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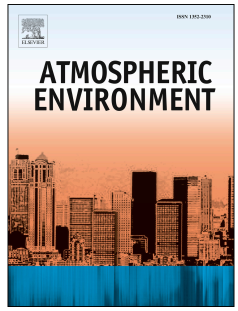

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Identifying the impact of Beirut Airport's activities on local air quality - Part I: Emissions inventory of NO_2 and VOCs

Tharwat Mokalled[a,b], Stéphane Le Calvé[b], Nada Badaro-Saliba[a], Maher Abboud[c], Rita Zaarour[a], Wehbeh Farah[c], Jocelyne Adjizian-Gérard[a]

[a]Département de Géographie, Faculté des sciences humaines, Université Saint-Joseph, Liban

[b]Institut de Chimie et Procédé pour l'Energie, l'Environnement et la Santé (ICPEES, UMR 7515 CNRS/Unistra), Equipe de physico-chimie de l'atmosphère, 67087 Strasbourg, France

[c]Unité de recherche Environnement, Génomique et Protéomique (UR-EGP), Faculté des sciences, Université Saint-Joseph, Liban

Abstract

In Lebanon, the steady growth of aircraft movements at Beirut-Rafic Hariri International Airport (RHIA) and its geographical characteristics, signifies the necessity to assess the impact of Beirut airport on air quality. Up till now, no study has assessed the impact of Beirut-Rafic Hariri International Airport (RHIA) on the air quality of Beirut. Hence, we produce the first emissions inventory of Beirut airport activities (2012) - including emissions from aircraft landing and take-off (LTO) operations, ground support equipment, stationary sources, as well as airside and landside vehicles. This study, in which the first comprehensive emissions inventory in the Middle East region is conducted, provides a methodology to assess airport emissions in a country with no data. We estimated that in 2012, Beirut airport emitted 454.8 t of NO_x, 50.7 t of NO_2, 404.1 t of NO, and 24.4 t of VOCs. Results showed that aircraft emissions (Landing/Take-off cycle and auxiliary power units) dominate the airport emissions for NO_x (91%), NO_2 (92%), NO (91%), and VOCs (58%). Our emissions estimates will be used in identifying the contribution of Beirut airport emissions to national emissions and in order to assess the airport's compliance with environmental legislations and to assess mitigation options.

Keywords: Aviation Emission; Emissions Inventory Toolkit (EMIT); Nitrogen dioxide; Volatile organic compound; Beirut

1. Introduction

Civil aviation is an integral part of the world economy providing 56.6 million jobs worldwide and its economic impact is estimated at $2.4 trillion, equivalent to 3.4% of world gross domestic product (GDP) (ATAG, 2014). Commercial aviation activity is predicted to grow by 5% per year over the next 10–15 years (CAEP 9, 2013). This would come at a cost, most notably a significant increase in pollutant emissions. These emissions include nitrogen oxides (NO_x), Volatile Organic Compounds (VOCs), carbon dioxide (CO_2), sulphur oxides (SO_x), particulate matter (PM) or soot, etc. that have the potential to impact both the global climate and local air quality (LAQ) near airports presenting risks to public health (nearby residents, airport workers and passengers) (Jung et *al.*, 2011; Levy et *al.*, 2012; Schindler et *al.*, 2013; Yim et *al.*, 2013) and the environment (FAA, 2015; Mahashabde et *al.*, 2011).

To implement mitigation measures and assess the potential health impacts of these aviation activities on residents, evaluating the emissions of airport operations – the airport emissions inventory – is necessary. Emission inventories are used as input for air quality modelling for the assessment of compliance with environmental legislation. Few studies have addressed airport pollutant emissions. At Dallas/Fort Worth International Airport, Nikoleris *et al.* (2011) conducted a detailed estimation of fuel consumption and emissions (NO_x, hydrocarbons, carbon monoxide); it was found that stop-and-go situations and taxiing at constant speed were the two largest sources of fuel burn and emissions among the taxi phases. In the middle east region, only few studies have addressed aircraft pollutant emissions at airports (Kesgin, 2006; Elbir, 2008; Yılmaz, 2017). Elbir (2008) estimated atmospheric emissions (NO_x, HC, CO) from commercial aircraft with gas turbine engines during the LTO cycle at a mid-sized Turkish airport – Adnan Menderes Airport – as 197 t /y for NO_x, 21 t /y for hydrocarbons (HCs), and 138 t /y for carbon monoxide (CO). Also, it was estimated that an increase of 1 min in taxiing time causes an increase of 0.4%, 4.2%, and 4.6% in the amounts of NO_x, HC, and CO emissions respectively (Elbir, 2008). A recent study conducted by Yilmaz (2017) estimated the total pollutant gas emissions (NO_x, HC, CO) from aircraft during the landing/take-off (LTO) cycles for the year 2010 at Kayseri Airport – Turkey. Results showed that 102.6 t/y of NO_x, 8.4 t/y of HC, and 66.9 t/y of CO were emitted. However, these studies were just limited to determine pollutants from aircraft emissions during the landing/take-off (LTO) cycle - not taking into account pollutant emissions from the different airport activities (e.g. auxiliary power units (APU), ground support equipment (GSE), power plants, landside vehicles, etc.). Also, only few studies took into account the real time-in-modes for aircraft operations.

In Lebanon, the steady growth of aircraft movements (+5%) at Beirut-Rafic Hariri International Airport (RHIA) makes sense from the geographic perspective. Beirut-RHIA is in the middle of a populated area and upwind of the capital Beirut. Hence, the pollution from the airport is expected to blow over the capital and its suburbs. This was supported by observations found in a previous study conducted by Chelala (2008), which reported that 34% of the total nitrogen dioxide concentrations at a measurement site located at the eastern part of Beirut (Pine Forest), was coming from the southwest direction (where the airport is located). This makes us hypothesize that the airport might be one of the reasons to explain this observation. Moreover, the airport's location and layout is such that the approach jet trajectory is above the seashore area (see Fig. 1 (a)), which presents a significant emission source up to distances greater than 8 km away from the airport. Also, the topography surrounding the airport as well as time-varying wind direction and speed, can have a substantial influence on the dispersion of aviation emissions. It is important to note that in our study, inhabitants and residential apartments surrounding the airport are much closer to it than the population surrounding other international airports worldwide.

In Beirut, many studies have focused on road transport emissions (Chélala, 2008; Daher et *al.*, 2013; Waked et *al.*, 2012). Up till now, no study have assessed pollutant emissions from Beirut-RHIA's activities *via* conducting an emissions inventory. The output of this inventory will be later exported to ADMS-Airport model in a future study to assess the pollutants dispersion taking into account the influence of meteorological factors. Conducting this emissions inventory was a real challenge because no previous inventory has been done for airport-related emission sources nor for road traffic around the airport. However, intensive work was dedicated to produce the first emissions inventory for Beirut Airport (2012). Emissions data were calculated and stored in the emissions inventory toolkit (EMIT) (CERC, 2015), requiring more than one year of exhaustive work.

While aircraft engine emissions include non-volatile particulate matter that are harmful to human health and the environment (Yim *et al*., 2015; Stettler *et al*., 2011; Barrett *et al*., 2010), this work mainly focused on gaseous species where also assessed in other complementary experimental studies (outdoor and indoor) to be published later. We have focused, in particular, on the effects of nitrogen dioxide (NO_2) and VOCs, key ozone and PM precursors emitted from aircraft exhaust. Nitrogen dioxide (NO_2) is the most significant local air quality pollutant emitted from aircraft (ICAO, 2008a) and presents a health risk in the Lebanese capital (Badaro-Saliba et *al.*, 2013). On the other hand, VOCs are harmful pollutants for health (alteration of the airways, cancer, and death) (Wood, 2008). The objectives of this paper are to: (i) provide a methodology to conduct the airport emissions inventory, especially in countries where no data is already available; (ii) develop the first emissions inventory for Beirut-RHIA's activities at the medium approach for the base year 2012; and (iii) assess the contribution of the different activities at Beirut airport to the total mass emitted for 2012.

2. Methods

2.1 Study Area

This study was conducted at Beirut–RHIA, the only operational commercial airport in Lebanon, located about 8 km south of the capital's city center (see Fig. 1 (a)). The airport is located on the eastern coast of the Mediterranean Sea making it affected by a Mediterranean climate. To the east of the airport, Mount Lebanon - a mountain range sloping up to 2500 m - is located (Daëron, 2005). Excluding its western side (Mediterranean Sea), Beirut Airport is embedded in a very urbanized area.

The airport code number is 2E. Beirut-RHIA handles a wide range of flights including international passenger, airfreight, military, and domestic air traffic, and is primarily utilized by the Middle East Airlines (around 50% of the total fleet). The distribution of aircraft by type at Beirut Airport for the year 2012 is shown in Fig. 2: the statistical results show that Airbus 320 (A320) (39%), Airbus 321 (A321) (13%), Boeing 738 (B738) (9%), Airbus 330 (A330) (9%), Airbus 319 (A319) (4%), Embraer 190 (E190) (3%), Boeing 737 (B737) (3%) are the most commonly used aircraft at Beirut - RHIA. Other aircraft types (< 20%) using Beirut – RHIA include Embraer 170 (E170), Canadair Regional Jet CRJ-900 (CRJ9), Boeing 777 (B777), Bombardier Challenger 605 (CL605), etc. (Lebanese DGCA, 2016, 2015).

Beirut airport has three runways and 14 taxiways (Fig. 2). The runways are named according to their magnetic heading; and are runways 03/21, 16/34, and 17/35. Runway 21, located to the east of the airport center, is the main departure runway due to the prevalence of southwest wind conditions. It extends to 3800 m and is 45 m wide (Lebanese DGCA, 2017), making it well equipped to accommodate a variety of aircraft. Runway 16 is the main landing runway due to the prevalence of wind conditions; while runway 17 is mainly used for landing and take-off of light private aircraft.

2.2 Generating an Emissions Inventory

An emissions inventory contains information regarding airport emissions (magnitude of emissions and the spatial allocation of emissions). Using appropriate input data, it calculates the total mass of emissions released into the environment from specific emission sources for a selected period of time (e.g. t/yr) to be used as input for modelling pollutant concentrations (ICAO, 2011). To minimize the uncertainty, the full range of sources (97% aircraft - engine combinations, 90% auxiliary power unit (APU), all generators and fuel tanks, all ground support equipment (GSE), etc.) which are important in assessing air quality in the vicinity of Beirut Airport, were included in the emissions inventory. These sources have been grouped into the following 5 categories: aircraft main engines (2.2.1), auxiliary power unit (2.2.2), aircraft ground support equipment (2.2.3), airport static sources e.g. fuel tanks (2.2.4), and other sources (2.2.5).

Emissions data were calculated and stored in EMIT (Emissions Inventory Toolkit), developed by CERC (2015); extra work was urged to be done in this regard due to the absence of any previous database (aircraft types and engine models, APU models, GSE, power plants, etc.). Within EMIT, the emissions inventory contains several groups. Each group contains only sources of the same source type, i.e. volume, point, area, road, etc. The magnitude of emissions for each source was calculated from source activity data using emission factor datasets stored in EMIT, using equation (1) below:

$$E = A \times e_f \quad (1)$$

where A is the unit activity/yr and e_f is the emission factor in tonnes of pollutant/unit activity. These emission factor datasets are activity datasets i.e. for these source types the total emission E of a particular pollutant in tonnes per year (t/yr) is equal to the product of the activity (A) and the emission factor (e_f). For example, the activity A can be the number of LTO cycles per year or working hours of APU per year. EMIT holds the emission factors and thus calculates the emission rate E (t/yr) when the activity data are entered by the user. This is applied to point, area, line, and volume sources. These emission rates (t/yr) were then converted by EMIT to units of $g/m^3/s$ (volume source) or $g/m^2/s$ (area source) or g/s (industrial point source), etc. according to the dimensions of each source type used (Section 2.3). Uncertainty analysis of emission rates generated by EMIT are rarely reported in literature.

On the other hand, the spatial allocations were plotted in ArcMap based on the real locations of the operations taking place in Beirut Airport. In a future study, these emissions rates and spatial allocations will be exported directly to ADMS-Airport as input for air dispersion modelling.

2.2.1 Aircraft Main Engines

The assessment of aircraft main engine emissions for 2012 included ca. 63000 aircraft movements during the different modes of operation of the Landing/Take-off cycle. A standard LTO cycle is comprised of four modal phases that represent approach (30% thrust), taxi-in/idle and taxi-out/idle (7% of the total thrust), take-off (100% of the total thrust), and climb-out (85% of the total thrust). The landing phase was further broken down into arrival (approach (3000-1500 ft), approach (1500 ft-touchdown)) and landing roll to obtain more accurate results. Each phase has a duration or time-in-mode and thrust settings as assigned by ICAO (2011).
There are various approaches or methodologies to quantify aircraft emissions, with varying degrees of accuracy and what determines the choice of approach (basic, medium, and complex)

is the availability of information (magnitude and spatial allocation) and the required accuracy of the concentration output (CERC, 2017). In brief, the basic approach requires basic knowledge with easily available data; the medium approach is more airport specific and requires additional information (e.g. volume sources for each of taxiing, take-off, climb-out, approach, and landing rather than representing all aircraft emissions as a single volume source (CERC, 2017)), whereas the complex approach requires in-depth knowledge (ICAO, 2011). In the complex approach, emissions generated are based on the actual performance of each aircraft i.e. a trajectory path and engine power setting is calculated for each aircraft-engine combination and specific aircraft weight, allowing accurate calculation. Hence, in the latter approach a more accurate TIM is known compared to the medium approach and the assumption that the aircraft power is set at a fixed level in a flight mode is not required (CERC, 2017). Despite the absence of any previous database or inventory for Beirut Airport, intensive work was performed to assess aircraft engine emissions using the medium approach for the year 2012. To achieve that, a detailed emissions inventory for about 63000 aircraft movements (31620 arriving and 31600 departing aircraft) was conducted covering 97% of aircraft-engine combinations. These movements included all commercial, cargo, and general aviation flights; however, it was impossible to access information regarding military fleet (2.5 % of the total fleet) due to security reasons.

The emissions inventory required detailed parameters, like aircraft-engine combination (e.g. B737-300 may have different engines installed: 2 × CFM-56-3B1, 2 × CFM-56-3-B2, 2 × CFM56-3C-1, or CFM56-5B6/P), thrust for each aircraft mode, annual number of LTO cycles for each aircraft-engine combination, and time-in-mode (TIM) for each mode in a single flight. For emission calculations, the ICAO dataset (year 2011) installed within EMIT was used along with activity data. The ICAO dataset provides the mode-specific emission factors (NO_x, NO_2, VOCs, etc.) for certified engines of every aircraft-engine combination in units of kilogram per min (kg/min), for the four power settings of the engine emissions certification scheme. For example, the general speciation for NO_x (NO and NO_2) according to ICAO's dataset (2011) for the aircraft-engine B737-CFM-56-3B1 are provided in Table 1. In comparison with the speciation (kg/LTO cycle) presented by Wood *et al.* (2008) for the same aircraft-engine combination and TIM presented in Table 2, the major difference in speciation was at idle power: the emission ratio (NO_2/NO_x) was equal to 91% (Wood *et al.*, 2008) versus 15% according to ICAO's datasheet (CERC, 2015). Also, the total LTO NO_x emissions presented by Wood (3.30 kg) was very similar to ICAO's total NO_x emissions (3.60 kg) presented by Wood *et al.* (2008). Hence, even the emission factors reported by ICAO at different times, i.e. 2011 and that presented by Wood *et al.* (2008), showed big discrepancies i.e. a factor of 2 (7.19/3.60). Of course, we implemented the most recent datasheet in our study (ICAO, 2011) since it takes into account the latest engine and aircraft technologies. Although NO is the major emitted pollutant; however, it is rapidly transformed to NO_2 which justifies why we focused on NO_2 in our emissions inventory and experimental field measurements.

Multiplying the mode-specific EF by the TIM yields a mode-specific emission rate in units of kilograms per LTO for each engine. The emission rates (kg/yr) were calculated using equation (2) (CERC, 2017).

$$\text{Emissions (kg)} = \sum_{i=0}^{n} LTO_i \times \left[N_i \times \sum_{j=0}^{3} TIM_{i,j} \times EF_{i,j}\right] \qquad (2)$$

where i: airframe-engine type

j: aircraft mode (take-off roll, climb-out, approach, taxi-in or out) n: number of different air frame-engine types (e.g. [A320-200, CFM56-5B4/3, (8CM055)], [Boeing 777-200 series, GE90-94B, (8GE100)], etc.)

$EF_{i,\,j}$: emission factor for airframe-engine type i in mode j (unit kg/min).

LTO_i: number of landings and take-off cycles of airframe-engine type i

N_i: number of engines installed on an airframe-engine

$TIM_{i,\,j}$: the time period (min) an airframe-engine type i spends at an identified power setting, pertaining to each of the four LTO operating modes j (i.e., take-off, climb-out, approach, and taxi/idle) of the operational flight cycle (ICAO, 2011).

Aircraft movements (timetable) for the year 2012 were obtained from the Directorate General of Civil Aviation (DGCA). Information regarding aircraft type and engine model were obtained by conducting field visits to airline companies, pilots, airport authority (Lebanese DGCA and Airlines, 2013), as well as from aircraft type certificate datasheets available online.

In general, times-in-mode differ depending on the characteristics of the airport. For example, the total time-in-mode for taxi-in and taxi-out is 26.0 min according to ICAO reference LTO (ICAO, 2011) (see Table 3); which is much longer than the actual duration for taxi at Beirut Airport. However, it was possible to determine more detailed times-in-mode to allow for a realistic emissions inventory through monitoring aircraft movements from the control tower. The taxi-out/idle duration was measured the moment the aircraft started its engine for taxiing until it entered the runway for take-off. The same procedure was used to measure TIM for taxi-in from the time the aircraft left the runway until reaching the gate. Thus, the total taxi time was estimated to be 10 min, which is less than the ICAO TIM by a factor of 2.6, which implies a significant reduction in emission estimations during taxi by a factor of 2.6. Similarly, real time-in-modes for the other LTO operational modes were determined as summarized in Table 3.

In fact, it was not feasible to obtain exact information regarding thrust settings at each site and for every aircraft. However, estimated thrust settings were used based on the ICAO (2008b) standard thrust settings; the thrust levels considered for idle, approach, take-off, and climb-out are respectively 7%, 30%, 100%, and 85% of the rated thrust (see Table 3). It is important to note that in real operation, the take-off thrust varies from aircraft to another according to the aircraft type and engine model, flight load, meteorological conditions, runway conditions, etc.

Regarding the spatial references of the different modes of the LTO cycle, information was obtained from monitoring the aircraft movements from the control tower as well as from pilots, air traffic controllers, and aircraft engineers to obtain representative values. The geographic coordinates for the arrival and departure sources were obtained from pilots and air traffic controllers using real aircraft observations and Standard Instrument Arrival Routes (STARs) that are published procedures followed by aircraft before reaching a destination airport, or Standard instrument departure (SID) routes that are published flight procedures followed by aircraft on an IFR flight plan immediately after take-off from an airport. Aircraft sources used in this study have the same location of emissions for all aircraft types i.e. all aircraft during climb-out are modelled within the same geographical extents although in reality there are differences in the trajectories. This is a simplification, and when modelling an airport more details can be given by assigning different geographical extents to different aircraft types. The depth and elevation used for each mode was adapted from ADMS-Airport Manual (CERC, 2017) for the medium approach and is explained as follows: (i) Take-off and taxi are emissions for the main engines, so the elevation used (1.75 m) represents typical engine heights (ii) the defaults (depth and elevation) for approach were used to represent the descent of aircraft: the first volume source assumes well-mixed emissions between 3000 ft and 1500 ft, and the second volume source assumes well-mixed emissions between 1500 ft and ground-level. Because approach (elevated source) has a relatively small impact on ground-level concentrations of gaseous pollutants, this relatively simple approach can be used to represent the aircraft and its environmental impact (Matthews, 2018; Peace et al., 2006).

2.2.2 Auxiliary Power Unit (APU)

APU emissions were also assessed to complement aircraft movements for about 63000 aircraft. These emissions, which take place at the gate prior departure or after landing, were modelled as volume sources. The activity data for APUs (APU type and operation hours) were obtained as follows: (i) An approximate time of 1.5 hr before departure and 1.5 hr after landing was used, as estimated by several airport engineers and pilots in RHIA; (ii) the APU models were obtained from several airline companies and by using several references (CERC, 2015; European Environment Agency, 2009; Unique, 2005). The depth (12 m) and elevation (6 m) were chosen according to ADMS-Airport manual values since APU units, typically located at the back of an aircraft, are located around 6 m above ground-level. For emission calculations, APU 2004 dataset (CERC, 2015) installed within EMIT was used along with activity data. The APU 2004 dataset, compiled by FAA, includes emission factors (kg/unit) for 29 different APU types which are associated to aircraft included in the inventory.

2.2.3 Ground Support Equipment (GSE)

Aircraft GSE included both GSE operating at the stand (e.g. GPU) and mobile sources across the apron (called airside vehicles (e.g. crew buses)). For GSE at the stand, detailed information about the working hours for each GSE type was obtained from the major handling companies like Middle East Airlines Ground Handling (MEAG) responsible for the majority of ground support equipment, Directorate General of Civil Aviation (DGCA) at Beirut Airport, Mideast Aircraft Services Company (MASCO), Middle East Airports Services (MEAS), Lebanese Air Transport (LAT), Trans Mediterranean Airways (TMA), Executive Air Services, Beirut Wings, and others. This included information about the various types of GSE utilized (> 16 GSE types): baggage belt loader, air climate unit, aircraft tug, baggage cart tractor, cargo loader, cargo loader main deck, catering truck, GPU, refuelling truck, forklift, lavatory truck, narrow body towbarless aircraft tug, passenger stairs, refuelling dispenser truck, refuelling tanker truck, water truck, etc. In section 3.1, the emissions of al GSE are grouped together according to literature (Celikel et al., 2002; Kennedy et al., 2009; Stettler et al., 2011). Since the majority of GSE emissions are from vehicles on the ground, lower values for the depth (2 m) and elevation (1 m) are suggested by CERC. For emission calculations, AIRPORT GSE 2007 dataset (CERC, 2015) installed within EMIT was used along with activity data. This dataset includes emission factors (kg/hr) for generic heavy GSE or based on equipment at Zurich airport (Unique, 2005). To assess airside vehicles (i.e. road traffic within the airport vicinity), emission rates were computed using the EMIT datasheet (EUROSCALED 03) with activity data related to traffic (vehicles/hr classified as motorcycles/light/heavy, hourly speed). Due to the lack of any previous assessment, activity data for airside vehicles was obtained by manually counting the vehicles on the airport ramp and classifying them (light or heavy) at low, medium, and high traffic activities during different times of the week between July and October.

2.2.4 Fuel Tanks

Airport fuel farm emissions are mainly constituted of VOCs, which result from the evaporation of the fuel stored in the airport tanks (aircraft fuel, GSE fuel, and power plant fuel). Because emissions from fuel tanks are dependent on the type and location of the tanks as well as the ambient temperature, a single set of emission factors are not available for this source type, so are not included in EMIT.

Annual emission rates (t/yr) for VOCs were first calculated using *TANKS* (EPA, 2016), which is a software designed by the United States Environmental Protection Agency (US EPA) to estimate emissions from organic liquids in storage tanks. *TANKS* allows users to enter specific information about a storage tank which include its dimensions (height and diameter in meters), turnovers/yr, construction, paint condition (roof and shell), roof type, radius, and height; the liquid contents (average and maximum liquid heights (ft), chemical components (chemical category and liquid temperature); and the location of the tank (ambient temperature, etc.), to generate an air emissions report. The combination of several parameters make the emission factor of a fuel tank as described by US EPA. Accordingly, the software TANKS calculates the total emission per year upon filling in all the required parameters (activity data). The detailed equations installed in the software are found in EPA's document (EPA, 2016). For example, for a fixed-roof tank (case of Beirut Airport), total losses are equal to the sum of the standing storage loss and working loss:

$$L_T = L_S + L_W \qquad (3)$$

$$\text{Standing Storage Loss } (L_S) = 365\, V_V W_V\, K_E K_S \qquad (4)$$

Where the activity data is V_v (the vapor space volume) and the emission factor is $W_V K_E K_S$

$$\text{Working Loss } (L_w) = 0.0010\, M_V\, P_{VA}\, Q\, K_N\, K_P \qquad (5)$$

All the parameters required for the 3 kerosene tanks found at Beirut Airport, as well as 20 other tanks (related to generators and GSE) were obtained, and the calculated emissions (kg/yr) were manually entered into EMIT. Upon entering the yearly emission rates and the spatial allocation of each fuel tank, emission rates for fuel tanks (modelled as area sources) were calculated by EMIT.

2.2.5 Other Sources (Power plants, urban sources)

Airport power plants (19 power plants) were modelled as point sources. Activity data (working hours) were obtained from Middle East Airports Services (MEAS) and Mideast Aircraft Services Company (MASCO). Due to the lack of previous measurements, the power plant stack heights and diameters were manually measured (measuring tape) and their geographic coordinates were taken using a GPS tracking unit. For emission calculations, activity data were used with emission factors based on the UK Emission Factor Database (UKEFD) 2007 Energy dataset (CERC, 2015) installed within EMIT. This dataset, based on private communication from

UK Atomic Energy Authority, contains emission factors (kg/unit) for different combustion sources.

Urban sources included airport landside traffic constituting road traffic at major roads close enough or directly related to the airport to require explicit modelling - the airport's main entrance road. Emission rates resulting from road traffic at the airport main entrance (landside traffic) were computed using the EMIT datasheet (EUROSCALED 03) with activity data related to traffic, i.e. vehicles/hr (motorcycles/light/heavy) and hourly speed. EURO SCALED 03 is a year-dependent emission factor dataset for vehicle emissions including the effects of new fuels and vehicle technologies (CERC, 2015). Spatial parameters included road width (m), elevation (m), canyon height (m) and gradient, as well as spatial allocation (vertices). Due to the lack of any information about these parameters, the flux of vehicles (count/hr) by vehicle category was determined by manual counting, which took place at the road leading to the airport entrance at different levels of activity (low, medium, high) and repeated several times a week to account for all the traffic variations during the week.

2.3 Emission Source Models

All of the aforementioned sources were modelled as explicit sources as shown in Fig. 3. Once calculated, these emissions were included in ADMS according to several types of sources (volume, area, point, road). In brief, a volume source corresponds to a source where the emissions are distributed in a volume, a point source (or industrial point source) represents typically a stack emission, and an area source (or industrial area source) corresponds to an industrial source that is too large to be treated as a point source and is distributed over a large area at ground level (CERC, 2015). Fig. 3 depicts the different types of source models used. All the aircraft sources, including APU, were modelled as volume sources. GSE was modelled both as a volume source (GSE at the stand) and a road source (airside vehicles). It is important to note that the GSE at the stand and APU are both located at the gates at the center of the airport, which leads to the increase in the estimated emissions at this location, as will be seen later in the model results. The other airport sources were considered as follows: fuel tanks were modelled as area sources, generators or power plants as point sources, and the airport main entrance as a road source as shown in Fig. 3.

3. Results and Discussion

3.1 Emissions

The emission rates calculated by EMIT are presented in Table 4 ~~3~~. EMIT first calculates the emission rates in t/yr and then converts them to units of g/s (point sources), g/m^2/s (area source) or g/m^3/s (volume source) or g/km/s (road source) by dividing the emission rates in t/yr by the product of the total volume or area with the total time (Fig. 4 and Fig S1and S2 in supplementary material). These converted emission rates will be used later in ADMS-Airport dispersion modelling equations.

Fig. 5 shows the estimated annual airport-related NO_2 and VOCs emission~~s~~ (t/yr) as a function of major source category. The estimated total NO_2 and VOCs emission~~s~~ for the year 2012 are 50.7 and 24.4 t respectively. As seen in Fig. 5, aircraft emissions (APU and LTO cycle) dominate the airport emissions for both NO_2 (92%) and VOCs (68%). As expected, aircraft emissions during the LTO cycle (37.4 t/yr) make the dominant contribution to airport NO_2 emissions, followed by aircraft APU emissions (9.3 t/yr), GSE (3.7 t/yr), whereas stationary and road sources are minor contributors (see Fig. 5 (a)). This order of contribution, observed in other studies (Celikel et al., 2002; Stettler et al., 2011), is due to the dependence of the total emissions on the yearly activity data (e.g. working hours) and emission factors (section 2.2) which are highest for aircraft engines. Similarly for VOCs, the major source is also the LTO cycle (11.5 t) (see Fig. 5 (b)). The estimated VOCs emission from GSE are 5.5 t, followed by stationary sources (3.8 t), and APU (2.7 t). In fact, the major contributors to these stationary source emissions are fuel tanks (99.7%), especially the 3 kerosene fuel tanks located at the eastern part of the airport which present a significant source of VOCs.

Aircraft NO_2 and VOCs emission are broken down further into emissions by the different modes of the LTO cycle (see Fig. 6). It is important to differentiate between ground level emissions and elevated emissions associated with aircraft where the former have the biggest impact on local air quality, whereas the latter have less impact as they take place at increasing heights. Aircraft ground NO_2 emissions (Landing roll, taxi-in, taxi-out, take-off) were approximately 15.45 t in 2012 constituting 41% of total aircraft engine emissions, whereas the corresponding Aircraft NO_2 and VOCs emission are broken down further were estimated to be 10.29 t constituting up to 90% (see Fig. 6). As shown in Fig. 6 (a), the 2 major contributors for NO_2 emissions are the climb-out and approach (arrival) phases each contributing to 11 t/yr. In fact, the emission rate per second for the climb-out phase (1.15×10^{-9} g/m^3/s) is greater than the approach phase ($4.7 – 5 \times 10^{-10}$ g/m^3/s), but the total volume for the approach phase led to equal emissions in tonnes per year. This is significant because this highlights the fact that the climb-out phase has a higher impact on the concentrations generated by the dispersion modelling (future study). Although the total duration for the take-off phase is 0.7 min, it contributes by 1.3 t/yr to the total NO_2 emissions (14% of the total LTO) (see Fig. 6 (a)) with an emission rate of 3.53×10^{-7} g/m^3/s (see Table 4). This is due to the fact that at high speed, the temperature within the combustion chamber is higher, which leads directly to the increase in the emission of nitrogen oxides (Dagaut et *al.*, 2006; Penner, 1999). On the other hand, the taxi phase (taxi-in and taxi-out) dominates the VOC emission sources with a contribution of 10 t/yr or 88% of the LTO cycle contribution as seen in Fig. 6 (b). This is followed by the approach (7%), climb-out (3%), take-off (1%), and landing roll (1%). This result is expected as the ICAO VOCs emission factors for the taxi phase are the highest and those of the take-off phase are the lowest. VOCs emission are higher at low power settings when the temperature of the air is relatively low and the fuel atomization and mixing process is least efficient. This is also in accordance with ICAO databank sheets for unburned hydrocarbons (UHC) for all modern turbine engines; all engines produce less CO and NMHC emission per kg of fuel burned as their power levels are increased above idle (Anderson *et al.*, 2006).

3.2 Comparison with Other Airports

Table 5 compares the annual LTO emissions at Beirut Airport (2012) with two mid-sized airports (Adnan Menderes Airport (AMA) (2004) and Kayseri Airport (2010)) in Turkey (Elbir, 2008; Yılmaz, 2017) which is a Middle Eastern country like Lebanon. Comparisons were also done with Toronto Pearson International Airport – Canada (2007) (Kennedy *et al.*, 2009) which represents a busy airport in North America. The total emissions of VOCs from LTO activities at Beirut Airport (11.5 t/yr) are comparable to emissions from Kayseri Airport (8.4 t/yr) and are almost half the VOCs emission by AMA (21 t/yr). However, much higher VOCs emission are produced by Toronto Pearson International Airport (TPIA) (222 t/yr) as summarized in Table 5. These observations can be explained by the higher number of LTO movements in TPIA (182122 movements/yr) which was almost 6 times the number of LTO movements in Beirut Airport for the year 2012. NO_x emissions exhibit the same relative variability among the airports listed in Table 5, reaching up to 2265 t/yr which is around 6 times NO_x emissions at Beirut Airport. This observation maybe explained by the higher number of LTO cycles in TPIA (182122 LTO movements for the year 2007) which is interestingly also around 6 times the LTO movements at Beirut Airport for the year 2012. As a comparison, we can see that the average VOCs mass emitted per LTO movement at Beirut – RHIA (0.00036 t/yr) is much less than the mass emitted by other airports (0.0012 – 0.0021 t/yr) listed in Table 5, which may be related to the fact that in this study we used the real TIM of taxi which is less than the time assigned by ICAO by a factor of 2.6 (see Table 3). On the other hand, NO_X emitted per LTO movement was in the same range (0.012 – 0.013 t/yr) for Beirut Airport, Izmir, and Toronto Airport. This is probably attributed to the use of similar TIMs for each of the take-off and climb phases (almost equal to ICAO TIMs presented in Table 3), which are the major contributors among the various LTO phases to NO_X emissions. It is important to note that while total pollutant emissions from Beirut Airport are much lower than emissions from large international airports (e.g. Toronto Pearson International Airport); however, the location of Beirut Airport in the middle of an urbanized area in very close proximity to nearby residents, upwind of the capital Beirut, surrounded by the sea to the west and mountains to the east – all make it a significant emission source.

4. Conclusions

A methodology to assess emissions from Beirut Airport's activities has been developed and applied despite the absence of any data (activity data related to aircraft, airport stationary and mobile sources, road traffic, etc.). This study provides the first emissions inventory for Beirut Airport's activities using a European emission inventory toolkit in the medium approach. In fact, it is the first study in the Middle East region to conduct a comprehensive emissions inventory for all the airport-related sources. This detailed emissions inventory took into account operational details for around 63000 aircraft movements for the year 2012, as well as detailed parameters for most of the airport's emission sources. We estimate that in 2012, Beirut airport emitted 402.9 t of NO_x, 50.7 t of NO_2, and 32 t of VOCs. This up-to-date and comprehensive emission inventory will be used in a future study to assess the impact of Beirut Airport activities on air quality-by providing emission rates for the dispersion model ADMS-Airport which uses a series of dispersion equations that take into account emission rates, meteorological parameters (e.g. wind, turbulence, and boundary layer), etc.

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Table 1: Mode-specific emission factors (kg/min) for the aircraft-engine Boeing 737 - CFM - 56 - 3B1 (ICAO, 2011)

Table 2: Comparison of the speciation of nitrogen oxides (kg/LTO) according to ICAO's dataset (2011) and Wood *et al.* (2008)

Table 3: Source details for aircraft taxiing, take-off, and climb groups. The realistic times-in-mode were determined in this work through monitoring aircraft movements, presented versus ICAO's (2011).

Table 4: EMIT emission rates calculated for Beirut Airport inventory (2012). Emission rates in t/yr are converted to units of g/s (point sources), $g/m^2/s$ (area source), $g/m^3/s$ (volume source), or g/km/s (road source).

Table 5: Comparison of annual LTO emissions (t/yr) at Beirut Airport and other airports worldwide

Table 1

Emission Factor (kg/min)	**NO_2**	**NO_x**
Idle	0.02	0.02
Approach	0.02	0.12
Climb-out	0.06	0.69
Take-off	0.09	1

Table 2

	ICAO dataset, 2011			**Wood *et al.*, 2008**		
Emission Factor (kg/LTO)	NO_2	NO_x	% (NO_2/NO_x)	NO_2	NO_x	% (NO_2/NO_x)
Idle	0.52	1.39	15.0	0.53	0.58	91.4
Approach	0.17	1.16	37.5	0.08	0.49	16.3
Climb-out	0.17	3.24	5.3	0.13	1.53	8.5
Take-off	0.06	1.41	4.5	0.06	0.70	8.6
Totals per engine/LTO	0.93	7.19	12.9	0.80	3.30	24.2

*For the sake of comparison with Wood et al. (2008), NO_2 and NO_x emissions for ICAO (2011) were calculated by multiplying the time-in-mode presented by Wood et al. (2008) with the emission factors (kg/min) provided by ICAO (2011)

Table 3

Source Group	Source Name	Thrust (%)	TIM (min) ICAO	TIM (min) This study
Arrival	Approach (3000-1500 ft)	30	4.0	2.5
	Approach (1500 ft-touchdown)			2.5
	Landing roll			0.6
Taxi	Taxi-in	7	7.0	4.0
	Taxi-out		19.0	6.0
Take-off	Take-off	100	0.7	0.7
Climb	Climb	85	2.2	2.0

Table 4

Source Group	NO_2		VOCs	
Volume Sources				
	t/yr	g/m^3/s	t/yr	g/m^3/s
Approach 3000 - 1500 ft	5.53	4.70×10^{-10}	0.39	3.32×10^{-11}
Approach 1500 - 0 ft	5.53	5.01×10^{-10}	0.39	3.57×10^{-11}
Landing Roll	1.33	8.81×10^{-8}	0.09	6.27×10^{-9}
Climb-out	10.95	1.15×10^{-9}	0.40	4.17×10^{-11}
Take-off	5.09	3.53×10^{-7}	0.17	1.16×10^{-8}
taxi in (1)	0.90	3.73×10^{-7}	1.00	4.14×10^{-7}
taxi in (2)	0.90	6.69×10^{-7}	1.00	7.43×10^{-7}
taxi in (3)	0.90	1.02×10^{-6}	1.00	1.13×10^{-6}
taxi in (4)	0.90	5.81×10^{-7}	1.00	6.45×10^{-7}
Taxi-in (total)	3.61	$3.73 - 10.2 \times 10^{-7}$	4.01	$4.14 - 11.3 \times 10^{-7}$
Taxi out (1)	0.90	1.13×10^{-6}	1.00	1.26×10^{-6}
Taxi out (2)	1.80	2.86×10^{-7}	2.01	3.19×10^{-7}
Taxi out (3)	0.90	9.94×10^{-7}	1.00	1.11×10^{-6}
Taxi out (4)	0.90	8.16×10^{-7}	1.00	9.08×10^{-7}
Taxi out (5)	0.90	1.67×10^{-6}	1.00	1.86×10^{-6}
Taxi-out (total)	5.41	$2.86 - 16.7 \times 10^{-7}$	6.03	$3.19 - 12.6 \times 10^{-7}$
APU	9.29	1.21×10^{-7}	2.65	3.45×10^{-8}
GSE (stand[1])	3.64	3.90×10^{-7}	5.22	5.59×10^{-7}
Area Sources				
	t/yr	g/m^2/s	t/yr	g/m^2/s
Fuel Tank	0.00	0.00	3.79	$0.035 – 3990 \times 10^{-5}$
Point Sources (g/s)				
	t/yr	g/s	t/yr	g/s
Power plants (g/s)	0.11	$8.56 – 646 \times 10^{-6}$	0.02	$1.48 - 111.53 \times 10^{-6}$
Road Sources (g/km/s)				
	t/yr	g/km/s	t/yr	g/km/s
Main Entrance	0.15	0.01	0.95	0.07
GSE (airside vehicles[2])	0.05	0.0015 - 0.0017	0.25	0.007 - 0.008

*Emission rates in t/yr are converted to units of g/s (point sources), g/m^2/s (area source), g/m^3/s (volume source), or g/km/s (road source) by dividing them by the product of the total volume or area with the total time.

[1]GSE at stand includes ground power unit (GPU), baggage belt loader, air climate unit, catering truck, forklift, lavatory truck, etc.

[2]Airside vehicles are mobile sources across the apron.

Table 5

Pollutants	This Study: Beirut Airport (2012)	Kayseri Airport, Turkey (2010)	Adnan Menderes Airport, Turkey (Izmir) (2004)	Toronto Pearson International Airport (TPIA) (2007)
VOCs	11.5	8.4	21	222
NO_x	402.9	102.6	197	2265
LTO movements*	31600	3944	14368	182122

*Landing and take-off movements are defined as an arrival and departure pair from the airport.

Fig. 1: (a) Study Area (Beirut - Rafic Hariri International Airport). The red dotted line reflects the main jet trajectory used for landing in Beirut-RHIA (b) Top view of Beirut Rafic Hariri International Airport, taken from Lebanese DGCA (2010) (Rwy: runway)

Fig. 2: Percentage of relative aircraft frequencies (2012) by aircraft type at Beirut Airport (Lebanese DGCA, 2015).

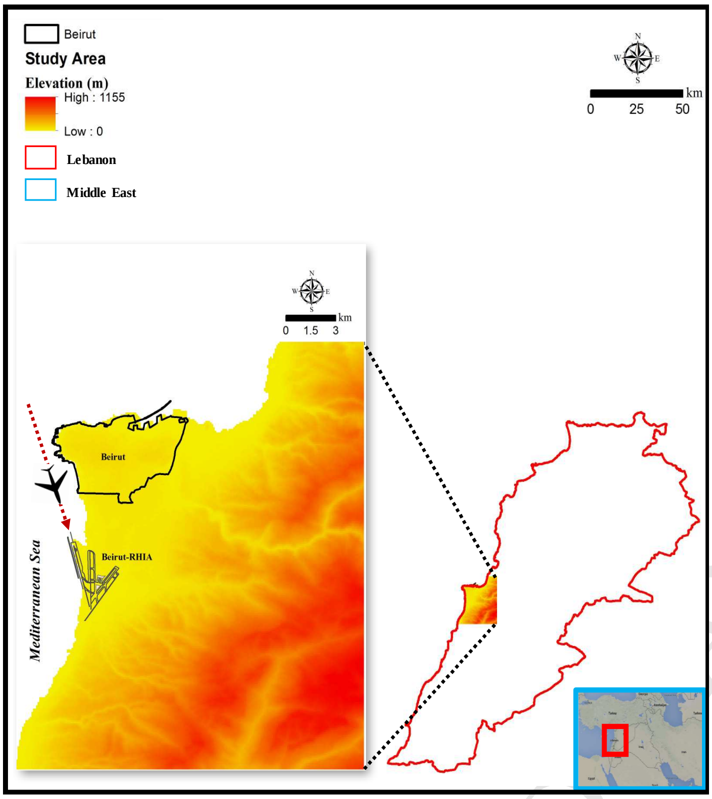
Fig. 3: 3-D geospatial emissions inventory created by exporting EMIT database to Arc Globe for the sources modelled at Beirut Airport in this study (year 2012)

Fig. 4 3-D geospatial emissions inventory (2012) created by exporting EMIT database to Arc Globe for volume sources (a) VOC, (b) NO_2

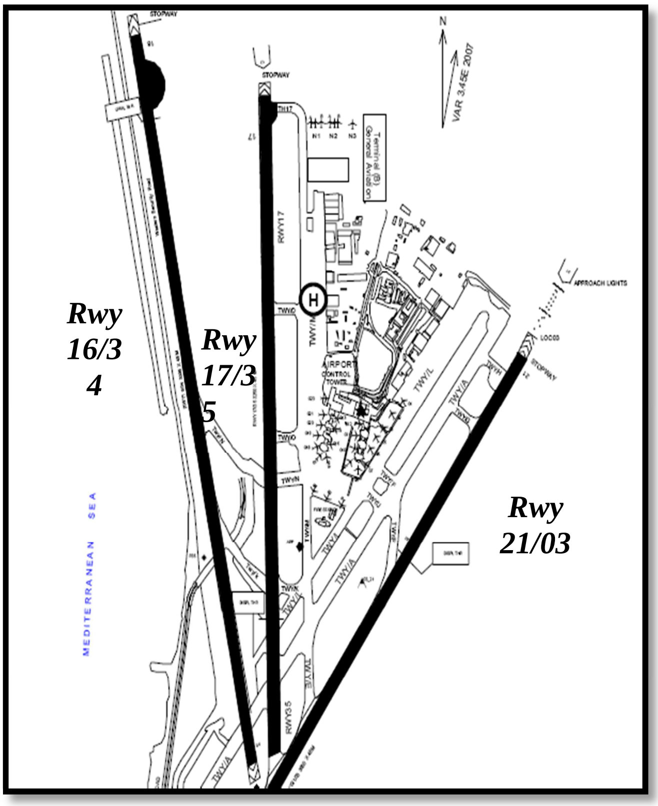
Fig. 5: Ground level airport-related emissions (in units of t) estimated in this work by EMIT from Beirut Airport in 2012 (a) NO_2 (b) VOCs

Fig. 6: Ground-level LTO emissions (in units of t) estimated in this work by EMIT from aircraft at Beirut Airport in 2012 (% by flight phase or mode of LTO cycle) (a) NO_2 (b) VOCs

Fig. 1


Beirut
Study Area
Elevation (m)
High : 1155
Low : 0
Lebanon
Middle East
km
0 25 50
km
0 1.5 3
Beirut
Beirut-RHIA
Mediterranean Sea

(a)


Rwy 16/34
Rwy 17/35
Rwy 21/03
MEDITERRANEAN SEA

(b)

Fig. 2

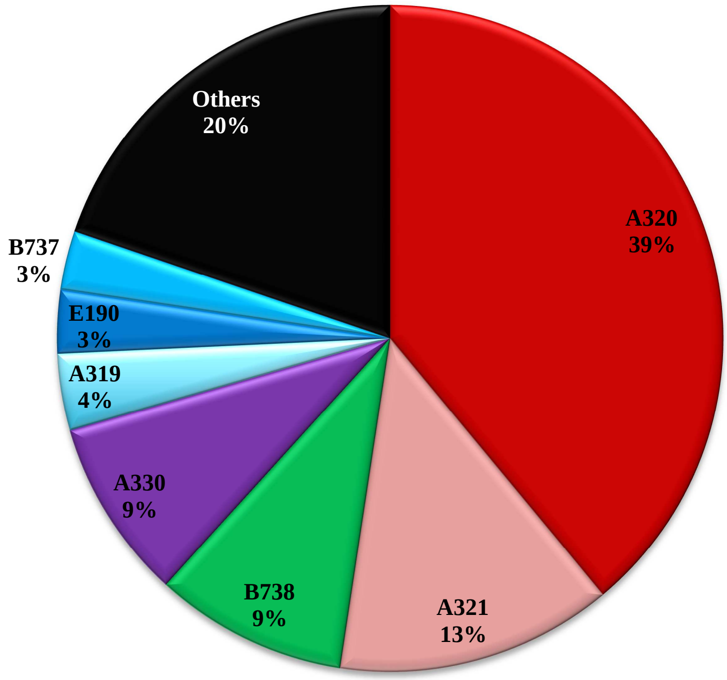


Fig. 3

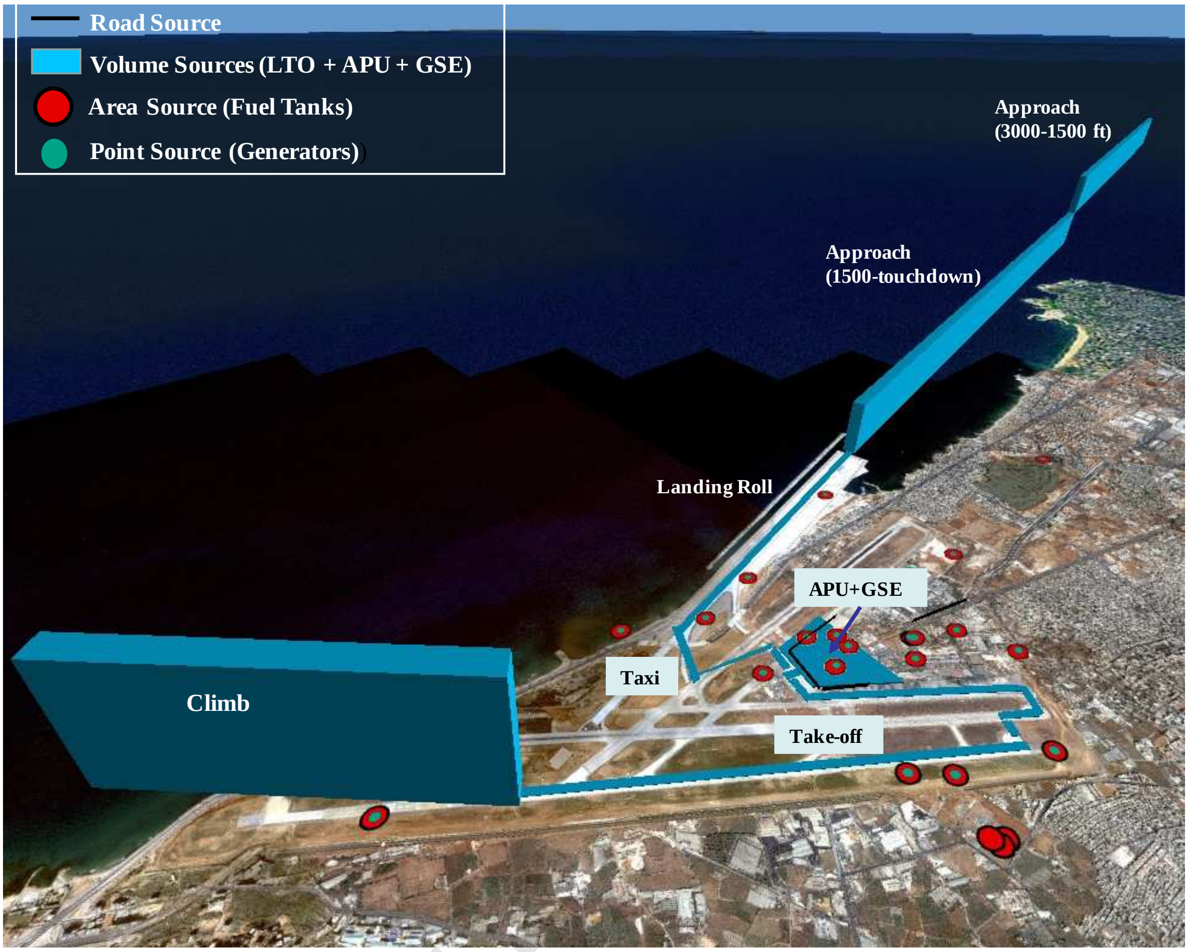
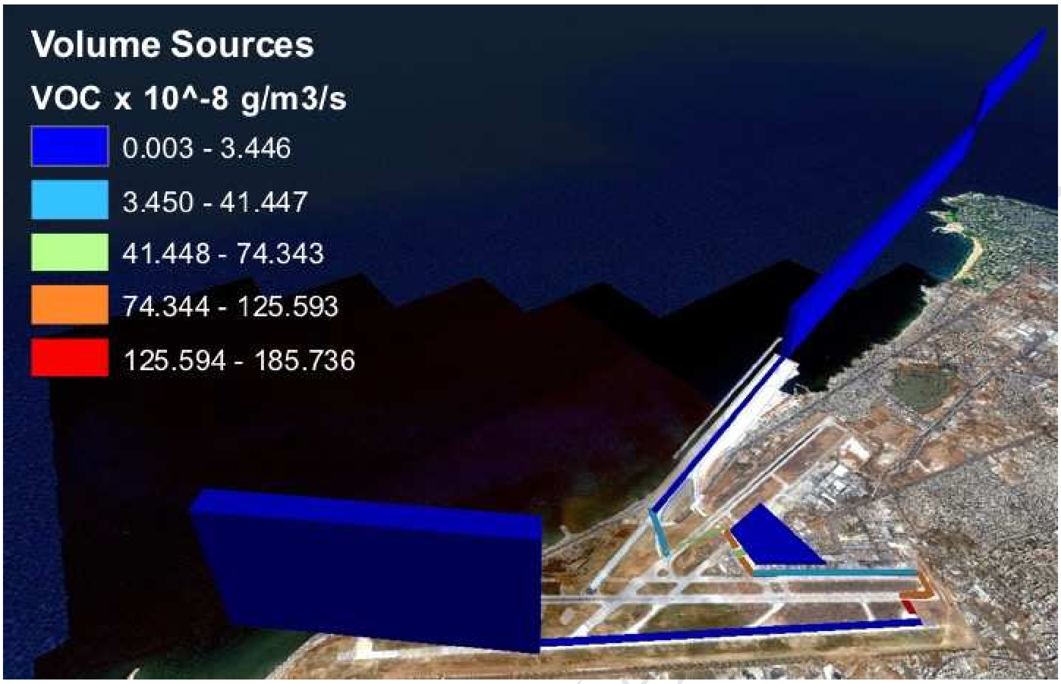
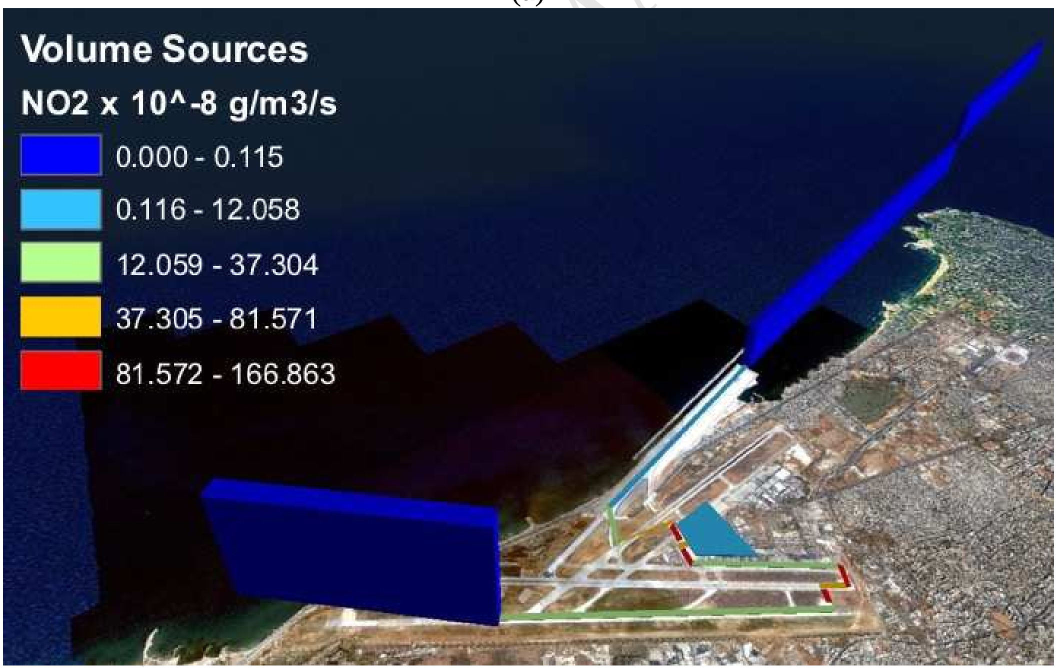

Road Source
Volume Sources (LTO + APU + GSE)
Area Source (Fuel Tanks)
Point Source (Generators)
Approach
(3000-1500 ft)
Approach
(1500-touchdown)
Landing Roll
APU+GSE
Taxi
Climb
Take-off

Fig. 4


Volume Sources
VOC x 10^-8 g/m3/s
0.003 - 3.446
3.450 - 41.447
41.448 - 74.343
74.344 - 125.593
125.594 - 185.736

(a)


Volume Sources
NO2 x 10^-8 g/m3/s
0.000 - 0.115
0.116 - 12.058
12.059 - 37.304
37.305 - 81.571
81.572 - 166.863

(b)

Fig. 5

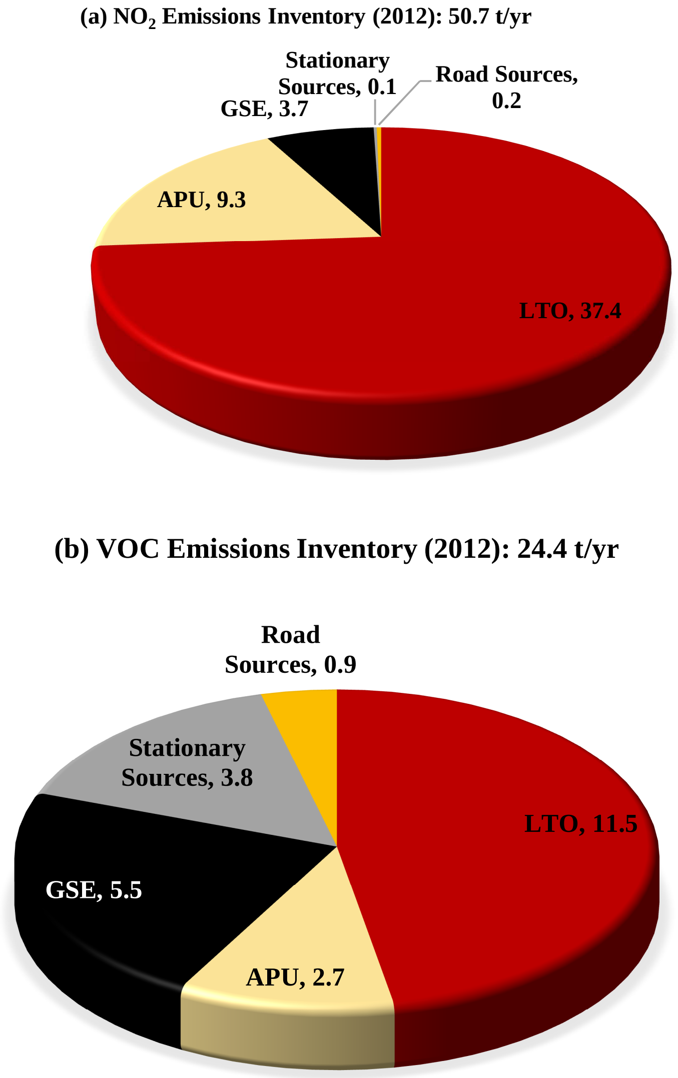
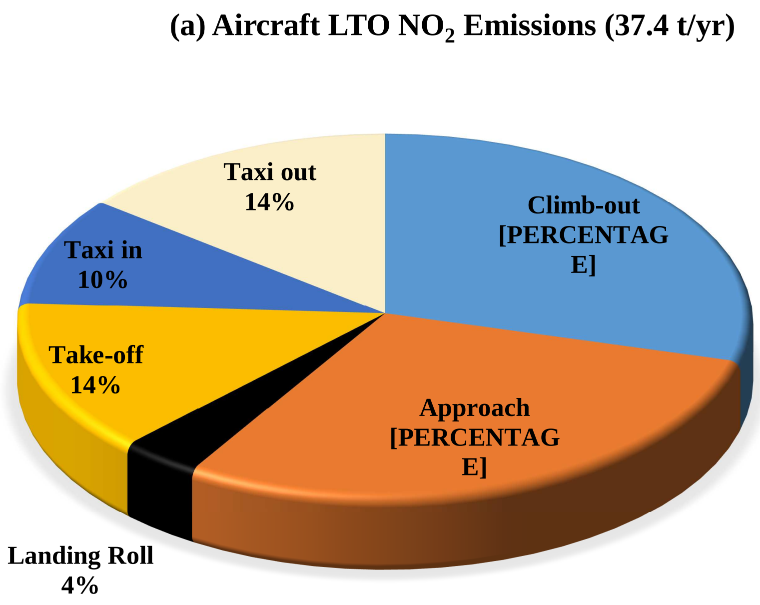
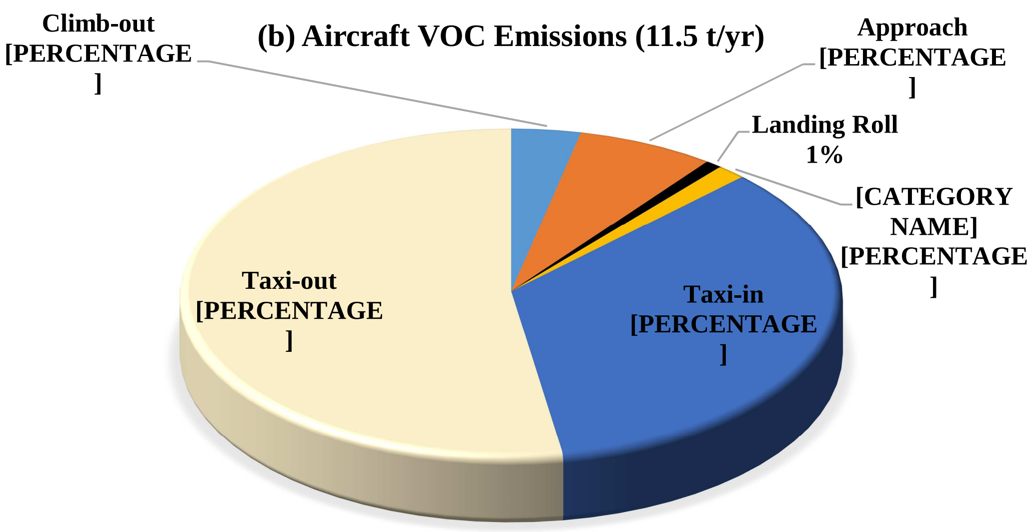

(a) NO_2 Emissions Inventory (2012): 50.7 t/yr
Stationary Sources, 0.1
Road Sources, 0.2
GSE, 3.7
APU, 9.3
LTO, 37.4
(b) VOC Emissions Inventory (2012): 24.4 t/yr
Road Sources, 0.9
Stationary Sources, 3.8
LTO, 11.5
GSE, 5.5
APU, 2.7

Fig. 6


(a) Aircraft LTO NO2 Emissions (37.4 t/yr)
Taxi out
14%
Climb-out
[PERCENTAG
E]
Taxi in
10%
Take-off
14%
Approach
[PERCENTAG
E]
Landing Roll
4%


Climb-out
[PERCENTAGE
]
(b) Aircraft VOC Emissions (11.5 t/yr)
Approach
[PERCENTAGE
]
Landing Roll
1%
[CATEGORY
NAME]
[PERCENTAGE
]
Taxi-out
[PERCENTAGE
]
Taxi-in
[PERCENTAGE
]

- Beirut Airport is located between the sea and mountains within a populated area.
- A methodology to conduct airport emission inventories has been established.
- Beirut Airport activities emitted 454.8 t of NO_x, 50.7 t of NO_2, and 24.4 t of VOCs.
- The methodology allowed identifying emission factors from airport activities.