and a measurement campaign on SO_2 and particle number was conducted in February-March 2011.

The measurement stations are briefly described in the beginning of the report, after which an overview of the measurements is presented (chapter 2). The key-results of the subprojects are presented in chapters 3-7. Chapter 8 is a summery of the main conclusions. A detailed description of applied methods and results are available in a Danish version, only: Ellermann, T., Massling, A., Løfstrøm, P, Winther, M., Nøjgaard, J. K. & Ketzel. M. 2011. Assessment of the air quality at the apron of Copenhagen Airport Kastrup in relation to the occupational environment. DCE - Danish Centre for Environment and Energy, Aarhus University. 148 p. - Technical report from DCE – Danish Centre for Environment and Energy No. 5. http://www2.dmu.dk/Pub/TR5.pdf.

2 Measurements

2.1 Measurement stations

The Air quality was measured on three measurement stations located at the apron at gate B4 (Station B4), and at Station East and Station West. The latter two stations are permanently monitoring the air quality on the outskirts of Copenhagen Airport. The location and type of measurements at the stations are shown in Figure 2.1 and Table 2.1.

Monitoring of the air quality at Station B4 was initiated in November 2009, and the DCE became responsible for running Stations East and West in January 2009. This assessment includes measurements from November 2009.

Figure 2.1. Locations of the measurement stations B4, East and West and the runways (Google Earth).

Table 2.1. Measured species at the fixed measurement stations. Permanent activities are marked "X", while "campaign" or seasons imply temporary activities with a duration of 1-5 months.

Measured species	Station B4	Station West	Station East
NO, NO_2, NO_x	X	X	X
Particle mass, $PM_{2.5}$	X	X	X
Particle number (ultrafine particles)	X	Spring 2011	Autumn 2010
Elementary (soot)/organic carbon	Campaign		
Benzene, toluene, xylenes	Campaign		Campaign
VOC	Campaign		
Particle-bound PAH	Campaign		

2.2 Measurement campaign of the horizontal variation of NO_2, $PM_{2.5}$, benzene and toluene at the apron

A 5-week measurement campaign from June 24th to July 28th 2010 served to map the horizontal variation at the airport. NO_2, $PM_{2.5}$, benzene and toluene were measured at 15 locations (Figure 2.2) with a time resolution of one week. The number of locations necessitated simple and relatively low-cost instruments. The measurement sites were selected in collaboration between DCE, Copenhagen Airports A/S and representatives of the apron staff.

Figure 2.2. Locations of 14 measurement sites selected for mapping horizontal variation of NO_2, $PM_{2.5}$, benzene and toluene. The location of Station East (the 15th site) is shown in Figure 2.1 (Google Earth).

3 Measurement results

3.1 NO_2

Annual average concentrations of NO, NO_2 and NO_X are shown in Table 3.1. It appears that NO_2 concentration at Station B4 is less than half of the concentration at H.C. Andersens Boulevard (HCAB) or about half of the annual EU limit value of 40 µg/m^3. NO_2 concentrations at Station East and West are comparable to Copenhagen urban background, which represents the urban air quality in the absence of direct sources. In Copenhagen, the urban background is measured at the rooftop of H.C. Ørsteds Instituttet located in Universitetsparken. The rural background concentrations are measured at Lille Valby/Risoe north of Roskilde. Both NO_2 and NO are lower at urban background than at Stations East and West. The lower fraction of NO at Stations East and West compared to Station B4 reflects more pronounced chemical aging in the atmosphere, since those stations are located more distant to direct sources. Hence, a higher fraction of NO has been converted to NO_2 by reaction with O_3.

Table 3.1. Annual averages of NO, NO_2 and NOx including the limit value for NO_2 as stated in the Air Quality Directive (EU, 2008). Measurements at HCAB, HCOE and Lille Valby/Risoe are from the Danish Air Quality Monitoring Program (Ellermann et al., 2011).

2010	Data capture days	NO µg/m^3	NO_2 µg/m^3	NO_x µg/m^3 (as NO_2)
Apron – B4	355	9	24	38
Station West	345	3	16	21
Station East	349	5	18	25
HCAB	316	51	56	134
HCOE	344	2	17	21
Lille Valby/Risoe	307	1	11	12
Limit value			40	

3.2 $PM_{2.5}$

Annual average concentrations of $PM_{2.5}$ are shown in Table 3.2. Measurements at Station B4 are comparable to those at the busy-street HCAB in Copenhagen equal to about 70% of the 2015 limit value of 25 µg/m^3. Concentrations at Stations East and West are higher than urban background, but lower than HCAB.

Table 3.2. Annual averages of $PM_{2.5}$, including the limit value of $PM_{2.5}$ (EU, 2008). Measurements at HCAB, HCOE and Lille Valby/Risoe are from the Danish Air Quality Monitoring Program (Ellermann et al., 2011).

2010	Data capture days	$PM_{2.5}$ µg/m^3
Apron – B4	206	17
Station West	297	15
Station East	327	16
HCAB	341	17
HCOE	290	14
Lille Valby/Risoe	310	13
Limit value		25

3.3 The spatial distribution of the air pollutants NO_2, $PM_{2.5}$ and benzene at the apron

The spatial distribution of atmospheric pollutants at the apron was evaluated for NO_2, $PM_{2.5}$ and benzene in a campaign from weeks 25-29, 2010. In addition to routine measurements at Stations East and West, 15 additional locations were selected (Figure 3.1). Although the concentrations of the species are fairly uniform, the highest concentrations appear to be at the central part of the apron, whereas the lowest concentrations are observed on the outskirts of the airport. Vehicular emissions at the eastern gate are the main reason for the high $PM_{2.5}$ concentrations at this location.

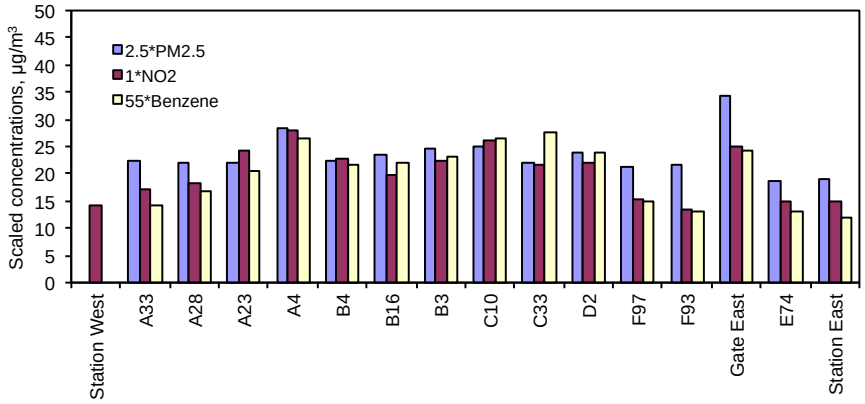

Figure 3.1. Average concentrations of $PM_{2.5}$, NO_2, and benzene measured in the campaign from weeks 25-29, 2010. The sites refer to the nearest gate, and the concentrations are scaled to fit the NO_2 level (scaling factors are shown on the Figure).

3.4 Particle number

The number of particles at the apron (Station B4) are about 3-4 times higher than the values observed at HCAB, while the levels at Stations East and West are only 20-40% of the HCAB level (Table 3.3).

Ultrafine particles in the size range 6-40 nm make up 85-90% of the particles at the apron (Station B4). Also at Stations East and West these particles account for about 70% of the total number. In fact, it is the particles located in the 6-40 nm size range, which exceeds the measured concentrations at HCAB. Consequently, particles within the range 40-700 nm are at about the same level as measured at HCAB, including the year 2011 with highest data capture and thus the highest degree of certainty.

The diurnal variation of the particle number concentration tracks the variation in arrival/departure of aircrafts. The number of arrivals/departures is used in the following as a measure of the total activity related to airplane engines, handling and use of APU, since arrival/departures and total activities are considered to be proportional.

Please note that the data capture at HCAB is low during the second half of 2010. However, the measurements at HCAB during the second half year are in excellent agreement with results from the first half year of 2010, which therefore are considered to be representative for 2010.

Table 3.3. Average number of particles with diameter in the range 6 – 700 nm per cm^3 ambient air, including particles with diameter 6-40 nm, 40 – 109 nm and 109 – 700 nm. In addition, results from the urban busy street (HCAB), urban background (HCOE) of Copenhagen, and rural background (Lille Valby/Risoe) are shown for comparison. Measurements at HCAB, HCOE and Lille Valby/Risoe are from the Danish Air Quality Monitoring Program (Ellermann et al., 2011), and The *Particle project 2008-2011* supported by the Danish EPA, Miljøstyrelsen (Massling et al., 2011).

Particle number cm^{-3}	August – December 2010				January – June 2011			
	Total number	6-40 nm	40-109 nm	109-700 nm	Total number	6-40 nm	40-109 nm	109-700 nm
Station B4	31900	27900	3100	900	38600	32600	4600	1400
Station West					11000	7500	2500	1100
Station East	10000	7500	1800	700				
HCAB	16100	9900	4700	1600	13400	7800	4100	1400
HCOE	5500	2300	2200	1000	6500	2300	2800	1400
Lille Valby/Risoe	3700	1400	1500	900	4000	1200	1700	1000

3.5 Intervention study at Station B4

A number of initiatives to reduce air pollution at the apron were tested by Copenhagen Airports A/S in the weeks 11-17, 2011:

1. Weeks 11-12: Omission of the start-up position M1
2. Weeks 13-14: Omission of the start-up positions M1, J4 and L2
3. Week 17: Normal start-up procedure, but only electrical equipment allowed during handling at Station B4.

Weekly averages of NO_X and particle number at Station B4 are shown in Figure 3.2 for the weeks 3-19. The values are time-integrated from 7 am - 8 pm. and background corrected by subtraction of NOx and particle number from Station West. Significant weekly variations are due to meteorological conditions, especially wind direction.

Only relatively small changes in the emissions are expected from the 3 initiatives above compared to the total emissions at the airport. It was not possible to detect changes in concentration due to the initiatives, because of the large week to week variation in meteorology. For example, the measured concentrations were higher in the second initiative as compared to the first initiative, indicating that the variations are mostly due to variations in meteorology.

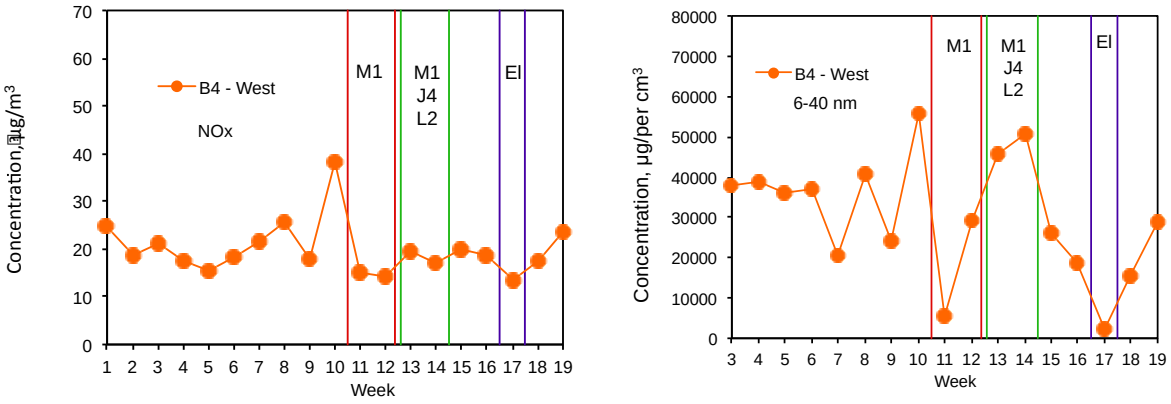

Figure 3.2. Weekly averages in the time interval 7:00 to 20:00 for NO_X and particle number at Station B4. The numbers are background corrected, see chapter 3.5. Vertical lines show the three test conditions. *M1*, and *M1, J4, L2* refers to the periods where the specified start-up positions are not in operation. *El* implies that only electrical equipment is used during handling at Station B4.

3.6 Source tracking by use of a simple approach

A simple experiment on direct source tracking of small particles was conducted in collaboration with Copenhagen Airports A/S on December 7th, 2010. Changes in the measured concentrations were related to observed activities at Station B4 by use of a simple handheld instrument. Figure 3.3 illustrates the relation between activities and measured concentrations. In conclusion, a number of vehicles used for handling, clearing snow etc., main engines and APU all contribute markedly to the measured concentrations. As expected, use of electrical equipment (initiative 3 in chapter 3.5) did not it-self contribute to small particles at the apron (Figure 3.3).

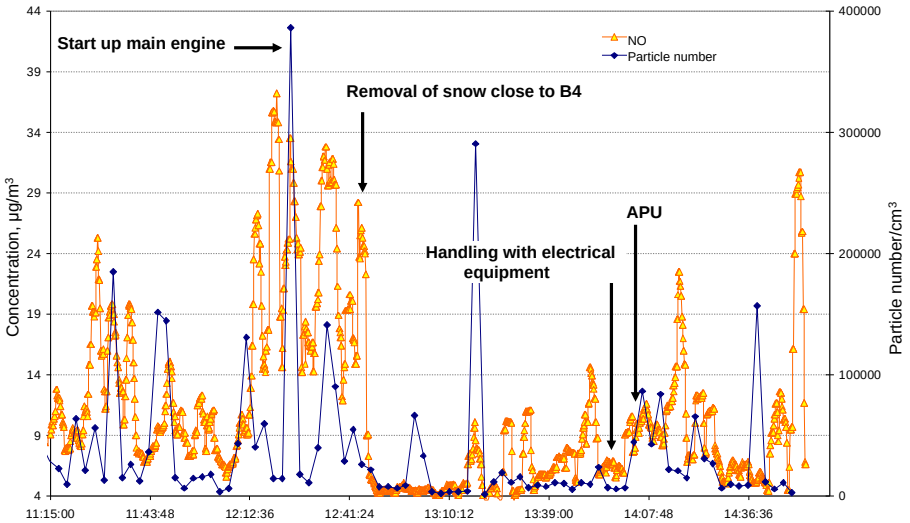

Figure 3.3. Particle number and NO concentration at Station B4 on December 7th, 2010. NO is directly emitted during combustion processes in non-electric engines. The majority of the larger peak-values are associated with activities in the vicinity of Station B4, as illustrated in the Figure.

3.7 The SO_2 campaign

SO_2 was measured in a campaign from February-March 2011 at Station B4. Concentrations are generally low (about 1 µg/m^3) relative to the EU air quality limit value, which is somewhat lower than at HCAB.

The objective of the SO_2 campaign was to study whether sulfur was associated with the large number of particles at the apron. Jetfuel has high sulfur content (940 ppm in Kastrup) relative to diesel fuel (10 ppm). Sulfur is converted to mainly SO_2 during combustion and to a lesser extent sulfate particles. SO_2 is readily measured in low concentration and is used as a tracer for sulfate particles in this campaign. Apparently from Figure 3.4, the SO_2 measurements and particle numbers are to some extent timely correlated. This indicates that the high numbers of particles may partly consist of sulfate particles. Furthermore, aircrafts are assumed to be the main source of sulfate particles, since the sulfur content is 100 times higher in jetfuel compared to diesel fuel.

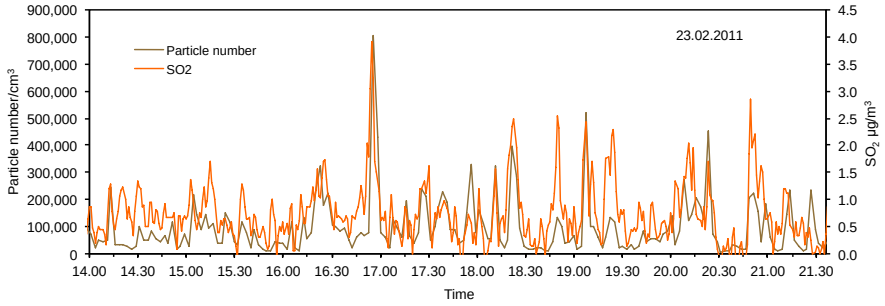

Figure 3.4. SO_2 and particle number at Station B4 on February 23rd, 2011.

3.8 Organic pollutants

Volatile and gaseous organic pollutants were collected at Station B4 in a 4-week campaign from October 20th to November 17th, 2010. Adsorbent tubes packed with Carbopack X targeted C_3-C_9 VOC's with a time resolution of 24 hours. DNPH coated cartridges were used for sampling of volatile aldehydes with a time resolution of 8 hours. A high-volume-sampler provided filter material with a time resolution of 24 hours for analysis of particulate organic (OC) and elementary carbon (EC or soot), and particle-bound polycyclic aromatic hydrocarbons (PAH) in the $PM_{2.5}$ particle fraction. The results are presented in Tables 3.4-3.7.

3.8.1 Volatile Organic Compounds

VOC origin from natural sources as well as anthropogenic sources. Several VOC's have contributions from both types of sources, e.g. benzene, which is a regulated carcinogenic substance with limit value of 5 µg/m^3 (EU, 2008). In the Danish air quality monitoring Program (Ellermann et al., 2011), benzene and 16 other VOC's are measured on the urban background station HCOE in Copenhagen, as motivated from their potential to form tropospheric O_3. These 17 VOC's and 7 additional VOC are measured during the campaign on organic pollutants at the apron and compared to urban background concentrations in Table 3.4.

Table 3.4. Average concentrations (μg/m^3) of selected VOC's measured at Station B4 during the campaign on organic pollutants from October 20th to November 17th, 2010. Measured concentrations in urban background (HCOE) in the same period are shown for comparison. Bold type VOC's are measured in higher concentration at Station B4 compared to HCOE." jetfuel" in brackets implies that the VOC's are found in jetfuel in addition to other sources (Aviation fuel technical review, 2006, Sorokin and Arnold, 2006).

Volatile Organic Compounds (VOC)	**Apron (B4)**	**Urban background (HCOE)**
1-pentene	0,05	0.04
n-pentane	0.39	0.51
trans-2-pentene	0.02	0.04
Isoprene (jetfuel)	0.03	0.03
2-methylpentane	0.27	0.33
n-hexane	0.21	0.20
Benzene (jetfuel)	0.57	0.71
n-heptane	0.19	0.25
2,2,2-trimethylpentane (isooctane)	0.05	0.08
toluene (jetfuel)	1.28	1.71
n-octane (jetfuel)	0.23	0.04
ethylbenzene (jetfuel)	0.34	0.28
m,p-xylene (jetfuel)	0.48	0.41
o-xylene (jetfuel)	0.38	0.30
1,3,5-trimethylbenzene	0.13	0.07
1,2,4-trimethylbenzene	0.59	0.26
1,2,3-trimethylbenzene	0.18	0.06
Other abundant VOC's measured at Station B4		
Methylcyclohexane	0.25	-
ethylcyclohexane (jetfuel)	0.14	-
n-nonane	0.41	-
n-tridecane	0.04	-
n-tetradecane	0.08	-
n-pentadecane	0.07	-
n-hexadecane (jetfuel)	0.04	-
VOC's total (μg/m^3)	5.4	5.3
Other VOC's (μg/m^3)	1.0	

Of the 17 VOC's routinely measured in urban background, 7 compounds are measured in higher concentration at Station B4 (Table 3.4). Of these, n-octane, ethylbenzene, o-xylene and p-xylene are reported to be representative of jetfuel (Aviation fuel technical review, 2006; Sorokin and Arnold, 2006). However, it should be noted that combustion of aviation fuel, gasoline and diesel are sources to several VOC's, including benzene, ethylbenzene, toluene in addition to the trimethylbenzene isomers (Kuykendall et al., 2009). Other VOC's which are reported to be formed during combustion of aviation fuel are ethylcyclohexane and n-hexadecane. The averaged total concentration of the VOC's at Station B4 routinely measured in urban background was 5.4 μg/m^3 during the campaign compared to 5.4 μg/m^3 at HCOE in the same period.

3.8.2 Volatile aldehydes

A total of 9 volatile aldehydes, which were previously reported in studies of aircraft emissions (Brasseur et al., 1998; Sorokin and Arnold, 2006), were identified and measured during the campaign (Table 3.5). Other

sources cannot be excluded, since gasoline and diesel powered vehicles are known sources of aldehydes (Kuykendall et al., 2009).

Table 3.5. Max, min and average concentration (μg/m^3) of selected volatile aldehydes measured at Station B4 during the period October 20th to November 11th, 2010. Measurements are based on 8-hour time-integrated samples.

Aldehydes	Max	Min	Average
Formaldehyde	4.5	0.13	0.82
Acetaldehyde	4.6	0.08	1.1
Acrolein	6.8	0.08	1.4
Propanal	0.9	0.04	0.27
Methacrolein	4.6	0.08	0.63
Butanal	0.9	0.05	0.24
Benzaldehyde	0.9	0.01	0.12
Pentanal	0.4	0.01	0.07
Hexanal	0.7	0.01	0.1

For several of the aldehydes, a decreasing trend is observed throughout the campaign (Figure 3.5). One possible explanation is a decreasing global radiation throughout the campaign, and thus less available sunlight as illustrated in Figure 3.5. Less sunlight decreases the rate of the photochemical reactions, which take part in the formation of aldehydes from VOC's (Sorokin and Arnold, 2006). However, the formation of aldehydes depends on other meteorological parameters as well. Aldehydes are also directly emitted into the atmosphere from natural sources and from aircraft emissions (Brasseur et al., 1998; Sorokin and Arnold, 2006).

On average, aldehyde concentrations were 0.1-1.4 μg/m^3 during the campaign. However, peak values of 6.8 μg/m^3 acrolein and 4.6 μg/m^3 methacrolein was measured on single occasions.

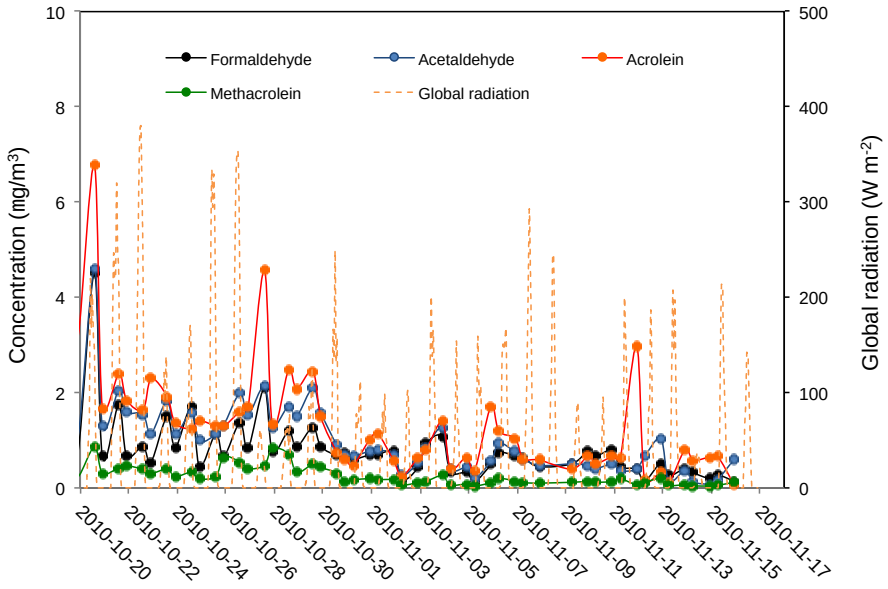

Figure 3.5. Volatile aldehydes (left y-axis) and global radiation (right y-axis) measured at Station B4 from October 20th to November 11th, 2010.

Irritation of nose, airways and eyes may arise from exposure to acrolein and methacrolein (references in Woodruff et al., 2007). For example, a reduced respiration rate, eye and nasal irritation has been observed following exposure to increasing exposure to acrolein during 40 min (Weber-Tschopp et al., 1977). The authors suggested a no adverse effect limit value of 200-700 $\mu g/m^3$. Darley et al. (1960) reported eye irritation during 5 min of exposure. A lowest observed adverse effect level was reported at 140 $\mu g/m^3$. Measured concentrations at Station B4 were significantly lower. However, it should be noted that the measurements are integrated over 8 hours and thus represents the average concentration in this period. Higher concentrations will occur during measurements with higher time resolution.

3.8.3 Elementary and organic carbon in the $PM_{2.5}$ fraction

The organic or carbonaceous fraction of the particulate matter ($PM_{2.5}$) measured at Station B4 was differentiated into organic carbon (OC) and elemental carbon (EC), the latter which is roughly equivalent to soot. EC and OC are routinely measured in the Danish Air Quality Monitoring Program (Ellermann et al., 2011). These species in addition to the fraction of EC in total carbon are shown in Table 3.6 for Station B4, a busy-street in Copenhagen HCAB, and Risoe that is representative of rural background in Denmark. As apparent from Table 3.6, OC at station B4 is comparable to HCAB, whereas the concentration of elementary carbon is between the two stations though closer to that of rural background. The results indicate that a strong source of particulate OC is present at the apron or other parts of Copenhagen Airport.

Table 3.6. Average concentrations ($\mu g/m^3$) of elementary (EC), organic (OC) and total carbon (TC), including the carbon fraction of EC (EC/TC). The corresponding measurements from a busy-street urban street station and rural background are listed for comparison. Measurements are based on 24 hour integrated samples.

Location	OC	EC	TC	EC/TC
Station B4	2.7	1.2	3.8	0.31
HCAB	2.6	2.6	5.2	0.51
Rural background (Risoe)	1.2	0.4	1.6	0.25

3.8.4 Polycyclic aromatic hydrocarbons in the $PM_{2.5}$ particle fraction

Table 3.7 shows the average concentrations of 9 particle-bound PAH's, including benzo(a)pyrene, measured at Station B4 during the campaign. Average concentrations measure at HCAB during the same period are shown for comparison. The concentrations at Station B4 are about one third of those at HCAB.

Table 3.7. Average concentrations (ng/m^3) of particle-bound PAH's at Station B4 and at the busy-street station HCAB, Copenhagen in the same period. Also shown are measurements (January – February 2005) at the Leonardo Da Vinci Airport in Rome (Cavallo et al., 2006)

PAH (ng/m^3)	Copenhagen Airport (B4)	Busy street (HCAB)	Cavallo et al., 2006
Chrysene	0.18	0.51	1.1
Benzo(a)anthracene	0.10	0.33	1.5
Dibenzo(a,h)anthracene	0.02	0.07	0.0
Benzo(g,h,i)perylene	0.17	0.64	1.9
Indenopyrene	0.17	0.53	1.7
Benzo(e)pyrene	0.13	0.38	0.5
Benzo(a)pyrene	0.12	0.34	0.4
Benzo(b+j+k)fluoranthene	0.44	1.15	3.1
Perylene	0.02	0.06	0.0

Volatile and particle-bound PAH's at the apron of the Leonardo Da Vinci Airport in Rome have been reported from a 5-working day campaign (Cavallo et al., 2006). Significantly higher concentrations were measured, though the Italian and Danish study differed with respect to season and duration. The PAH concentrations in the former study were about 4-15 times higher, except for dibenzo(a,h)anthracene and perylene, which were virtually absent in the two studies. Benzo(a)pyrene was about three times higher at the Leonardo Da Vinci Airport.

Benzo(a)pyrene is a carcinogenic PAH, which is regulated by the European Union. The target value of 1 ng/m^3 (EU, 2008) was neither exceeded at station B4, nor at HCAB or at the Leonardo Da Vinci Airport during the respective campaigns. According to international Agency for Research on Cancer (IARC) some of the PAH's are classified as *probably carcinogenic to humans*, which include benzo(a)anthracen, benzo(b)fluoranthen, benzo(k)fluoranthene, chrysene, dibenzo(a,h)anthracene and indenopyrene. The concentrations of these species are lower at Station B4 than at HCAB.

3.9 Measurements - conclusion

The majority of the air pollutants at the apron were at the same levels or lower than measured at HCAB. Furthermore, the relevant limit values (or target values) on air quality were not exceeded.

Ultrafine particles was an exception to this, since measured number concentrations were about three times higher at the apron compared to HCAB. However, no air quality limits apply to ultrafine particles.

Measurements of SO_2 at Station B4 indicate that the relatively high sulfur content in jetfuel partly explains the high particle number concentrations at the apron. This is further supported by a literature study (http://www2.dmu.dk/Pub/TR5.pdf).

Volatile and particle-bound carbonaceous species were measured in a campaign from October 20th to November 17th 2010 at the station B4. VOC concentrations were comparable to measurements in the urban background during the same period. Somewhat higher levels were observed for VOC's representative for jetfuel, which was most evident for octane measured in about six times higher concentration than in urban background. Isomers of trimethyl benzene are slightly higher at the apron as compared to urban background. Aldehydes is a class of VOC's

known to cause sensory irritation. Although single measurements were as high as 6.8 µg/m^3, the concentration of e.g. acrolein was substantially lower than reported effect levels. However, the measurements were based on 8-hour time-integrated samples and therefore represents an average concentration in this period. The peak-concentrations on short time scales are not known. However, they will be higher than measured for the 8-hour averages.

The organic carbon fraction OC of $PM_{2.5}$ at Station B4 was comparable to concentrations at the busy street HCAB in Copenhagen. On the other hand, the elemental carbon fraction EC and the ratio of EC to total carbon was intermediate between the rural background and the busy street. This indicates a significant source to OC at the apron or elsewhere at the airport, which is yet not identified.

Selected particle-bound PAH's measured at Station B4 were compared to measurements at HCAB and the Leonardo Da Vinci airport in Rome. At Station B4, the average PAH concentrations were about 1/3 or less the concentrations measured at HCAB in the same period. At the Leonardo Da Vinci Airport, PAH concentrations were about 4-15 times higher than at station B4, except for dibenzo(a,h)anthracene and perylene, which were virtually absent.

Only benzene and benzo(a)pyrene are regulated by the EU Air Quality Directives (EU, 2005 and 2008). Average concentrations during the campaign did not exceed the respective limit (5 µg/m^3) and target values (1 ng/m^3).

Further details are available in a Danish version of the report at http://www2.dmu.dk/Pub/TR5.pdf.

4 Emission inventories at the apron

Figure 4.1 illustrates a section of the airport. Terminal gates are numbered (e.g. B7 or C28) and marked with a small (black) dot. The main engine start-up marks are shown as larger (red) dots (e.g. P or Q1). The aircraft taxiways close to the gates are shown as (green) curves and (red) lines and connect to the shared taxiways that lead from/to the runways (blue lines). The remaining small (black) dots in the Figure are points in the digitalized road network.

In the following, emissions from the different sources at the apron are evaluated based on the map in Figure 4.1.

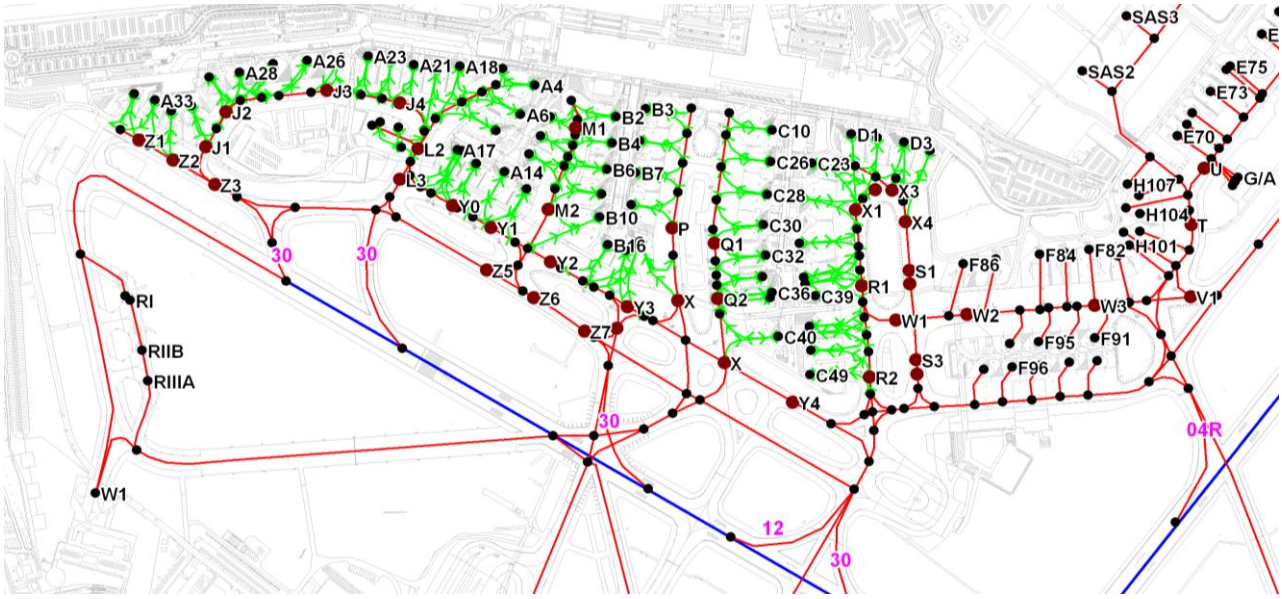

Figure 4.1. Detailed map of the airport illustrating the apron with gates (numbers and black dot), main engine start-up marks (red dots), taxiways (green and red) and partly the runways (blue). The map is described in detail in chapter 4.2.

4.1 Activity data

Aircrafts

An activity log from 2009 of duration 4 days was provided by Copenhagen Airports for use in this project. During this period, mainly the runways *12, 30, 04L/R* and *22L/R* were used. Data consisted of the type of aircrafts and their associated registration number, the airline operator, gate, off/on block time, takeoff and landing times, as well as the runways and gate that were used during this activity.

Auxiliary Power Unit

The International Civil Aviation Organization (ICAO) recommends specific time periods (Airport Air Quality Guidance Manual (doc. 9889)) for operation of the Auxiliary Power Units (APU). These recommendations are implemented in the model (Table 4.1). The total APU time prior to off-block is specified for *APU start up* and *Boarding* corresponding to different engine loads.

Table 4.1. APU activity schedule. The APU time during push-back is calculated.

	Arrival	APU start-up	Boarding	Push-back	Main engine start-up
APU load	**Normal**	**Start-up**	**Normal**	**Normal**	**High**
2 engines	300 s	180 s	216 s	to be calculated	35 s
4 engines	300 s	180 s	318 s	to be calculated	140 s

Copenhagen Airports generally accepts the APU's to run for 5 minutes following on-block and prior to off-block, which is somewhat shorter than ICAO's recommendations for departures. APU usage prior to off-block can exceed 5 minutes if the temperature is lower than -10 ^{o}C or above 25 ^{o}C. Under these conditions the APU is allowed to run for 45 min on large aircrafts and 15 min on small aircrafts. For these reasons it was concluded to apply ICAO's recommendations for APU when calculating emission inventories at Copenhagen Airport.

Following off-block, when the aircraft is pulled towards the start-up mark, the APU is assumed to be in normal operation. At the start-up mark, the aircraft starts-up the main engines and the APU load is high (Table 4.1).

Start-up of main engines

In the model calculations it is assumed that the pushback truck pulls at 5 km/h (1.5 m/s) along the green lines towards the start-up mark after which the main engines start-up (Figure 4.1).

Use of handling vehicles

Table 4.2 lists the handling equipment types and activity data provided by the handling companies in Copenhagen Airport. The Table is divided into the aircraft types denoted B-E, which are included in this project. Type B includes the smallest jetplanes, whereas the largest aircrafts belong to E (A330/A340/B747/B777).

Toilet trucks and water trucks are assumed to be in use prior to departure, whereas catering and fuel are handled after arrival. Where fuel pipelines are not available, trucks are assumed to fuel the aircrafts at the gates.

Pushback trucks pull the jet aircrafts from the gate to the start-up marks, where the main engines normally start-up. According to the airport, the aircrafts are pulled to the start-up mark with a velocity of approximately 5 km/h (1.5 m/s). The time period, in which the pushback truck is in use following off-block, thus depends on the distance between the gate and the start-up mark for each departure.

The list of handling equipment in Table 4.2 is provided by the handling companies, including information about the type of equipment, fuel type, engine norm and displacement as well as production year.

Table 4.2. Handling equipment types and activity data for Copenhagen Airport.

	Aircraft category				
	B	**C**	**D**	**E**	**All**
Handling period (min) →	**15**	**20**	**30**	**40**	
Arrival		**Working time (min)**			**Load factor**
Baggage truck	9	10	15	25	0.15
Conveyor belt	10	20	20	20	0.15
Push-back at gate	0	0	0	0	0.15
Push-back moving	0	0	0	0	0.75
Container loader	0	15	27.5	35	0.45
Container transporter	0	15	27.5	35	0.35
Fuel (dispenser truck)	10	15	30	50[a]	0.1
Fuel (refueling truck)	10	15	30	50[a]	0.1
Cleaning high loader	0	0	10	15	0.45
Cargo/Post tractor	0	5	5	5	0.15
Toilet truck	0	0	0	0	0.25
Catering B/C/D/E	1	3	5	5	0.1/0.2/0.22/0.22
Water truck	0	0	0	0	0.25
Handling period (min) →	**15**	**20**	**30**	**40**	
Departure		**Working time (min)**			**Load factor**
Baggage truck	9	10	15	25	0.15
Conveyor belt	10	20	20	20	0.15
Push-back at gate	10	10	10	10	0.15
Push-back moving	0	0	0	0	0.75
Container loader	0	15	27.5	35	0.45
Container transporter	0	15	27.5	35	0.35
Fuel (dispenser truck)	0	0	0	0	0.1
Fuel (refueling truck)	0	0	0	0	0.1
Cleaning high loader	0	0	10	15	0.45
Cargo/Post tractor	0	5	5	5	0.15
Toilet truck	0	10	20	20	0.25
Catering B/C/D/E	0	0	0	0	0.1/0.2/0.22/0.22
Water truck	0	7.5	15	15	0.25

Ground-based vehicles

Copenhagen Airports A/S has provided traffic counts of passenger cars, vans and minibuses, busses, trucks and borage trucks divided into 15 minutes intervals during 24 hours. Counting's were based on airport cameras located at the taxi rank, the bus stops at T2, the drop-off at T3, Finger B-C and Check East. The composition of the vehicle fleet is assumed to equal the national average with respect to age, type of fuel and engine displacement. Furthermore, it is assumed that the composition of baggage truck fleet equals that of the vehicles used during handling with respect to engine norm, displacement and type of fuel. Assumptions about the duration of idle and average operation time are used in the following calculations of emissions.

4.2 Digitalization of activity data

Aircrafts

A section of the airport is illustrated in Figure 4.1. All gates are marked with a number. Start-up marks are shown as red dots, and the taxiways close to the gates are visible as green lines. Shared taxiways are visible as red lines. The remaining small (black) dots in Figure 4.1 are points in the digitalized road network. The movement of the aircrafts and the activities of the APU, pushback trucks, main-engine start-up and handling are digitized in a 5 m x 5 m grid on the electronic map of the airport.

The digitalization of the aircraft movements is split into taxi prior to start, taxi waiting in line, start, takeoff, descend, landing, and taxi following landing (Table 4.3). Runway aircraft velocity, priority taxiways are derived from a previous survey on noise at the airport. A number of assumptions on taxi velocity, acceleration, deceleration, as well as ascend and descend angles were necessary in order to define time periods and duration of individual operations in the grid cells.

Table 4.3. Individual steps during the digitalization of aircraft operations

Type of operation
Taxi arrival (taxi way)
Taxi departure (taxi way)
Taxi departure (queing)
APU arrival
Landing (runway deceleration)
Landing (runway taxi)
Take off (runway)
Landing (descent)
Take off (climb out)
APU start-up
APU boarding
APU start-up of main engine
Push-back moving
Main engine at engine start
Handling arrival
Handling departure
APU at push-back
Main engine at push-back
Push-back at gate

APU, push-back truck and main engine start-up

At the gate, the APU is used after aircraft arrival at the gate and during boarding of the aircraft. The pushback truck follows the green lines from the gate to the start-up mark. Meanwhile the APU is running, and in some cases one aircraft main engine is turned on as well. The dimensions of the aircraft determine the height of the APU in each case.

Use of handling vehicles

It is difficult to determine exactly *when* the different types of operation are in use during handling. The duration of the different types of operation are therefore averaged over the entire handling period for arrival and departure. An exception is the pushback trucks, which are assumed to be in use during approximately 10 minutes prior to off-block in case the aircraft is pulled out. The handling activities are assumed to take place at the right side of the aircraft within an area corresponding to the length of one wing multiplied by the length of the aircraft.

4.3 Emission factors

Main engines

Factors relevant for fuel consumption and emission rates are identified for all aircrafts relevant for Copenhagen Airport. From the aircraft registration number, information about the individual aircrafts motor ID and number and engines are available from a global database *JP Airline-Fleets 2009/2010* (www.flightglobal.com).

Fuel consumption (FF; kg/s), emission indices (EI; g/kg fuel) and *smoke number* are available from ICAO's Engine Exhaust Emission Database (www.caa.co.uk) for jet engines. An emission factor database maintained by the FOI (Totalförsvarets Forskningsinstitut, www.foi.se) in Sweden is used for the turboprop engines. The particle emission is not available for specific engines. In stead, the FOA3.0 method as validated by ICAO, is used. FOA3.0 takes into consideration the particle contributions from soot and hydrocarbons in the exhaust, and the sulfur content of the jet-fuel.

APU and start-up of main engines

Emission factors (kg/h) are taken from ICAO's Airport Air Quality Guidance Manual (doc. 9889), and fuel factors from the German air quality model for airports LASPORT (LASat for airPorts, Janicke 2010). APU factors represent different aircrafts with respect to seat capacity and type/year of aircraft. Emission of hydrocarbons during start-up of jet main engines is calculated from the method used in LASPORT.

Handling vehicles

Emission factors for diesel engines are grouped according to the EU legislation for non-road (Stage I-IV) and road transport (Euro I-V) vehicles. In addition, factors are used for older engines. Emission factors (g/kWh) from the official Danish emission inventories, which have been reported to the UNECE CLRTAP convention, are applied to non-road vehicles. For road transport vehicles, the EU emission norms (g/kWh) from the stationary test cycle ESC are applied directly, regardless of engine displacement. The engine technology of the oldest baggage trucks is estimated to be comparable to gasoline vehicles from the 1970'es. On the other hand, the engine technology of the most recent baggage trucks are estimated to be comparable to the first vehicles equipped with 3-way catalysts (Robert Hagen, SGS, personal communication 2010).

4.4 Calculation method

Emission rates (g/s) for the main engines, APU, engine start-up and handling equipment are derived from the emission factors, which are described in chapter 4. Emissions and fuel consumption are calculated for each 5 m x 5 m meter grid cell as the product of emission rate (g/s) and the time interval, which is designated to a particular activity (s):

$$\Delta E(t,i) = ER \cdot \Delta t(t,i)$$

ΔE = Emission/fuel consumption (g) in the i'th grid cell at time t
ER = Emission rate/fuel consumption (g/s) for the main engine, APU, engine start-up an handling equipment
i = Grid cell number in the dispersion model
Δt = Time interval applied to the i'th grid cell
t = Time of the day measured in seconds ($0 < t < 86{,}400$)

4.4.1 Results

In Figure 4.2 the diurnal emissions of particles and NO_X are shown for a section of the airport. Significant contributions to the emissions are visible on the right side of the aircrafts, from the handling activities as well as the pushback truck and APU activities prior to off-block. These are visible as red marks on the inner and outer side. The emission trails from the pushback truck and APU are also clear during taxiing from the gates to the start-up marks. By the start-up mark the emissions from APU and main engine are visible too. Furthermore, the contribution from the main engines is clearly visible on the taxiways towards the runways, and when the aircrafts arrive at the gates.

Figure 4.2. Diurnal emissions of particles and NO_X at the apron averaged over 24 hours.

Generally, the calculated emission levels can be explained from the fuel related emission factors and the calculated energy consumption. Figure 4.3 shows the relative emissions from handling, APU and aircraft engines for the entire airport in addition to a limited section of the apron called the inner apron (Figure 4.4). The calculated emission levels are generally explained from the fuel related emission factors and calculated energy consumption. At the apron, handling and APU contributes significantly to the emission of NO_X and particles by mass. The handling part may be explained by the diesel fuelled handling vehicles and associated fuel related emission factors. With respect to APU, the smaller fuel related emission factors are compensated by significant larger energy consumption. Emissions of NO_X and in particular particle mass from the main engines are small at the apron due to low fuel related emission factors at low engine load. Conversely, large amounts of hydrocarbons and CO are emitted from the main engines during taxiing and engine start-up, because of the poor combustion under these conditions. For the entire airport area the main engine shares of hydrocarbons and CO are particular high. During takeoff, the NO_x emissions from the main engines are particular high because of the high combustion temperatures.

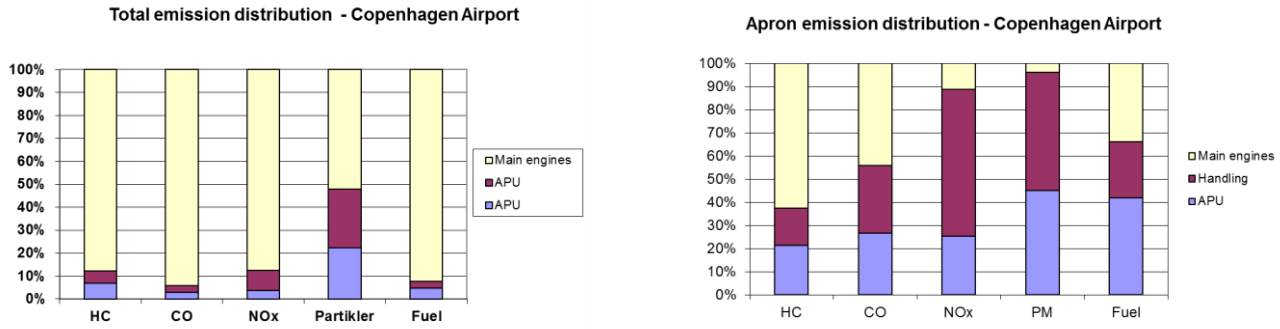

Figure 4.3. Relative emissions of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_X), particles and fuel. The shares are specified for the entire airport (left) and the inner apron (right).

Figure 4.4. The section of the apron referred to as the *inner apron*.

Figure 4.5 shows the particle emission for the entire airport related to the three main sources, in addition to vehicular emissions other than handling associated traffic. According to the fuel declarations from the airport refueling company, the average sulfur content in jetfuel is 942 ppm. This sulfur content has been used in the calculation of the particle emission rates from the aircrafts, of which particle-bound sulfate contributes largely. As a consequence hereof, particle emissions are expected to be reduced by more than 50% by mass if all sulfur is removed from the jetfuel. In this context it should be mentioned, that particle emissions from the APU's would probably also decrease, if jetfuel with low sulfur content is used. Apparent from Figure 4.5, the contribution from vehicular traffic is very small.

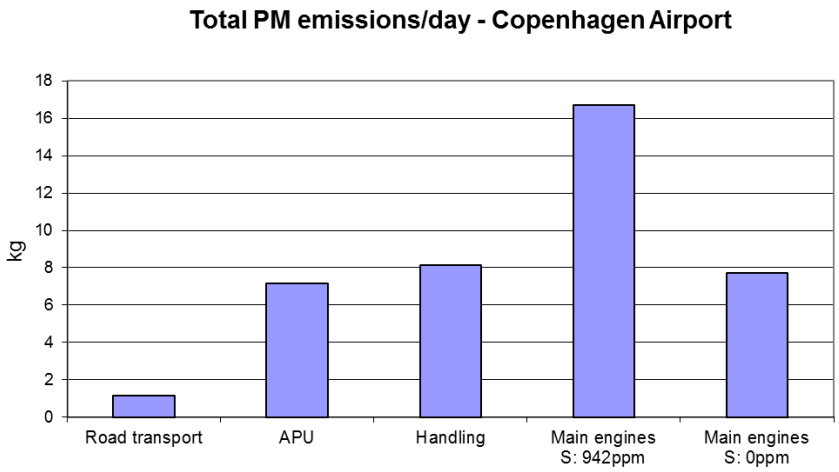

Figure 4.5. Particle emission (kg/ day) for the entire airport specified on vehicular transport, APU, handling, main engine using fuel with normal sulfur content (ME % S) and main engine using sulfur-free fuel (ME 0% S).

4.5 Emission inventories - conclusion

The emission inventory for the airport includes fuel consumption and emissions from activities related to main engines (start-up and running), APU, handling equipment and vehicular traffic. The inventory has a high spatial resolution of 5 m x 5 m per grid cell, in which fuel consumption and emissions are calculated for each activity.

The activity data is based on the number of aircraft operations provided by Copenhagen Airports, the fleet of handling equipment and associated time schedules provided by the handling companies. Emission factors are calculated for each aircraft based on international databases. Emission factors for the handling equipment are based on age, engine displacement, and type of fuel and engine load. Emissions related to a specific activity is calculated in the relevant grid cells as the product of emission factors and the time period assigned to the activity.

The calculated emission levels can generally be explained by the fuel related emission factors and the calculated energy consumption:

- Handling constitutes the largest share of the total NO_X and particle emissions at the apron, which is explained by the fuel related emissions factors for the diesel fueled handling vehicles.
- APU constitute the second-largest share of the total NO_X and particle emissions by mass at the apron. Fuel related emission factors are smaller compared to those of the diesel fueled handling vehicles. On the other hand, the fuel consumption is significantly larger.
- For main engines, NO_x and in particular the particle mass emissions on the apron are small, due to the low emissions factors at low engine load.
- The main engine constitutes the largest share of hydrocarbon and CO emissions at the apron. Emission factors during taxiing and engine start-up are high because of the poor combustion efficiency under these conditions.

- The main engines constitute the largest share of NO_X, particle mass, hydrocarbons and CO for the entire airport. For CO and hydrocarbons this is due to the large fuel consumption and poor combustion during idle. For NO_X, the high emissions from the main engines are mainly due to the high combustion temperatures during takeoff.

- Vehicular traffic contributes only to a minor extent to the total emissions at the airport, i.e. 1.6% for NO_X, 3.5% for particle mass, 0.8% for HC and 0.9% for CO. The contribution from vehicular traffic is expected to be much smaller at the apron.

According to the emission inventories, the combustion of sulfur in the jetfuel is responsible for about 50% of the emitted particle mass as sulfate particles from the main engines. A large share of the emitted particle mass from the APU is also expected to origin from sulfur in the jetfuel.

Further details are available in a Danish version of the report, only, at http://www2.dmu.dk/Pub/TR5.pdf.

5 Model calculations for the area around the apron

The contributions to the atmospheric concentrations of NO, NO_2 and $PM_{2.5}$ at the apron is calculated in three steps. Stepwise, three different air pollution models zoom in at the apron details:

- DEHM covers the Nordic hemisphere and is applied to step 1. The model has a spatial resolution of 5.6 km x 5.6 km for Denmark and is routinely used in the Danish National Air Quality Monitoring program. Further information is available (Ellermann et al., 2011). The results from step 1 serve as input for step 2.
- OML is a local scale model. OML is applied with a spatial resolution of 50 m x 50 m to step 2 and the results serve as input for step 3.
- MISKAM is applied to step 3 and operates at the most detailed level on the inner part of the apron with a spatial resolution of 5 m x 5 m. MISKAM is a computational fluid dynamics (CFD) model, which can calculate airflows around the building at the apron. The results from these calculations are therefore considered the most accurate.

This section describes the results of the calculations during step 1-2 with focus on step 2. The results from step 3 are described in chapter 6.

5.1 Method

Dispersion calculations and emission inventories are divided into two areas: (1) an area of 10 km x 10 km covering the entire Copenhagen Airport, the majority of Amager and parts of Copenhagen, also referred to as the OML domain, and (2) the area outside the OML domain, also referred to as the DEHM domain. OML is applied to the OML domain, where the emissions have a spatial resolution 50 m x 50 m, 250 m x 250 m and 1 km x 1 km. The DEHM model is applied outside the OML domain with a coarser spatial resolution of 5.6 km x 5.6 km in Denmark and 50 km x 50 km outside Denmark.

DEHM calculates the background contribution to OML, which again calculates a background contribution to a section of the apron covering 750 m x 1250 m. The contribution to this MISKAM area is calculated without including the emissions from the area. These concentrations serve as input to the detailed MISKAM calculations at the apron. The different model domains are illustrated in Figure 5.1. The results of the OML calculations, where MISKAM calculations are not included, cover all emissions including those from the MISKAM domain.

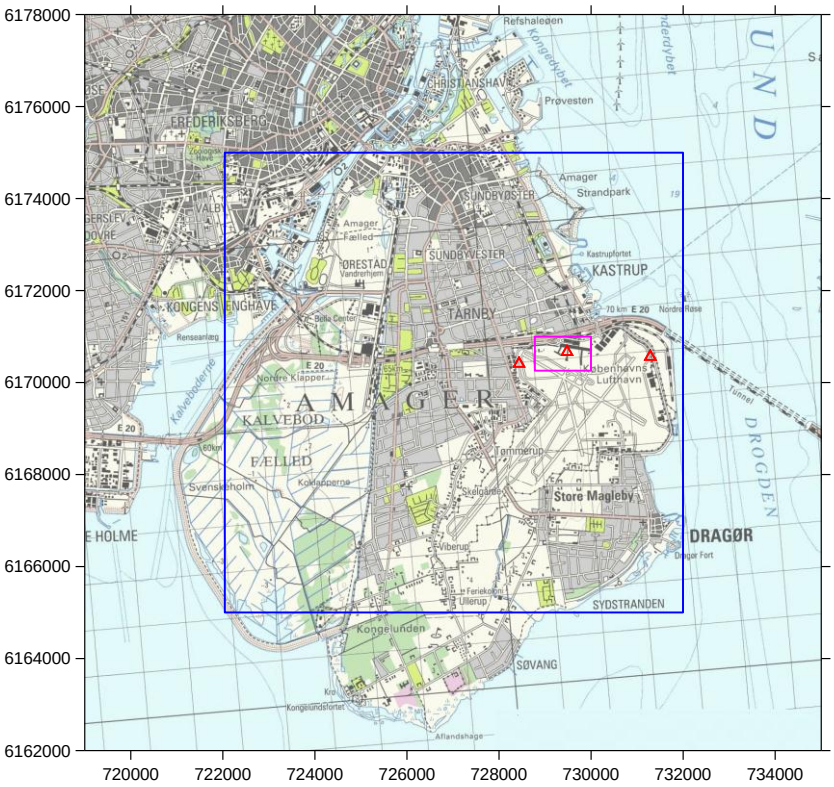

Figure 5.1 Model domain map. The blue square shows the 10 km x 10 km OML domain. The DEHM domain is outside the OML domain. The pink square illustrates the MISKAM domain at inner part of the apron (750m x 1250m), the MISKAM domain. The measurement stations West, B4 and East are indicated by red triangles.

OML uses airport emissions, which are estimated for 4 representative days, with 4 different but constant wind directions, where the emissions are mainly associated with one of the possible runways 22 L+R, 04 L+R, 12 or 30 (Figure 2.1). Emissions are calculated every hour in grid cells of 50 m x 50 m. During the dispersion calculations the actual wind direction and speed determine which runway emissions will be used, and thereby what representative day will be used as basis for the calculations. In 2010 the runways 22, 04, 30 and 12 were used in 54%, 44%, 1.3% and 0.3 % of the hours based on the available meteorological conditions.

5.2 Spatial distribution of atmospheric pollutants in the airport area and nearby

The 2010 annual averages of NO_x, NO_2 and $PM_{2.5}$ are calculated at the airport area and locality using OML at the airport area and nearby. The annual average of NO_2 is shown in Figure 5.2, where the spatial resolution is 150 m.

Elevated concentrations are observed locally at the apron. Very high concentrations are modelled at runways 22 and 04, where the aircrafts initiates takeoff, or are waiting in line during western and eastern winds. The concentrations in the northeastern end of the map are generally higher than in the southern end, due to transport of pollutants from Copenhagen. Along the highway just north of the airport, an area with relatively high concentrations is observed.

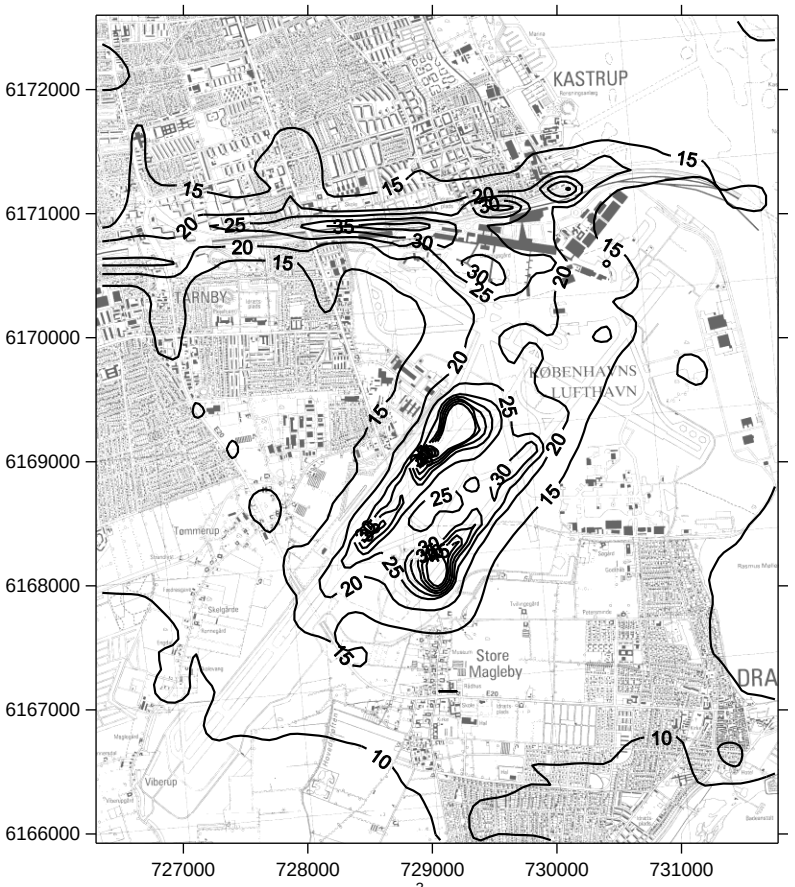

Figure 5.2. Spatial distribution of the NO_2 (µg/m^3) annual average. A grid of 150 m x 150 m is applied. Iso-curves are from 10-50 µg/m^3.

Annual averages for $PM_{2.5}$ are shown in Figure 5.3. Concentrations vary less than NO_2 does, but the general trend is similar. However, the apron shows relatively high concentrations, whereas relatively lower concentrations are observed during takeoff/queue.

5.3 The stations B4, East and West

The individual source contributions can be identified in OML, by comparison of runs where a particular source are included, and then turned off in a following run. Measured and calculated concentrations of NO_x, NO_2 and $PM_{2.5}$ are compared in Figure 5.4 for Stations B4, East and West. The sources are: *Background* (input from DEHM), *Copenhagen city* (input from the OML-domain 10 km x 10 km), *Traffic CPH* (traffic in the airport), *Handling*, *APU* and *Main engines*.

Measurements and model calculations of NO_x are in good agreement at station West, i.e. 21.3 µg/m^3 and 20.6 µg/m^3 respectively. The contribution of sources within the airport area amounts to approximately 25%.

OML underestimates the NO_X concentration by 32% at Station East, i.e. 16.8 against the measured 24.8 µg/m^3. The reason for this may be too low emissions from the inner and outer circular road east of the station. Alternatively, a local source is missing in the model or the grid cell may be to close to edge of the OML domain, which may cause a problem with the DEHM background contribution.

OML calculations at Station B4 cannot take into account the detailed airflows close to the buildings, and thus cannot reproduce the NO_x levels at Station B4. Small errors in the contributions from handling and APU will dominate, since these sources are very close to Station B4. In fact, the model calculations overestimates the concentrations by 65%, i.e. 62 compared to the measurements of 38 µg/m^3. Handling accounts for a relatively large share of the modeled NO_x concentration.

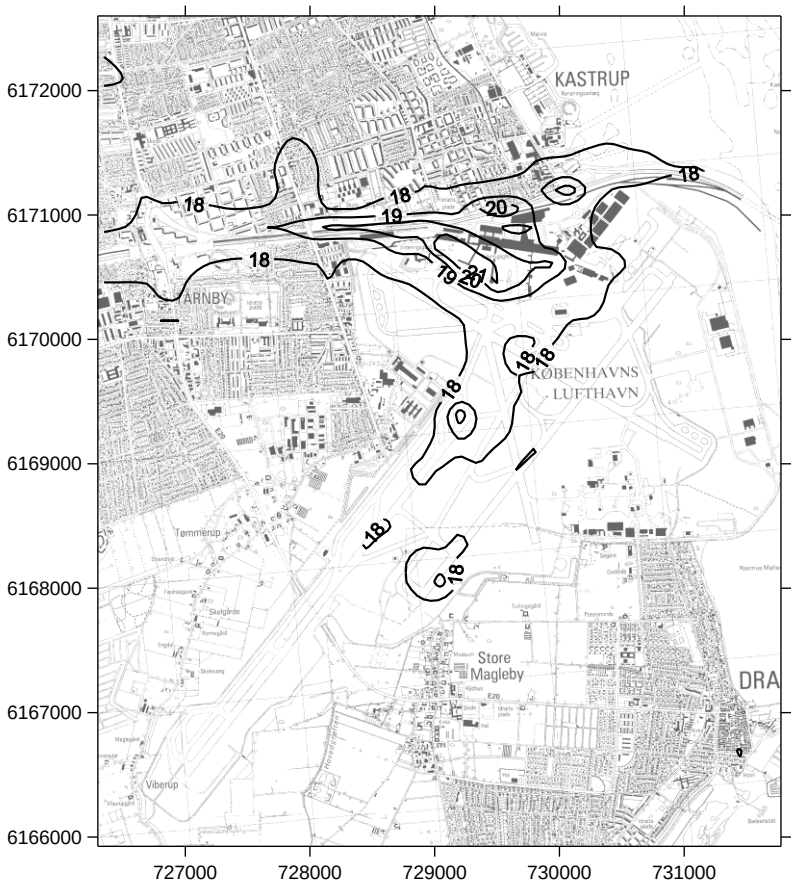

Figure 5.3. Spatial distribution of the annual average concentration of $PM_{2.5}$ (µg/m^3). A grid of 150 m x 150 m is applied.

The model calculation of NO_2 at Station B4 is 29 µg/m^3 compared to the measured concentration of 24 µg/m^3. This agreement is better than for NO_X, since a smaller fraction of NO is converted to NO_2 due to a low ozone concentration in the background air. The agreement is good for Station West, while the model calculation underestimates NO_2 at Station East.

Modeled and measured $PM_{2.5}$ concentrations are virtually identical at Stations East and West, i.e. 17.6-17.8 µg/m^3. The background level accounts for approximately 98 %. However, the modeled concentrations at Station B4 are again higher than measured, i.e. 21 µg/m^3 compared to 20 µg/m^3. $PM_{2.5}$ at Station B4 is 16% and 9% higher compared to Station West, evaluated from model calculations and measurements respectively.

The model calculations of $PM_{2.5}$ and NO_2 at Station B4 and the apron in general (chapter 6) are somewhat overestimated, albeit with reservations

about the complicated airflows at Station B4 and the limited reliability of the OML model under these conditions.

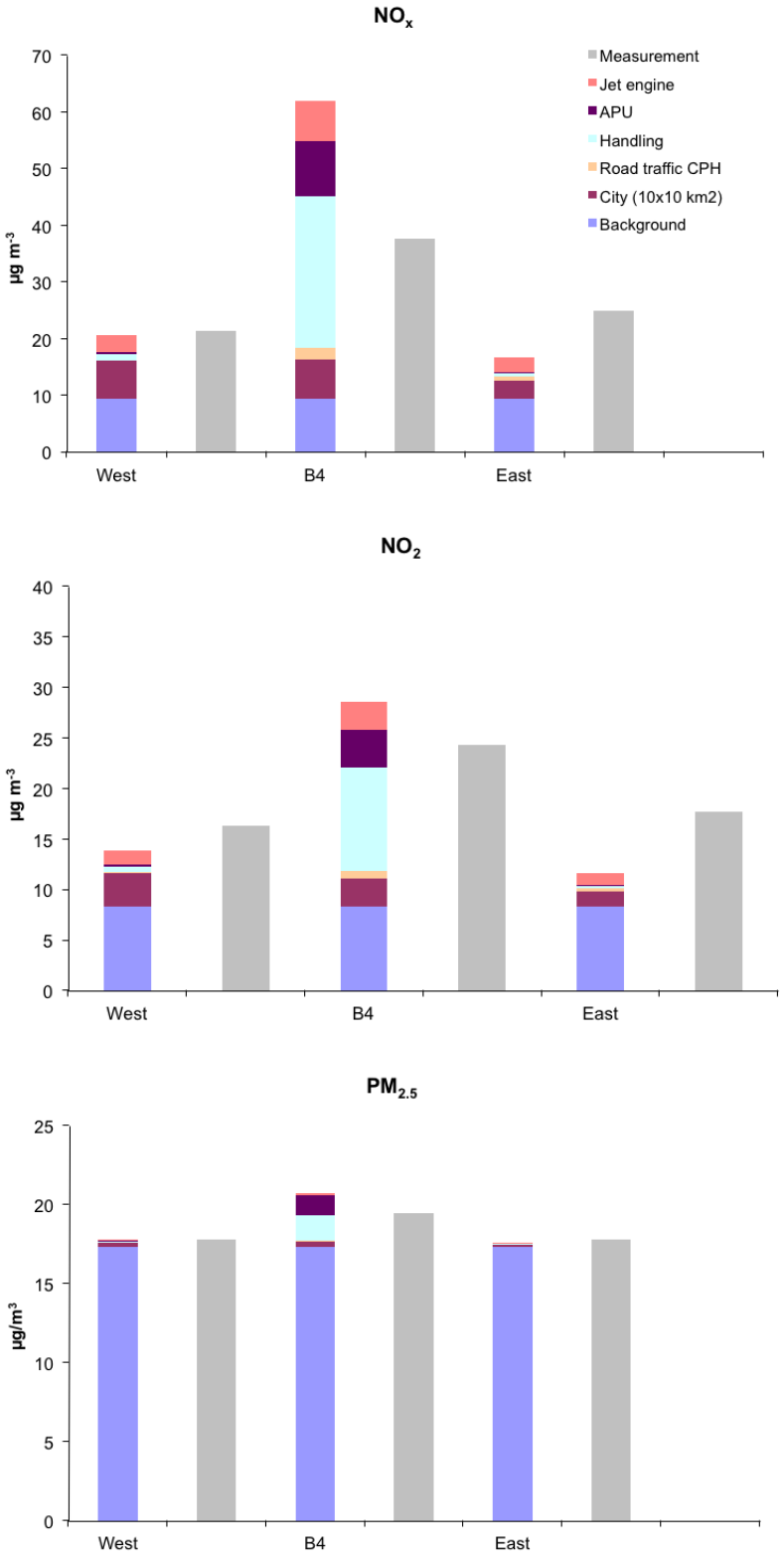

Figure 5.4. Comparison of measured at calculated annual averages (µg/m^3) of NO_x NO_2 and $PM_{2.5}$. The individual source contributions are specified for the model calculations.

5.4 Conclusion – Model calculations for the area around the apron

Modeling of the spatial distribution of NO_x, NO_2 and $PM_{2.5}$ shows that the pollutant concentrations in the airport are highest at the apron. The exposure of the airport personnel to NO_x, NO_2 and $PM_{2.5}$ is consequently highest at the apron.

The model calculations at Station West are in good agreement with the measurements in 2010, while those at Station East are underestimated. The concentrations at the apron are somewhat overestimated. Detailed analysis shows that too high emissions from mainly handling activities are probably the explanation for this discrepancy. However, the relative spatial variation of the pollutants is well reproduced

Further details are available in a Danish version of the report, only, at http://www2.dmu.dk/Pub/TR5.pdf.

6 Model calculations at the apron

The MISKAM model is based on Computational Fluid Dynamics (CFD) and is used for model calculations on the apron itself. A spatial resolution of 5 m x 5 m (in the center of the domain) enables the model to perform detailed calculations of air turbulence and air flows close to the buildings at the apron. Local dispersion of air pollution at the apron can therefore be calculated using MISKAM, and take into account local sources and meteorology. The results focus on the air pollution levels in relation to handling of the aircrafts. Furthermore, the model calculations illustrate the horizontal variation of pollutants at the apron, which makes it possible to identify *hot spots*.

6.1 Method

The shape of the airport buildings affect the local meteorological conditions and thereby the dispersion of air pollution at the apron. For these reasons a CFD-model is applied, which is developed to handle complex air flows around buildings.

The German CFD-model MISKAM (Eichhorn, 1996, Lohmeyer, 2011) has previously been used by AU (Olesen et al. 2009). In the present model calculations we used the latest version (6.1). A number of limitations apply to MISKAM. However, these may be obviated through appropriate setup and input to the model. For example, the grid resolution is highly important, and the grid geometry should be rectangular. Another limitation to the model is the assumption of neutral atmospheric conditions. Furthermore, it is not possible to simulate hot exhaust emissions directly, whereas lifting of the smoke plume is accounted for indirectly by assuming a larger initial dispersion.

Figure 6.1 shows the MISKAM grid with 5 m x 5 m grid cells in the center and increasing grid cells towards the edge of the model area. Building polygons and building heights were provided by Copenhagen Airports and following projected onto the MISKAM grid.

Emissions are divided into 4 groups of sources, i.e. aircraft main engines, APU, handling, and traffic at the apron. The location and timely variation of the emissions are based on the emission inventory described in chapter 4.

The background concentrations outside the MISKAM domain are modelled using OML, where source inside the MISKAM domain were set to zero in order to avoid duplicate source contributions (chapter 5).

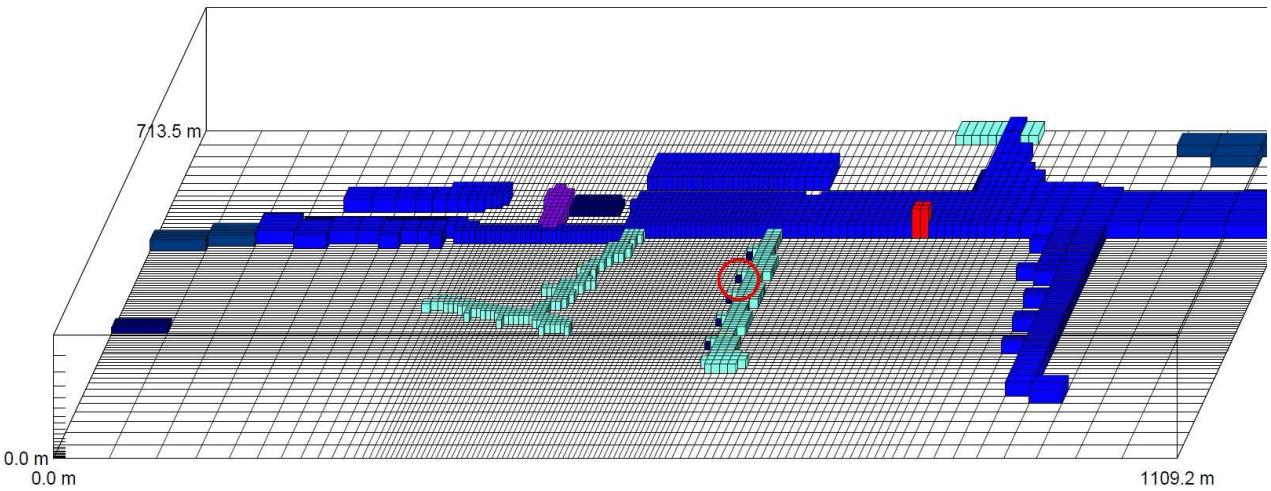

Figure 6.1. Grid cell domain in the MISKAM model in a skewed 3D visualization. The colors indicate different building heights and the red circle indicates the location of Station B4.

Initially the MISKAM model calculates airflows at the apron for 36 different wind directions (0, 10, 20, … 350 degrees). The calculated flow conditions, i.e. wind direction and velocity at Station B4 were compared to meteorological measurements from a Sonic instrument in 2 meters height. The MISKAM model reproduced the airflows well, and modelled results showed good agreement with the measurements.

Following, the dispersion of the emissions from the 4 source categories were calculated and used to generate time series of NO_X and $PM_{2.5}$ concentrations in selected data points, e.g. at Station B4. Included is the diurnal variations in emissions based on emission inventories, wind direction and velocity, which are identical to those used in the OML model, and background concentrations modeled using OML.

6.2 Results

MISKAM results show that emissions from different locations at the apron will result in dispersion, according to the complex airflows arising from the buildings in the airport. Figure 6.2 shows modelled NO_x concentrations at the apron, where only emissions from handling are considered for a wind direction of 240 degrees. Elevated concentrations are observed locally under influence of their associated sources, however declining quickly with the distance to the source.

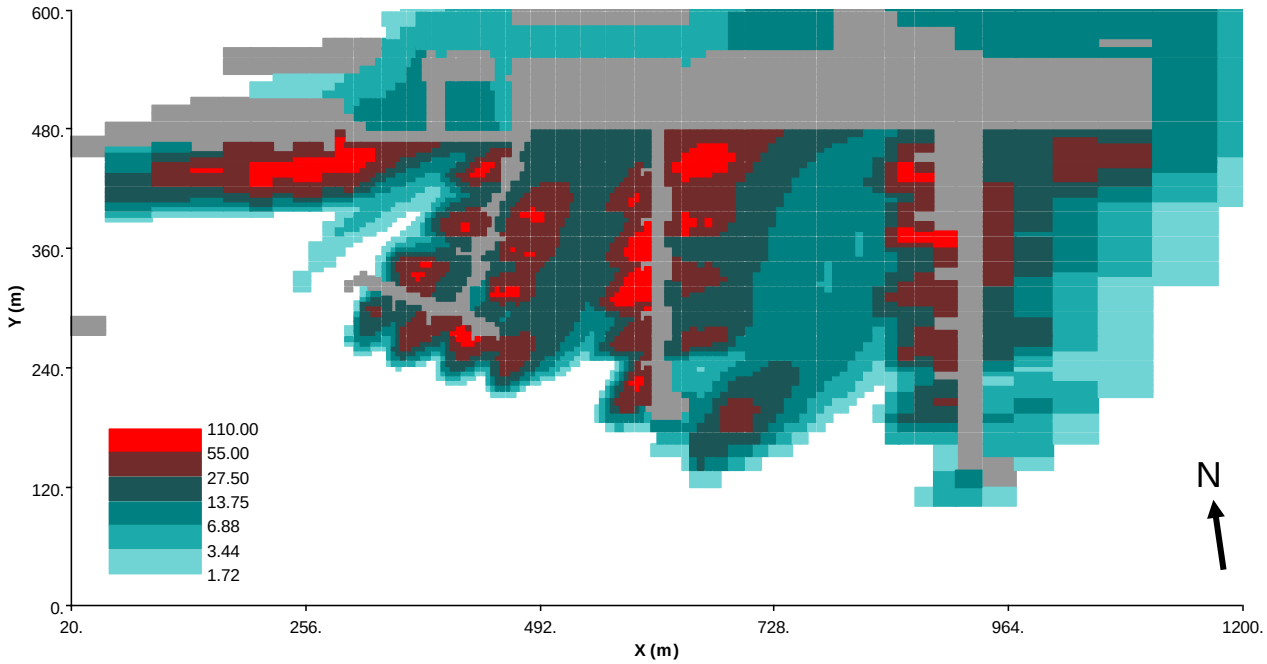

Figure 6.2. NO_x (µg/m^3) concentrations at the apron modelled for a wind direction of 240°. Only NO_x-emissions from handling are considered. Red fields denote the highest concentrations and the arrow indicates north (N).

Naturally, the wind direction determines which sources contribute at a given location. In Figure 6.3 NO_X is modelled at Station B4 and the concentration is split into 4 source contributions as a function of wind direction. Handling is the largest contribution to NO_X during southern wind directions (100-280º), where the contributions from APU and main engines are similar. Traffic at the apron contributes to a minor extent and origin from mainly northern wind directions, where traffic sources are located.

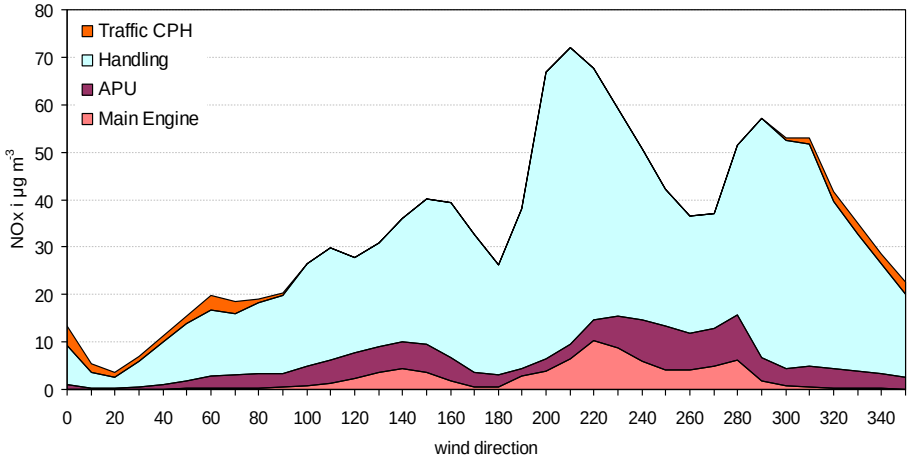

Figure 6.3. Modelled NO_X concentrations at Station B4 as function of wind direction, using MISKAM. An average emission is assumed, and individual wind directions have not been weighted. Only local sources at the apron are considered, i.e. other sources and background are not included.

Figure 6.4 shows NO_x and $PM_{2.5}$ model results at Station B4 in 2010 using MISKAM and OML. MISKAM and OML show good agreement with respect to NO_X, however both modelled concentrations are considerably higher than the measurements. Also $PM_{2.5}$ is overestimated, which is less

obvious due to the high background. Possible explanations are the following:

- The emission inventory results in too high emissions from the airport area, that is activity data or emission factors are too high.
- Gates B2 and B4 were not in use for a longer period of 2010, because of a reconstruction. So far it has not been possible to account for this in the model calculations.
- A number of assumptions were made to describe the initial dispersion of the emissions. Possibly, the assumptions cause an underestimation of the initial dilution of the APU and main engine emissions.

The emission inventory is the most likely cause for the too high model results, which however, must be studied in further details. The contributions from 4 source categories are somewhat different using the two models, in particular the high contribution from handling when using MISKAM. Most likely, this is due to a higher spatial resolution in the MISKAM model, where the location of sources are specified with 5 m resolution, compared to 50 m in the OML model.

Additionally, a different approach was suggested in order to better utilize the information from the modeling calculations and measurements, and to better estimate the source contributions to NO_X and $PM_{2.5}$. In this approach, the local contribution modeled by MISKAM was scaled using an empirical factor. However, the background concentration was left unchanged, since there is a good agreement between model results and model calculations. Using this method the best estimates for source contributions to NO_X and $PM_{2.5}$ at Station B4 are identified (Table 6.1).

Table 6.1. Source contribution (%) to NO_x and $PM_{2.5}$ at Station B4 estimated using MISKAM with scaled local contributions.

Compound	Back ground	Main engine	APU	Handling	Traffic
NO_X	44	7	7	41	1
$PM_{2.5}$	91	0.4	3	6	0.1

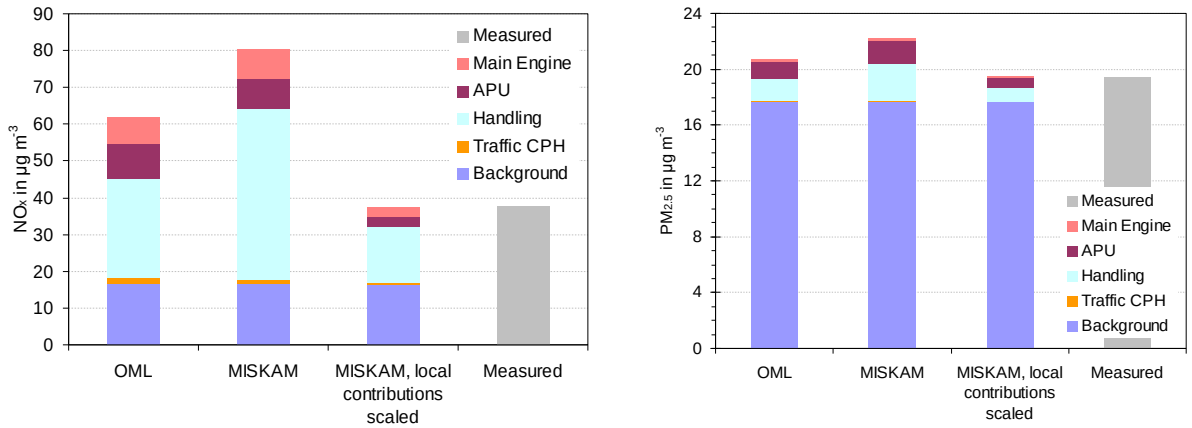

Figure 6.4. Annual average NO_x and $PM_{2.5}$ concentrations at Station B4 in 2010. Actual measurements are compared to modeled concentrations using OML and MISKAM in addition to an estimate, where all local contributions are scaled by a factor of approximately 1/3 to show consistency between measurements and model calculations.

Concentrations and source contributions were modelled at 17 data points along the terminal building (Figures 6.5 and 6.6) in order to illustrate the horizontal variation. Table 6.2 is derived from these results.

Table 6.2. Source contributions to NO_X based on 17 data points at the apron using MISKAM and scaled local contributions. Traffic covers sources at the airport.

NO_X	Background	Main engines	APU	Handling	Traffic
Average (µg/m^3)	16	3	2	13	1
Share (%)	46	8	6	37	3
Share Min (%)	35	5	3	19	0.3
Share Max (%)	59	15	11	54	17

Table 6.2 shows that NO_x mainly origins from the background (46%; min 35%- max 59%) and handling (37%; 19-54%). Smaller contributions are found for APU (6%; 3-11%), main engines (8%; 5-15%) and traffic at the apron (3%; 0.3-17%).

Traffic emissions at the apron contributes only to the data points in the near vicinity of the terminal buildings (7, 11, 12 and 17 in Table 6.5). The largest contribution from the aircraft main engines are observed in the data points farthest away close to the taxiways, e.g. data points 4 and 5. These data points further more illustrate the large influence of direction and distance to the handling areas. The contribution from handling at data point 4 is about 1/3 of that at data point 5. The main reason for this, is that data point 4 is 30 m away from the handling area whereas data point 5 is located within the handling area. Moreover, the location of data point 4 is more open relative to the buildings compared to data point 5, which also influence the handling contribution on these two locations.

In the same way, the contribution from the APU depends on the distance to the area, where the APU is typically used at the gates. Data points 1, 3, 12 and 16 are distantly related to these areas, for which reason only a small contribution from the APU is observed.

Figure 6.5. Apron map showing the location of the 17 data points and the buildings as they are represented in the MISKAM grid cells. Building colors illustrates different building heights. Emissions from the handling vehicles are colored according to the concentrations ranging from low (green) to high (red). Station B4 is located at data point 8.

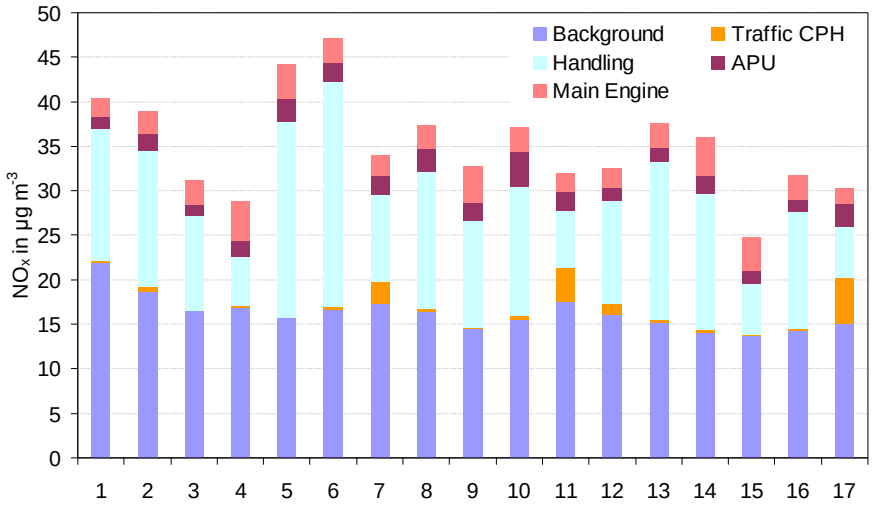

Figure 6.6. Results from the model calculations at the 17 data points in Figure 6.5. The annual average concentration of NO_x is specified for the 4 source categories. Local contributions are scaled using an empirical factor to show consistency between measurements and model calculations at Station B4.

6.3 Conclusion - Model calculations at the apron

NO_X and $PM_{2.5}$ were modelled on the airport area and at the apron.

There is a fair agreement between model calculations and measurements, taking into account the uncertainty of activity data and emission inventories.

Model calculations show that NO_x at Station B4 mainly origins from the background (44%), handling (41%) and to a smaller extent APU (7%), main engines (7%) and traffic at the apron (1%). $PM_{2.5}$ at Station B4 mainly originates from the background (91%) with smaller contributions from handling (5.5%), APU (3.4%), main engines (0.4%) and traffic at the apron (0.1%). These estimates are subject to uncertainty from e.g. uncertain emission inventories and should be considered with precaution.

The modelled NO_X concentrations are generally too high at the apron, which is believed to be caused by too high calculated emissions at the apron. Therefore, the activity data of which the emission inventory is based on should be reevaluated.

Further details are available in a Danish version of the report, only, at http://www2.dmu.dk/Pub/TR5.pdf.

7 Conclusion

The key findings in this assessment are summarized in the following.

NO_2, $PM_{2.5}$, benzene and spatial distribution of pollutants

- The concentration of NO_2, $PM_{2.5}$ and benzene at the apron at Station B4 are all below the air quality limit values.
- The spatial distribution of NO_2, $PM_{2.5}$ and benzene are relatively similar and reflects activity, building structures and meteorology. The highest concentrations are found at the inner part of the apron, while the concentration decreased towards the outer apron and the airport periphery. A similar spatial distribution of particle number is expected.
- A relatively high pollution level is measured at Gate East due to traffic.

Particle number

- The number of particles with diameter in the range 6-700 nm at the apron at Station B4 is 2-3 times higher than measurements at the busy street measurement station HCAB in Copenhagen in the same period.
- 85 - 90% of the particles are particles with diameter in the range 6-40 nm.
- The particle number at Station East and West is 20-40% lower than HCAB. The relation between wind direction shows that a large fraction of these particles origin from the airport.
- The diurnal variation corresponds to the total variation in activity evaluated by the number of departures.

Intervention study at Station B4 and source tracking

- A number of initiatives to reduce air pollution at the apron were tested by Copenhagen Airports A/S, including changed practice for start-up of main engines and application of electrical equipment around Station B4. Change in practice during start-up and application of electrical equipment around Station B4 did not reduce NO_x and particle number significantly at Station B4. However, the substantial week to week variation in meteorology resulted in a pronounced variation in NO_x and particle number, which made it impossible to evaluate the effect of changes practice.
- Experiments with source tracking clearly showed that vehicles (handling and snow clearing), main engines and APU's are sources to the high particle numbers measured at the apron.
- Experiments with source tracking furthermore illustrated, that handling using electrical handling equipment resulted in lower particle number concentrations.

The role of sulfur in jetfuel

- Results from a measurement campaign showed that SO_2 is substantially below the limit value.
- There is a timely relation between high SO_2 concentrations and high particle number.
- The sulfur content in jetfuel is about 100 times higher than in diesel fuel, i.e. 940 ppm compared to 10 ppm.
- The measurements, the high sulfur content in jetfuel in addition to literature references all indicate that the high particle numbers measured at the apron partly origin from sulfate particles formed during combustion of sulfur in the jetfuel.

Organic compounds

- Measured Volatile Organic Compounds (VOC) at Station B4 was comparable to urban background concentrations in Copenhagen. Slightly elevated levels were observed for VOC's representative for jetfuel, e.g. n-octane and the isomers of xylene.
- Average concentrations of volatile aldehydes are generally well below the effect levels established for sensory irritation. However, the measurements were time-integrated over 8 hours, for which reason higher concentrations will appear over shorter time scales.
- Concentrations of particulate Organic Carbon (OC) are comparable to HCAB, while "soot" or particulate elemental carbon (EC) and the ratio of EC to total carbon is intermediate between that of HCAB and rural background in Denmark.
- Measured concentrations of Polycyclic Aromatic Hydrocarbons (PAH) at Station B4 are only about 1/3 of those at HCAB, and typically 6-31% of the concentrations measured at the Leonardo Da Vinci Airport in Rome (Cavallo et al., 2006).
- The concentration of benzo(a)pyrene during the 4-week campaign averaged 0.12 ng/m^3 and will most probably not exceed the annual air quality target value of 1 ng/m^3.

Emission inventory

- A detailed emission inventory was established for the whole airport area, including emissions from handling, main engines, APU and traffic.
- The emission inventory encompasses NO_X, $PM_{2.5}$, CO and hydrocarbons.
- The emission inventory show that handling and APU are the main sources to air pollution at the apron. Handling, APU, and main engines contribute 51%, 45% and 4% to $PM_{2.5}$. In the case of NO_x, handling, APU and main engines contribute 63%, 25% and 12%. Emission inventories suggest that half the emitted particle mass from the main engines is sulfate particles originating from sulfur in the jetfuel. In the same way, emissions from the APU's are to some extent sulfate particles.

Model calculations and sources

- Model calculations were performed for the airport and the apron.
- There is a fair agreement between model calculations and measurements, taking into account the uncertainty of activity data and emission inventories.
- According to the model calculations, the NO_x concentration at the apron origins from mainly the background (44%), handling (41%), APU (7%), main engine (7%) and traffic at the apron (1%). In the same way, $PM_{2.5}$ at the apron origins from mainly the background (91%), handling (5%), APU (4%), main engines (0.3%) and traffic at the apron (0.5%). These estimates are subject to relatively high uncertainty from e.g. emission inventories and should be considered with precaution
- Model calculations overestimate NO_X at the apron, which is most probably explained by too high emissions at the apron. There is a need to reevaluate the activity data behind the emission inventory.
- Model calculations do not include particle number. It is expected, that the main sources to the measured high particle number concentrations origin from handling, main engines and APU. An actual quantification of these sources was not possible.

Chemical composition of 6-40 nm particles

- It has not been possible to derive a chemical composition of the small 6-40 nm particles.
- Measurements of SO_2, emission inventories and literature references indicate that a substantial fraction of the particle number can be composed of sulfate formed during combustion of sulfur in the jetfuel.
- Measurements of particulate EC or *soot* indicate that the particles are partly elemental carbon.
- Partly combusted jetfuel and diesel is expected to constitute a significant part of the remaining small particles with diameter 6-40 nm.

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ASSESSMENT OF THE AIR QUALITY AT THE APRON OF COPENHAGEN AIRPORT KASTRUP IN RELATION TO THE WORKING ENVIRONMENT

In the period 2009-2011 DCE - Danish Centre for Environment and Energy, Aarhus University assessed the air quality on the apron of Copenhagen Airport, Kastrup, in relation to the working environment. The assessment was prepared for Copenhagen Airports A/S and included measurements of pollutants on the apron, emission inventories for Copenhagen Airport, Kastrup, and model calculations of the air pollution based on the inventories. The measurements included nitrogen oxides, the mass of particles with diameter less than 2.5 µm ($PM_{2.5}$), particle number and selected organic pollutants, including polycyclic aromatic hydrocarbons.
The concentrations of the majority of the species were in the same range or lower than typically measured on H.C. Andersens Boulevard in Copenhagen, that is one of the streets with most traffic in the capital of Denmark. However, the particle number at the apron were 2-3 times higher than at H.C. Andersens Boulevard. The two most important sources to air pollution at the apron were handling vehicles, the airplanes main engine and Auxillary Power Units (APU).

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