QUANTIFYING EMISSIONS FROM THE COMMERCIAL AIRCRAFT IN THAILAND'S AIRSPACE

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QUANTIFYING EMISSIONS FROM THE COMMERCIAL AIRCRAFT IN THAILAND'S AIRSPACE

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Deegree.

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การศึกษานี้มีวัตถุประสงค์เพื่อประเมินการปล่อยมลพิษที่เกิดขึ้นจากวัฏจักรการบินอันได้แก่ แก๊สคาร์บอนมอนอกไซด์ แก๊สไนโตรเจนออกไซด์ และแก๊สไฮโดรคาร์บอน จากเครื่องบินพาณิชย์ในขอบเขตแผ่นดินของประเทศไทย ด้วยการคำนวณผ่านสมการทางคณิตศาสตร์ร่วมกับค่าปัจจัยการปลดปล่อยและข้อมูลเที่ยวบินพาณิชย์ของประเทศไทยภายในปี พ.ศ. 2558 และสร้างแผนที่เส้นทางการบินของเครื่องบินพาณิชย์บนน่านฟ้าไทยจากข้อมูลพิกัดตำแหน่งของเครื่องบิน ผลที่ได้ใช้ประเมินการแพร่กระจายของมลพิษเชิงพื้นที่ด้วยฟังก์ชั่นในโปรแกรมทางระบบสารสนเทศภูมิศาสตร์

ผลที่ได้จากการคำนวณปริมาณมลพิษที่เกิดขึ้นจากวัฏจักรการบินในโหมดแท็กซี่ (Taxi) มีค่า 2.42, 0.44 และ 0.44 เมกะตัน/ปี สำหรับแก๊สคาร์บอนมอนอกไซด์ แก๊สไนโตรเจนออกไซด์ และแก๊สไฮโดรคาร์บอน ตามลำดับ ขณะที่มลพิษที่ถูกปล่อยจากโหมดทะยานขึ้น (Take-off) มีค่า 0.08, 3.83 และ 0.04 เมกะตัน/ปี ตามลำดับ นอกจากนี้มลพิษในระดับภาคพื้นดินในโหมดลงจอด (Landing) มีค่า 0.21, 0.05 และ 0.04 เมกะตัน/ปี ตามลำดับ สำหรับมลพิษจากวัฏจักรการบินที่ระดับความสูงในโหมดการบินขึ้นตอนต้น (Initial-climb) เท่ากับ 0.03, 1.53 และ 0.01 เมกะตัน/ปี ตามลำดับ ในขณะที่โหมดการบินขึ้นตอนปลาย (Climb-out) มีค่ามลพิษเท่ากับ 0.05, 1.42 และ 0.01 เมกะตัน/ปี ตามลำดับ ส่วนมลพิษที่เกิดขึ้นในระหว่างโหมดการบินลง (Approach) มีค่า 0.52, 0.96 และ 0.09 เมกะตัน/ปี ตามลำดับ นอกจากนี้มลพิษที่เกิดขึ้นในขณะโหมดการบินที่ระดับความสูงเกินกว่า 1,000 เมตร (Cruise) มีค่าเท่ากับ 1.06, 2.95 และ 0.65 เมกะตัน/ปี ตามลำดับ ซึ่งมลพิษที่เกิดขึ้นจากวัฏจักรการบินตลอดระยะเวลาทั้งปีมีค่า 4.36, 11.17 และ 1.28 เมกะตัน สำหรับแก๊สคาร์บอนมอนอกไซด์ แก๊สไนโตรเจนออกไซด์ และแก๊สไฮโดรคาร์บอน ตามลำดับ โดยอัตราการปลดปล่อยของแก๊สคาร์บอนมอนอกไซด์ แก๊สไนโตรเจนออกไซด์ และแก๊สไฮโดรคาร์บอนมีค่าอยู่ในช่วง 1.06 - 4.69, 0.17 - 15.82 และ 0.09 - 0.84 ตันต่อเที่ยวบิน ตามลำดับ แผนที่เส้นทางการบินของเครื่องบินพาณิชย์บนน่านฟ้าไทยที่ถูกสร้างขึ้นแสดงถึงการเคลื่อนที่ของเครื่องบินพาณิชย์ในวัฏจักรการบิน โดยที่ระดับความสูงต่ำกว่า 1,000 เมตร การเคลื่อนที่ของเครื่องบินพาณิชย์จะเกิดขึ้นภายในอาณาเขตรัศมีช่วง 5 - 10 กิโลเมตร รอบท่าอากาศยาน การแพร่กระจายของแก๊สคาร์บอนมอนอกไซด์เชิงพื้นที่พบว่า มีค่าสูงในโหมดแท็กซี่ (Taxi) เช่นเดียวกับแก๊สไฮโดรคาร์บอนซึ่งเป็นผลมาจากเผาไหม้ที่ไม่สมบูรณ์ของเครื่องยนต์ของเครื่องบินขณะอยู่ในสภาวะพักของ

เครื่องยนต์ ในขณะที่การแพร่กระจายของแก๊สไนโตรเจนออกไซด์ถูกพบมีค่าสูงในโหมดทะยานขึ้น (Take-off) ซึ่งเป็นผลมาจากการเร่งความเร็วของเครื่องยนต์ ทำให้เกิดสภาวะที่มีอากาศมากเกินพอในห้องเครื่องที่มีความร้อนสูง โดยมลพิษเชิงพื้นที่ของแก๊สทั้งสามชนิด เกิดขึ้นที่บริเวณตลอดเส้นทางการบินที่ระดับภาคพื้นภายในท่าอากาศยาน

สาขาวิชามลพิษสิ่งแวดล้อมและความปลอดภัย ลายมือชื่อนักศึกษา วีรพงษ์ ทันจังหรีด

ปีการศึกษา 2561 ลายมือชื่ออาจารย์ที่ปรึกษา Naum Chu

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EMISSIOINS/COMMERCIAL AIRCRAFT/AIR POLLUTANTS/THAILAND/ ESTIMATION METHODS

This study aims to quantify the emissions of carbon monoxide (CO), nitrogen oxide (NO_x), and hydrocarbon (HC) from the commercial aircrafts in Thailand's land territory. The equations and emission factors together with number of flight data in the year 2015 were used to estimate the emissions. The route maps of the commercial aircrafts were created from coordinate data. The data were later used for spatial analysis of the emissions.

The results showed that the annual emissions from the commercial aircrafts during aircraft taxi mode were 2.42 Mtons of CO, 0.44 Mtons of NO_x, and 0.44 Mtons of HC. CO from take-off mode was 0.08 Mtons, 3.83 Mtons for NO_x, and 0.04 Mtons for HC. The annual emissions at the ground level for the landing mode were 0.21 Mtons for CO, 0.05 Mtons for NO_x, and 0.04 Mtons for HC. The annual emissions during the initial-climb mode were 0.03 Mtons of CO, 1.53 Mtons of NO_x, and 0.01 Mtons of HC, while the emissions in climb-out mode accounted about 0.05 Mtons of CO, 1.42 Mtons of NO_x, and 0.01 Mtons of HC. For approach mode, the annual emissions were 0.52 Mtons of CO, 0.96 Mtons of NO_x, and 0.09 Mtons of HC. The emissions during cruise mode accounted about 1.06 Mtons of CO, 2.95 Mtons of NO_x, and 0.65 Mtons of HC, annually. The total annual emissions from the commercial aircraft in 2015 were 4.36 Mtons for CO, 11.17 Mtons for NO_x, and 1.28 Mtons for HC, where of emissions emitted from the commercial aircraft at Suvarnabhumi airport were the highest. The emission rates were in the range 1.06 - 4.69 tons per flight of CO, 0.17 - 15.82 tons per flight of NO_x, and 0.09 - 0.84 tons per flight of HC. The spatial emission of CO was the highest in taxi mode similar to HC, resulting from incomplete combustion. The spatial emission of NO_x showed the highest during take-off mode, around the runways, due to the excess air at high temperature combustion.

School of Environmental Pollution and Safety Student's Signature W. Thanjongreed

Academic Year 2018 Advisor's Signature

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Weerapong Thanjangreed

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LIST OF ABBREVIATIONS

AOT	Airport of Thailand Public Company Limited
AOC	Aeronautical operational control
BFV	Buriram airport
BKK	Suvarnabhumi airport
C	Celsius degree
CJM	Chumphon airport
CEI	Mae Fah Luang Chiang Rai airport
CNX	Chiang Mai airport
CO	Carbon monoxide gas
CO_2	Carbon dioxide gas
DOA	Department of Airports
DMK	Don Mueang airport
FAA	Federal Aviation Administration
GHG_s	Greenhouse gases
GIS	Geographic Information System
HC	Hydrocarbon
HDY	Hat Yai airport
HKT	Phuket airport
KOP	Nakhon Phanom airport
KBV	Krabi airport
KKC	Khon Kaen airport
HGN	Mae Hong Son airport
HNO_3	Nitric acid
H_2O	Water
HO_2	Peroxy radical

LIST OF ABBREVIATIONS (Continued)

hυ	The energy of photon
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
km	Kilometers
LOE	Loei airport
LPT	Lampang airport
LTO	Landing and Take-off cycle
MAQ	Mae Sot airport
Mtons	Million tons
N_2	Nitrogen gas
NAW	Narathiwat airport
NNT	Nan Nakhon airport
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Oxide of nitrogen (Nitric oxide and nitrogen dioxide)
NST	Nakhon Si Thammarat airport
O_2	Oxygen gas
O_3	Ozone gas
OH^-	Hydroxyl radical
PHS	Phitsanulok airport
PM	Particulate matter
PM_{10}	particulate matter 10 micrometers or less in diameter
PRH	Phrae airport
RO_2	peroxy radicals
ROI	Roi Et airport
SEA	South East Asia
SNO	Sakhon Nakhon airport

LIST OF ABBREVIATIONS (Continued)

SO_2	Sulphur dioxide
TDX	Trat airport
THS	Sukhothai airport
TST	Trang airport
UBP	Ubon Ratchathani airport
UNN	Ranong airport
URT	Surat Thani airport
U.S.EPA	United States Environmental Protection Agency
USM	Samui airport
UTH	Udon Thani airport
UTM	Transverse Universe Mercator
UTP	U-tapao airport

CHAPTER 1

INTRODUCTION

1.1 Rationale

Air pollution is a serious problem with the potential impact on human health and the environment. Increasing of air transports in recent years has emitted more pollution and greenhouse gases into the atmosphere. Moreover, economic and tourism growth are influencing the rise of air pollution. Assessment of air emissions from the commercial aircrafts will enhance the emission inventory process and provide a comprehensive accounting of the air transport sector.

The sources of air pollution in large urban settings are generally from fossil fuels burning in transportation, household, commercial, and industrial activities. Fuel burning from the commercial aircrafts is often ignore and seems farfetched to most people. Carbon monoxide (CO), nitrogen oxides (NO_x), and non-methane volatile organic compounds (VOCs) are emitted from fossil fuel combustion. The number of increased flights may lead to high emissions in the atmosphere. In terms of greenhouse gas, an aviation emissions study showed that carbon dioxide from aviation in atmosphere was accounted 2.0 - 2.5% of total carbon dioxide in the atmosphere (Lee et al., 2009).

International Civil Aviation Organization (ICAO) reported that carbon dioxide emission from aviation in the year 2006 was in the ranged of 600 million tons (ICAO, 2006). The emissions of hydrocarbon, carbon monoxide, and nitrogen oxides at Raleigh-Durham international airport in the year 2006 were 60.2, 514, and 429 tons, respectively (Graver and Frey, 2009). In Thailand, the aircraft emission data is very rare and there is no research on the emissions of the commercial aircraft. Lack of data on aircraft emissions will certainly jeopardize the overall effort to inventory the emission. The aircraft emissions can be measured at sites but this method needs more resources such as budget, specialist, and equipment. This method often is not practical. Creating the database on aircraft emissions involves the use of emission factors because this method has more advantages than the direct measurement method. Activity data, however, vary and thus influence the emission estimation. This study demonstrates the approaches to estimate the emissions from the commercial aircrafts in Thailand.

1.2 Research objectives

1.2.1 To estimate the emissions of commercial aircrafts over land territory of Thailand using emission factors

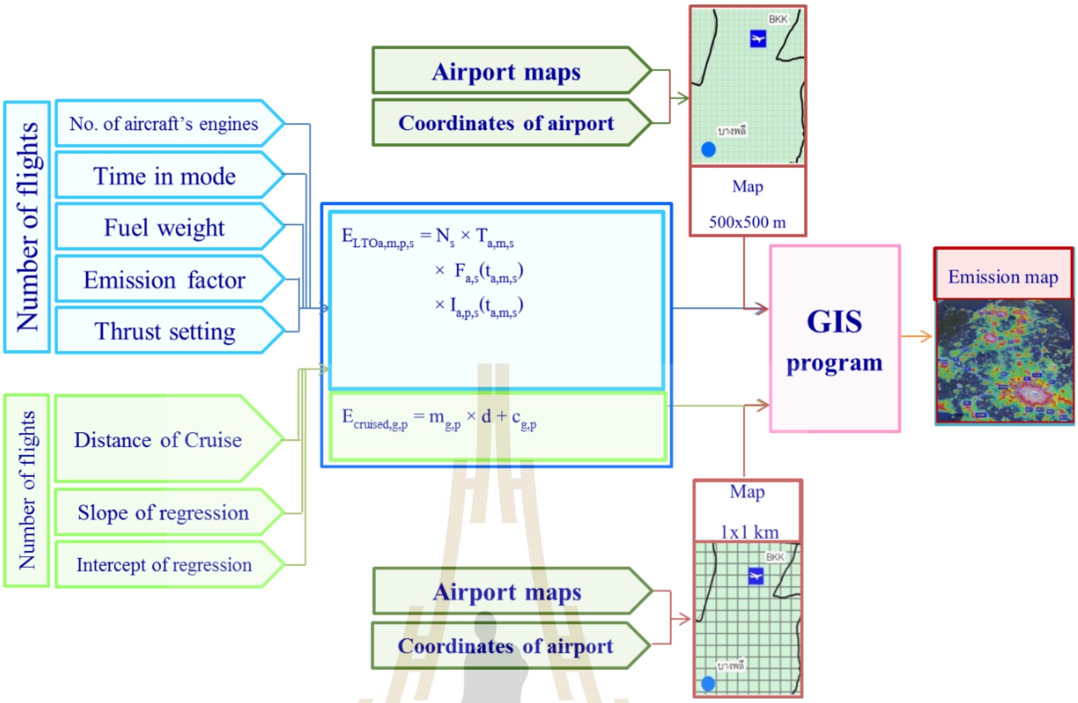
1.2.2 To create the spatial emission maps of pollution from the commercial aircrafts around the airports and flight paths

1.2.3 To propose the approaches of emission estimates from the commercial aircrafts using flight tracking

1.3 Scope of the study

This study estimated air emissions from the commercial aircrafts over land territory of Thailand. The pollutants included carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbon (HC). The annual emissions were estimated using mathematics equations and emission factors, based on data in the year 2015. The spatial emissions were based on the annual data.

1.4 Conceptual framework



1.5 Expected outcomes

1.5.1 The database of annual emissions from the commercial aircraft in Thailand

1.5.2 Emission distribution from the commercial aircraft around the airport

1.5.3 The approaches for emission estimates from the commercial aircrafts using flight data and emission factors

CHAPTER 2

LITERATURE REVIEW

Estimation of emissions from the commercial aircraft requires understanding of data required in calculation processes. Air transportation and aviation emission data as well as aircraft activity data are important information. The followings are the details of relevant literatures.

2.1 Air transportation in Thailand

Thailand’s air transportation is growing due primarily to changes in the economy, and tourism development. Air transportation is a part of the government strategy to establish Thailand as the transportation hub of South East Asia (SEA). Well develop facilities have changed several domestic airports into international airports to ease direct and charter flights and avoid heavy traffic at Suvarnabhumi and Don Mueang airports. Aviation service providers play a key role in increasing of passenger and flights.

2.1.1 Air transportation authorities of Thailand

Air transportation authorities of Thailand include both government agency and government-owned company as well as private company. Airport of Thailand Public Company Limited (AOT), Department of Airports (DOA), and Bangkok Airways Public Company Limited are the organizations that own several commercial airports in Thailand. Airports under the supervision of these organizations are listed in Table 2.1.

Table 2.1 Commercial airports under the supervision of each agency [1]

Authorities	Commercial airport	Services
Airports of Thailand Public Company (AOT)	Suvarnabhumi (BKK), Don Mueang (DMK), Phuket (HKT), Chiang Mai (CNX), Mae Fah Luang Chiang Rai (CEI), and Hat Yai (HDY)	Domestic and international flights
Department of Airports (DOA)	Krabi (KBV), Surat Thani (URT), Udon Thani (UTH), and Ubon Ratchathani (UBP)	Domestic and international flights
	Chumphon (CJM), Trang (TST), Nakhon Phanom (KOP), Nakhon Ratchasima (NAK), Narathiwat (NAW), Hua Hin (HHQ), Nakhon Si Thammarat (NST), Nan Nakhon (NNT), Buriram (BHV), Pai (PYY), Phitsanulok (PHS), Phetchabun (PHY), Phrae (PRH), Mae Sot (MAQ), Mae Hong Son (HGN), Roi Et (ROI) Ranong (UNN)Lampang (LPT), Loei (LOE), and Sakon Nakhon (SNO)	Domestic flight
Bangkok Airways Public Company Limited	Samui (USM)	Domestic and international flights
	Sukhothai (THS) and Trat (TDX)	Domestic flight

[1]Ministry of Transport's strategic policy year 2011 – 2015

The commercial airports under the supervision of AOT and DOA are important in driving air transportation in Thailand. AOT and DOA have several airports under the supervision and the numbers of flights in the airports influence the emissions.

2.1.2 Trend of air transportation

Globally, the number of passengers on scheduled flights were high in 2015. The numbers of passenger from 2014 to 2015 increased to about 3.5 billion and the numbers of increased passengers were accounted for 6.4 percent from 2014 (ICAO, 2016).

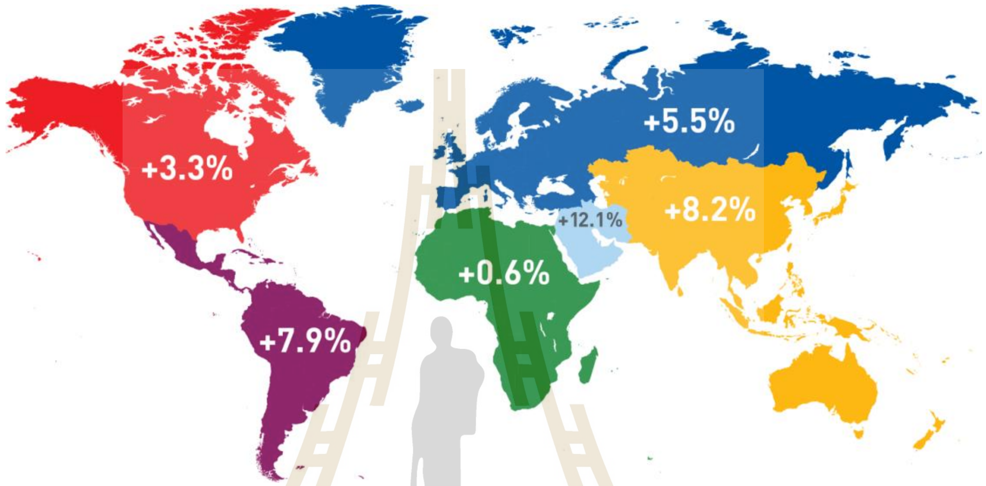


Fig. 2.1 Increasing of number of passengers in each continent in the year 2015 (ICAO, 2016)

Aviation industry consists of about 1,400 commercial airlines, 4,130 airports, and 173 aviation services, as of 2015 (ICAO, 2016). The increased number of flights from business and tourism expansion contributes the growth of air transportation.

In Thailand, air transportation is desired by long-distant travelers due to convenience and safe travel, leading to higher number of passengers and flights, according to the AOT Annual report 2014-2015. Increased in numbers of passengers and flights for 6 airports were 21.94 and 15.97 percent, respectively (Airports of Thailand Public Company Limited [AOT], 2016), as showed in Table 2.2

Table 2.2 Numbers of passengers and flights during the year 2014-2015 (AOT annual report 2014 -2015, 2016)

		Year		Increased percentage
		2014	**2015**	
Passenger	Domestic	36,376,943	45,452,854	24.95
	International	51,195,490	61,337,060	19.81
	Total	87,572,433	106,789,914	21.94
Flight	Domestic	285,145	342,041	19.95
	International	324,792	365,321	12.48
	Total	609,937	707,362	15.97

Data in Table 2.2 shows increase number of passengers and aircraft movement for both domestic and international flights, similar to 5-year trend from year 2010 to 2015, as showed in Fig. 2.2.

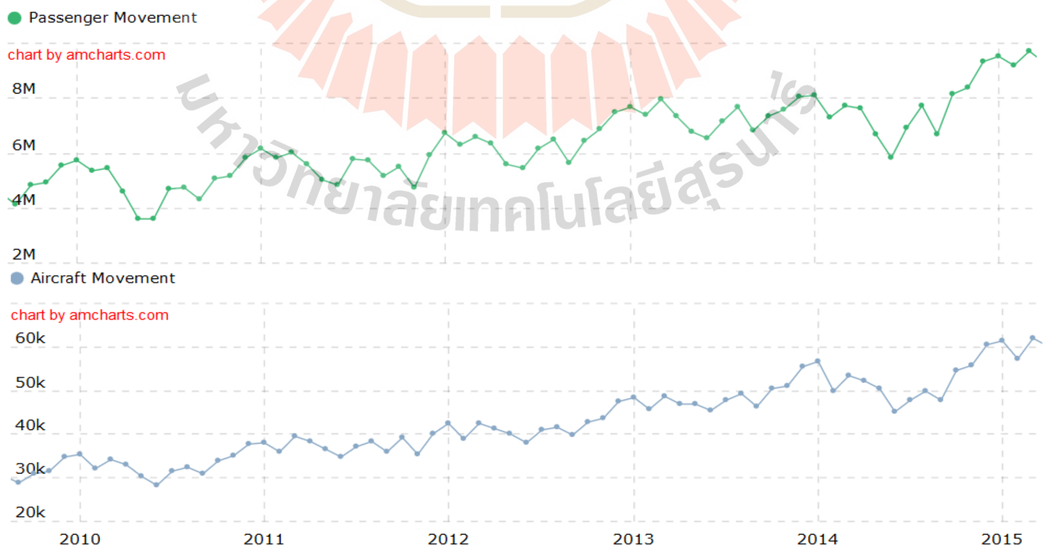


Fig. 2.2 Trends of passengers and flights between year 2010 and 2015 (AOT, 2015)

AOT has estimated the number of passengers in 2020 with the jump to 70.12 million at Suvarnabhumi airport. The number of passengers in 2020 will increase to 27.58 million at Don Mueang airport (Ministry of Transport's strategic policy 2011 - 2015).

Data from DOA also reported that the numbers of passengers and flights in 2010 to 2015 increased around 68 and 67 percent, respectively (Fig. 2.3).

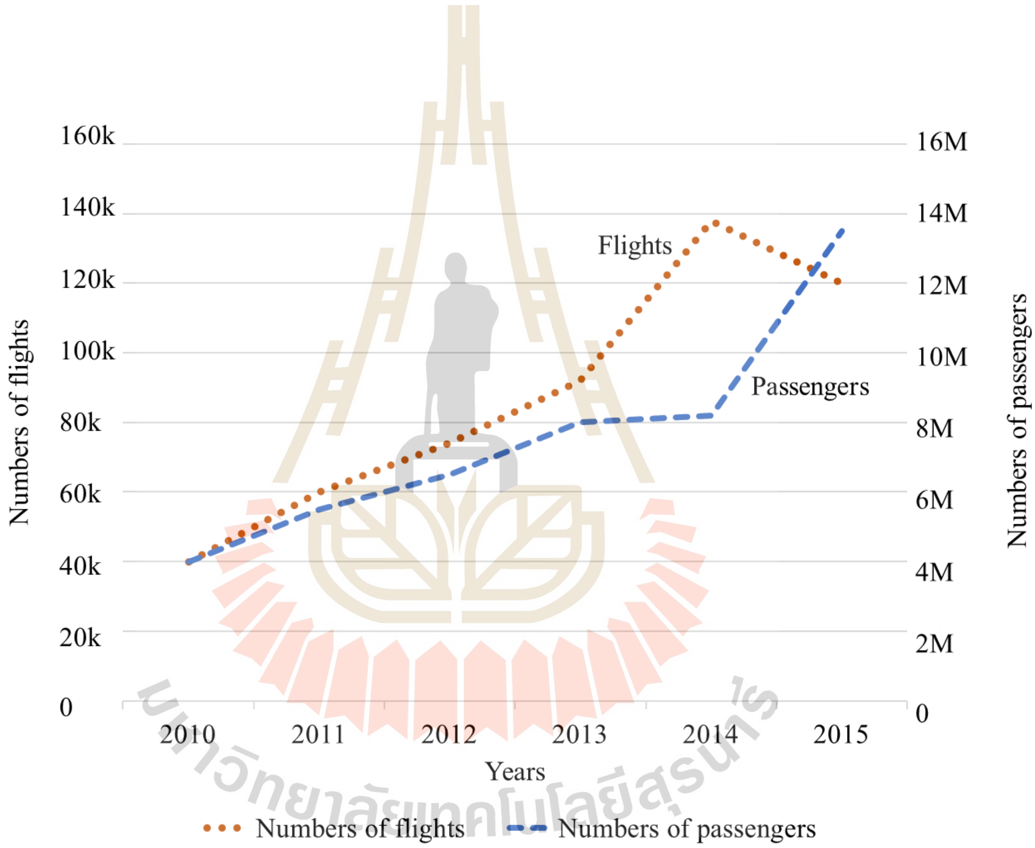


Fig. 2.3 The increased number of passengers and flights for airports under the supervision of the Department of Airports (DOA, 2016)

2.2 Air emissions

Air emission sources are categorized into naturogenic and anthropogenic sources. Air pollutants may occur from one or many sources. The overview of common gas pollutants and sources from documentary review that is relevant to this study is reviewed and summarized in Fig. 2.4 and Table 2.3.

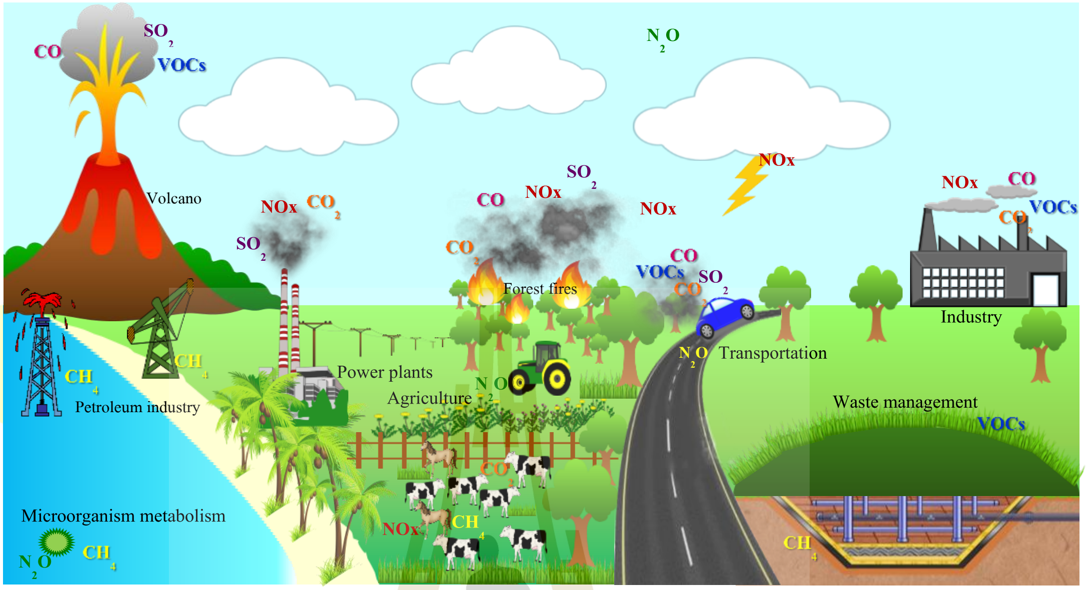


Fig. 2.4 The overall of air emission sources

Table 2.3 Air pollutants and sources

Pollutant		Sources
Carbon monoxide	Naturogenic	Natural phenomena such as photochemical reaction in troposphere (Weinstock and Niki, 1972), volcano eruption, and forest fire.
	Anthropogenic	Incomplete combustion in the engine, melting in steel production (Ayres, 2009)
Nitrogen oxide	Naturogenic	Natural phenomena such as lightning, forest fires, and nitrification reaction of microorganism in soil (U.S.EPA, 1999)
	Anthropogenic	The ground level nitrogen dioxide is related to fuel combustion in the engine, emissions by power plants and industry (U.S.EPA, 2011)

Table 2.3 Air emission sources (Continued)

Pollutant	Sources	
Sulphur dioxide	Naturogenic	Natural phenomena such as volcano eruptions release range 10 ppm of SO_2 to the atmosphere
	Anthropogenic	Combustion of fuel element of sulphur, such as coal and diesel in ship's engine (U.S.EPA, 2007)
Volatile organic compound	Naturogenic	Natural biodegradation of microorganism
	Anthropogenic	Combustion in vehicle's car and using solvent in industry

Greenhouse gases (GHGs) including carbon dioxide, methane, and nitrous oxide are emitted from fuel combustion (Intergovernmental Panel on Climate Change [IPCC], 2005). The major sources of GHGs are showed in Table 2.4

Table 2.4 Greenhouse gases emission sources

Greenhouse gases	Sources		
Carbon dioxide	Naturogenic (Kaufman and Franz, 1996)		Natural phenomena such as volcano eruption, forest fire, photo synthesis of plants, algae, and some bacteria
	Anthropogenic (U.S.EPA, 2015)	Transport	Fuel combustion in engine
		Industrial	Fuel combustion in boiler, lime kiln, steel production

Table 2.4 Greenhouse gases emission sources (Continued)

Greenhouse gases	Sources		
Methane	Naturogenic (Bousquet et al.,2006)		Methanogen bacteria activities, microorganism's metabolism in the deep ocean
	Anthropogenic (U.S.EPA, 2015)	Industrial	Petroleum process
		Agricultural	Livestock, landfill, waste management, and wastewater treatment plant
Nitrous oxide	Naturogenic (IPCC, 2007)		Degradation of nitrogen compound through nitrification and denitrification
	Anthropogenic (U.S.EPA, 2015)	Agricultural	Fertilizers using in agriculture
		Transport	Fuel combustion in engine

2.3 Aircraft emissions

Emissions from the aircraft relate to the aircraft flying cycle. The flying cycle includes 7 modes, namely taxi, take-off, initial-climb, climb-out, cruise, approach, and landing. Different modes emitted different emissions.

2.3.1 Aircraft flying cycle

Aircraft flying cycle is the operating modes that used to control the aircraft through the flight journey. Each mode defines as the flying features. The aircraft flying cycle is showed in Fig. 2.5.

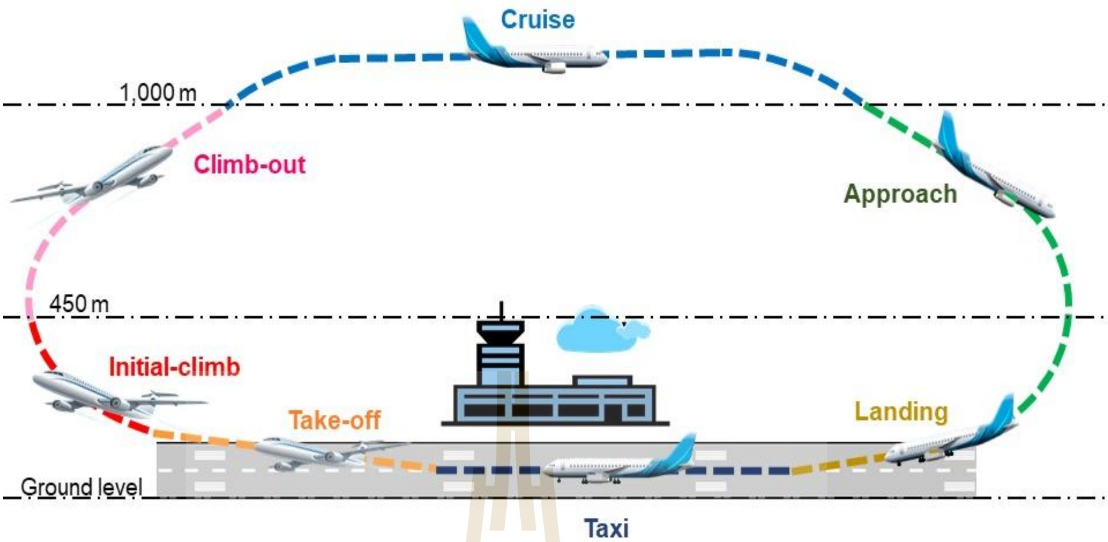


Fig. 2.5 Standard flying cycle (Adopt from Carbon Planet, 2009 and IPCC, 2000)

For flying cycle based on the altitude, the operating modes at the level under 1,000 meters (3,000 feet) is classified as LTO cycle (Landing and Take-off cycle) in the absence of cruise mode (Graver and Frey, 2009). The details for different modes are summarized in Table 2.5.

Table 2.5 The operating modes in standard LTO cycle (Watterson et al., 2004)

Mode	Operation
Taxi-out and taxi-in	The time aircraft takes to move from pit to runway and runway to pit
Hold	The time for aircraft parks or waits for cross runway
Take-off	While aircraft accelerate the speed until left from the ground
Initial-climb	The time since the aircraft's wheel left from the ground and go to the altitude 450 meters
Climb-out	Time aircraft takes to climb up from the altitude 450 meters to 1,000 meters
Approach	Time aircraft take to climb down from the altitude 1,000 meters
Landing-roll	While aircraft run on ground and stop

Operating modes in LTO cycle occur at the altitude between 0 and 1,000 meters. However, an article defines the altitude of LTO cycle up to 1,066.8 meters (3,500 feet) (Graver and Frey, 2009). Cruise mode occurs at the altitude over 1,000 meters. Air turbulence usually occurs at the altitude under 1,000 meters, the lowest height. Pollution emissions at the altitude above 1,000 meters do not interfere pollution emissions at lower altitude (Wayson and Fleming, 2000). A cruise mode in the aircraft operation occurs when the aircraft operates above 1,000 meters, but the upper limit is not defined (IPCC, 2000).

Various modes in LTO cycle affect the emissions. There is the default thrust setting and time of each mode in the flying cycle (Table 2.6). The default thrust setting and time is often used for the estimating of emissions.

Table 2.6 The default thrust setting and time in mode values for each mode of aircraft operation in LTO cycle.

Operating mode	Default thrust setting (1)(2) (%)	Operating mode (1) (min)
Taxi-out, hold, and taxi-in	7	26.0
Take-off	100	0.7
Initial-climb	100	-
Climb-out	85	2.2
Approach	30	4.0
Landing-roll	7	-

(1) Watterson et al., 2004

(2) Winther and Rypdal, 2014

Emissions at the altitude below 1,000 meters have an effect on the concentration of pollution at the ground level (Graver and Frey, 2009). Emissions from an aircraft relate to various factors, aircraft modes and composition of fuel and combustion conditions. Flying cycle is a very important factor effecting the aircraft emissions, especially, LTO cycle. The LTO uses more power to push the aircraft up in the sky (Belgian Science Policy, 2007).

2.3.2 Emissions from aircraft

Emissions from an aircraft depend on several factors including aircraft engine type, fuel used, engine emission properties (portion of fuel used depending on engine loads), aircraft operating mode, and traffic density (numbers of flights and distance)

(European Environment Agency [EEA], 2006). Aircraft emissions are represented in Fig. 2.6.

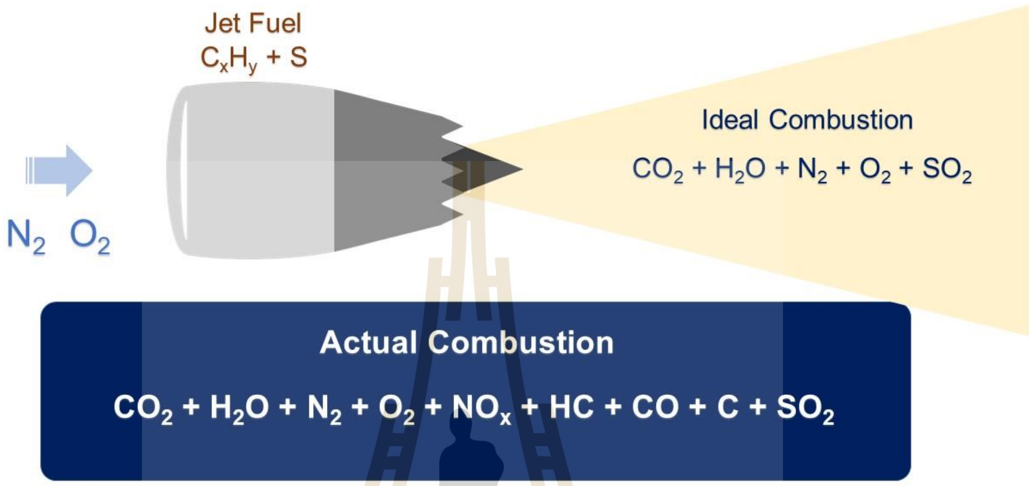


Fig. 2.6 Emissions from combustion of aircraft's engine (Adopt from Weubbles et al. 2007: Norton, 2014)

Emissions from the aircraft engines consist of CO_2, H_2O, N_2, O_2, and SO_2 for ideal combustion, but the actual combustion may be CO_2, H_2O, N_2, O_2, NO_x, HC, CO, C, and SO_2 (Norton, 2014). Carbon dioxide accounts about 70 percent, water vapor 30 percent, and other 10 percent (Federal Aviation Administration [FAA], 2005). Cruise mode emits less than LTO cycle (Belgian Science Policy, 2007) due to the complete combustion in this mode.

In each mode of aircraft operations, fuel is used differently (Belgian Science Policy, 2007). Fuel types and properties used in aircrafts are showed in Table 2.7.

Table 2.7 Types and properties of aircraft fuel (IPCC, 1997)

Fuel	Properties
Aviation gasoline	Fuel for aviation piston engine, increase octane in the engine.
Jet gasoline	Fuel is distilled at 100 – 250 Celsius. Used for engine typed aviation turbine power units, this fuel is mixed between kerosene and benzene or naphtha. The aromatic ring is not exceeding 25 percent by volume and vapor pressure ranges from 13.7 to 20.6 kPa.
Jet kerosene	Fuel appropriates to the engine typed aviation turbine power units, distill at 100 – 300 Celsius (generally, not excess 250 Celsius) due to its ignition point of jet kerosene.

Aviation fuel is distilled from crude oil in the middle distillation process. Kerosene is mostly used for a civil aviation (Masiol and Harrison, 2014). Air emissions from aircraft are from the combustion of jet kerosene and jet gasoline (Winther and Rypdal, 2014). Emissions from aircraft such as carbon dioxide, nitrogen oxides, sulphur dioxide, volatile organic compound, and carbon monoxide, relate to combustion conditions and composition of elements in the fuel (Belgian Science Policy, 2007). CO, NO_x, and HC are estimated in this study.

Nitrogen oxides (NO_x)

Nitrogen oxides are accounted about two third of the emission at low altitude of the LTO cycle, due to high power to drive the engines (Air France, 2009). Nitrogen oxides are high in the LTO cycle comparing to other mode of flying cycle. Combustion conditions to form nitrogen oxides consist of 3 factors.

- Fuel component : fuel contain nitrogen element

- Combustion condition: nitrogen oxides form at high temperature (>1,200°C).
- Reaction activation: combustion condition at high temperature (>1,200°C), high pressure, and excess of oxygen result in the formation of nitrogen oxide, (US.EPA., 1999).

Moreover, nitrogen oxide emission is also related to flying distance (Belgian Science Policy, 2007) as shown in Fig. 2.7.

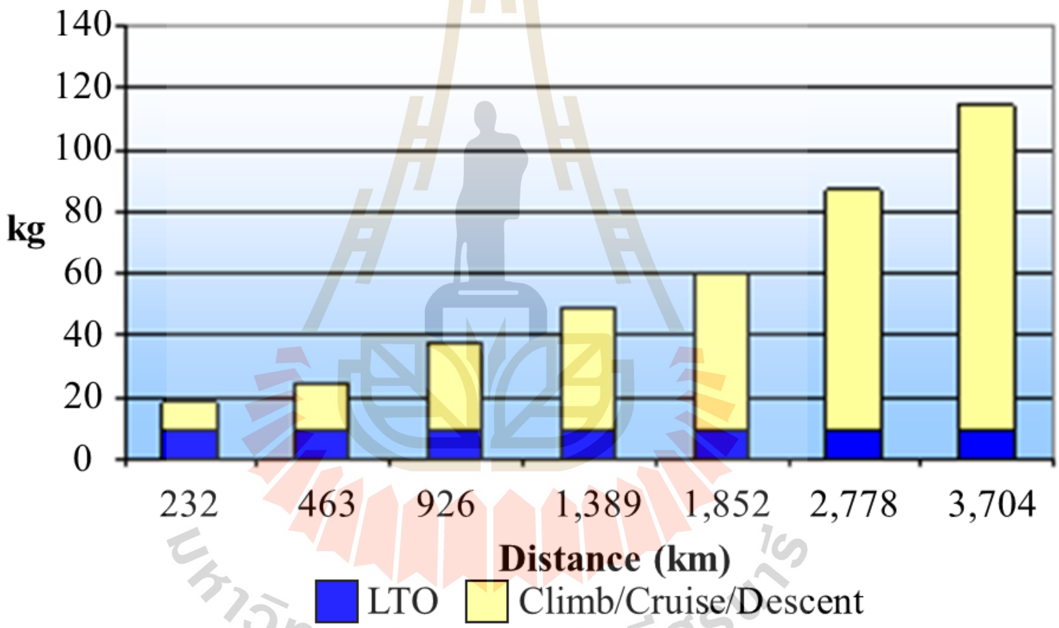


Fig. 2.7 Nitrogen oxide emission from the aircraft type B737 400 (Belgian Science Policy, 2007)

Nitrogen oxides are difficult to reduce as the engine's turbine swing to increase the power to take-off (Air France, 2009). Nitrogen oxides also relate to ozone formation through a photochemical reaction as shown in Fig. 2.8.

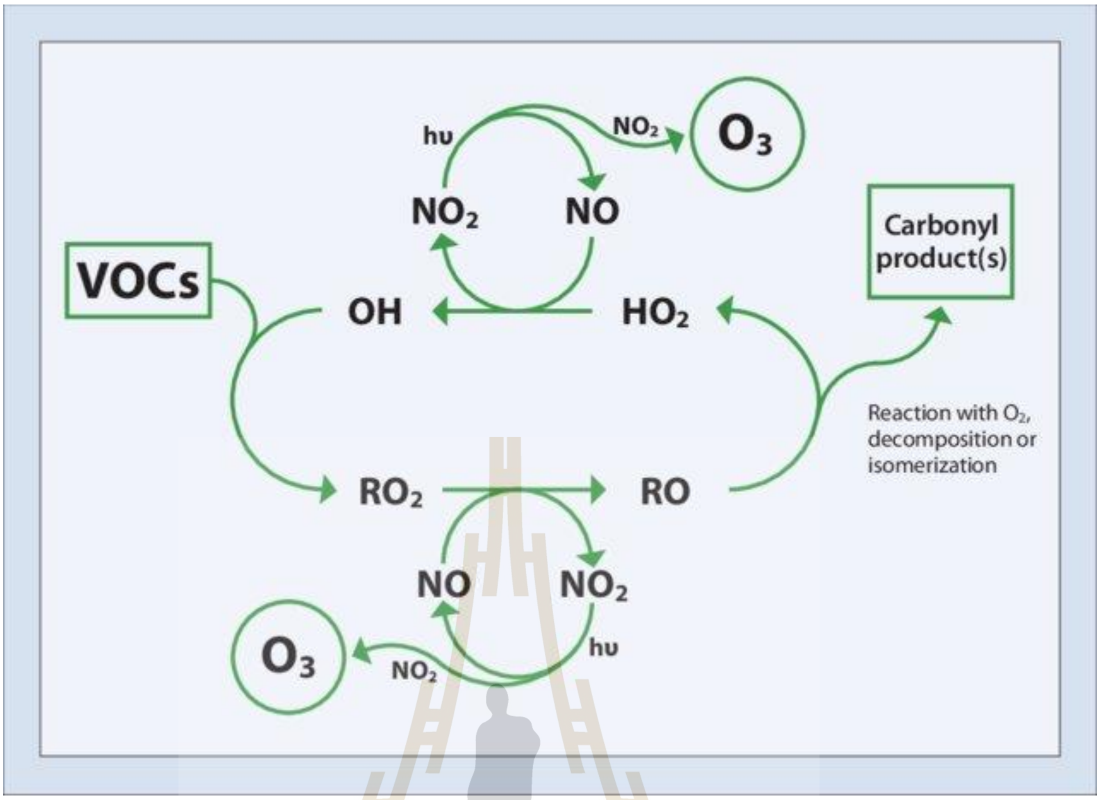


Fig. 2.8 Ozone formation through photochemical reaction (Amann et al., 2008)

Carbon monoxide (CO)

Carbon monoxide (CO) is mainly emitted from both natural phenomena namely photochemical reaction of methane and non-methane hydrocarbon and anthropogenic combustion (Masiol and Harrison, 2014). Emission of CO is high during the aircraft taxi mode because of incomplete combustion of jet fuel (Jacobson, 2012). CO emission is the highest at low power setting while temperature and pressure in the combustion chamber are low and less efficient combustion (Sutkus et al., 2001; Masiol and Harrison, 2014).

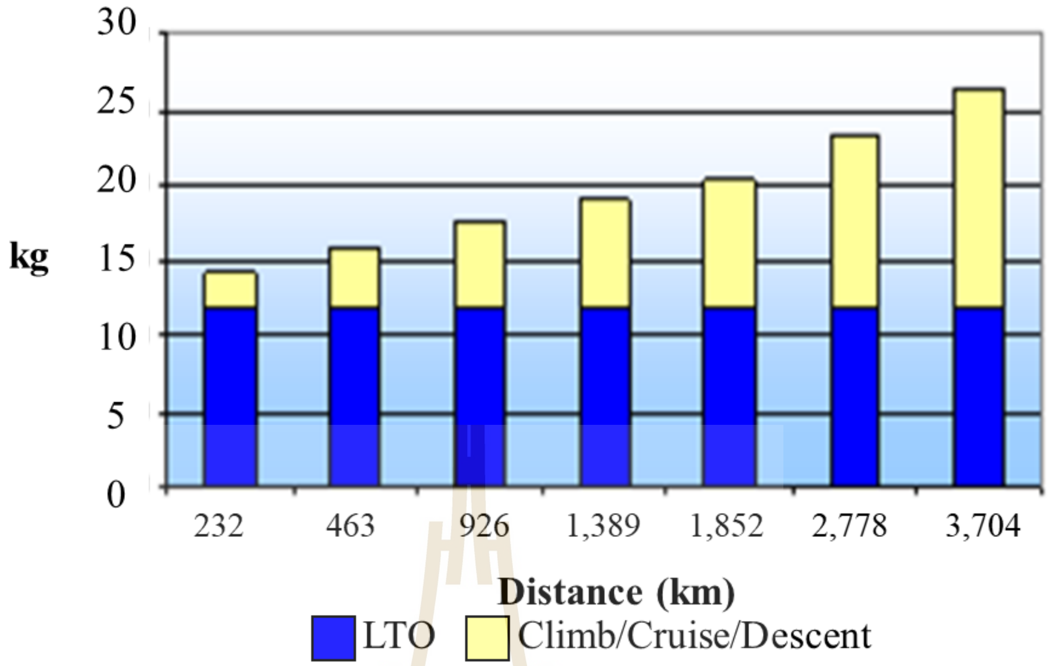


Fig. 2.9 Carbon monoxide emission from the aircraft type B737 400 (Belgian Science Policy, 2007)

CO emission is commonly released during LTO cycle, but less in cruise mode. When distances of flight increase, quantity of CO also increases.

Hydrocarbon (HC)

Hydrocarbon (HC) is in the residual from an incomplete combustion of fuel. HC is emitted from the aircraft as the results of inefficient combustion (Knighton et al., 2009; Masiol and Harrison, 2014). HC emission indices are the highest at low power setting while temperature and pressure in the combustion chamber are low and less efficient combustion, similar to CO (Sutkus et al., 2001; Yelvington et al., 2007; Masiol and Harrison, 2014). HC during the LTO cycle is higher than the cruise as shown in Fig. 2.10.

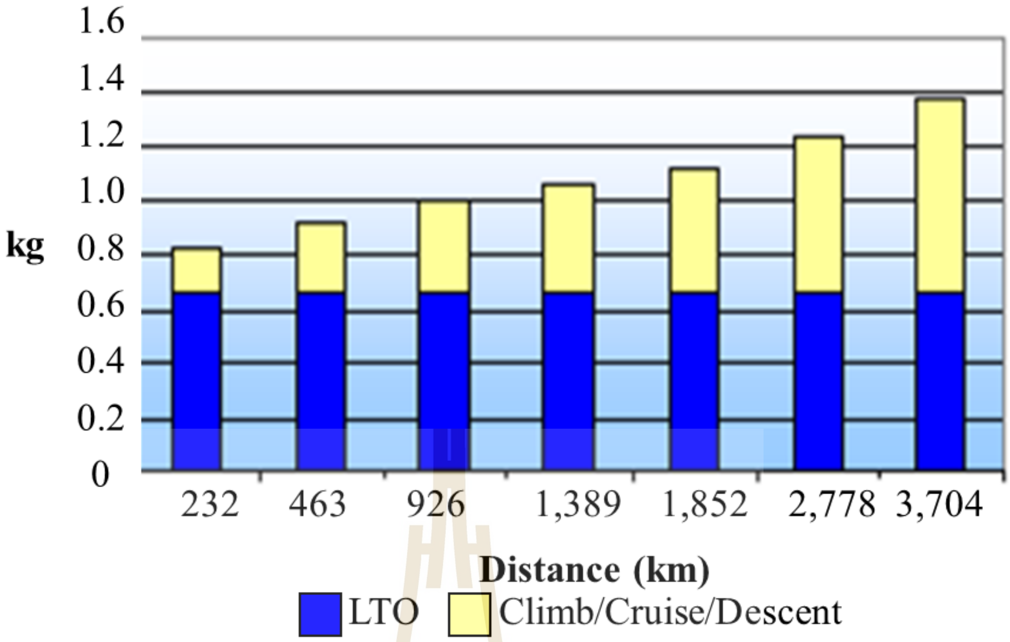


Fig. 2.10 Hydrocarbon emission from the aircraft type B737 400

(Belgian Science Policy, 2007)

CO and HC are emitted at the ground level and at high-altitude, accounted about 30 and 70 percent, respectively (FAA, 2005).

2.4 Effect of air pollution

When air pollutants are continuously emitted into the atmosphere, they are usually transported, accumulated, or transformed over time. The accumulation of air pollutants in earth's ecosystem has potential to cause changes and, in some cases, poses problems to human health. Air pollutants, historically, have caused catastrophes and continuously threat the quality of life of millions of world population. This section focuses on the main emissions from the commercial aircraft, namely CO, NO_x, and HC.

Carbon monoxide (CO)

Effect on the environment

Carbon monoxide (CO) can react with hydroxyl radical ($^{\bullet}OH$) to form carbon dioxide (CO_2) and peroxy radical ($^{\bullet}HO_2$) (Reeves et al., 2002). Nitrogen dioxide is produced from hydrogen dioxide and nitric oxide in the atmosphere as showed in the following equations;

$$CO\ (g) + {}^{\bullet}OH\ (aq) \rightarrow CO_2\ (g) + {}^{\bullet}HO_2\ (g),$$

$${}^{\bullet}HO_2\ (g) + NO \rightarrow {}^{\bullet}OH\ (aq) + NO_2\ (g).$$

Nitrogen dioxide reacts with water vapors become nitric acid (HNO_3), an acid with the potential to cause acid rain. In addition, nitrogen dioxide may lose the oxygen atom (O) to oxygen (O_2) to form ozone (O_3) (Reeves et al., 2002).

Effect on health

Certain concentrations of carbon monoxide affect respiratory system, cardiovascular, and central nervous system. When carbon monoxide enters the circular system, it can cause headache, dizziness, nausea, vomiting, and fatigue (Hardya and Thom 1994). It also impacts the nervous system such as anxiety, confusion, loss of vision and fainting, and convulsions (Blumenthal, 2001). The acute effect occurs when it exposes to carbon monoxide over 35 ppm for 6-8 hours. It may cause dizziness, headache, and dead, if the concentration of carbon monoxide is higher than 12,800 ppm for less than 3 minutes (Goldstein, 2008).

Nitrogen oxides (NO_x)

Effect on the environment

Nitrogen dioxide gas (NO_2) is a more stable gas. It can remain for a long time in the atmosphere, more than other forms. Nitrogen oxides (NO_x) were known as precursor of photochemical reaction (Peng, 2019). Photochemical reactions between NO_x and VOCs lead to ozone formation (US.EPA, 1999) as showed the following equations:

$$NO_2\ (g) + h\upsilon \rightarrow NO\ (g) + O,$$

$$O + O_2\ (g) + M \rightarrow O_3\ (g) + M.$$

Nitrogen dioxide reacts with hydroxyl ion in the atmosphere (Science daily, 1998) and forms nitric acid (HNO_3), a product from nitrogen oxide atmospheric reactions (U.S. EPA, 2008):

$$N_2\ (g) + O_2\ (g) \xrightarrow{\text{Lightning}} 2NO\ (g),$$

$$NO\ (g) + \tfrac{1}{2}\ O_2\ (g) \rightarrow NO_2\ (g),$$

$$3NO_2\ (g) + H_2O\ (aq) \rightarrow 2HNO_3\ (aq) + NO\ (g).$$

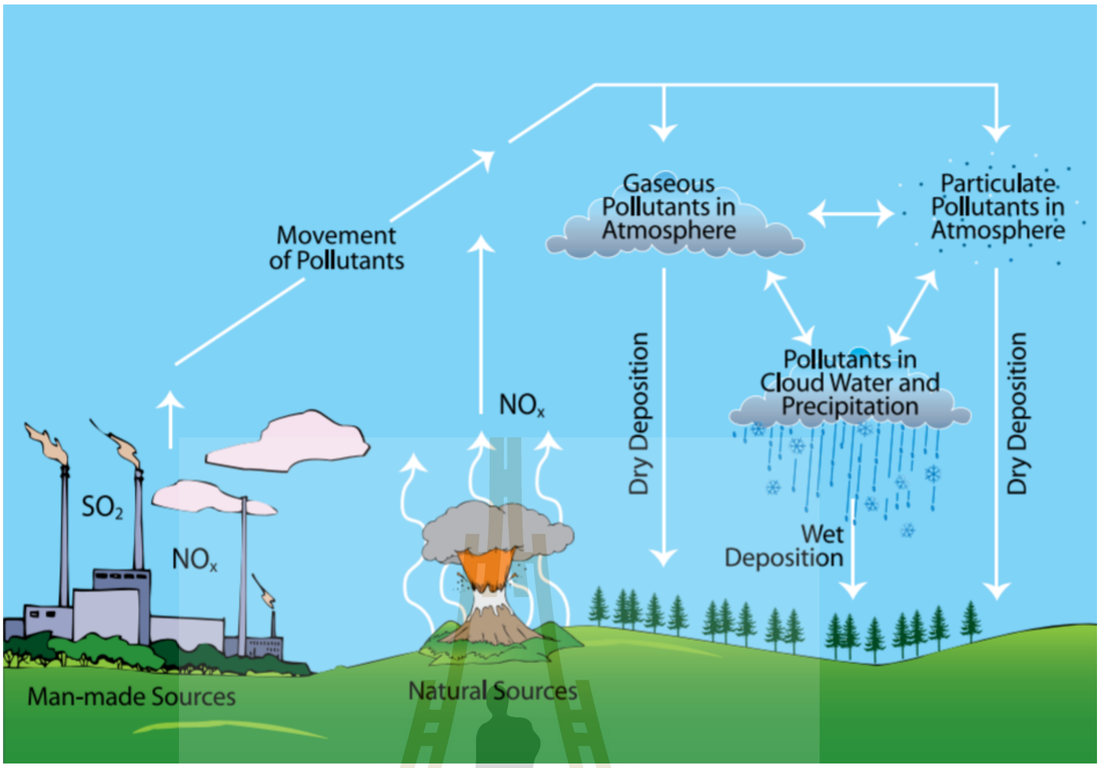


Fig. 2.11 Acid rain as nitric acid form (US.EPA., 2008)

Nitric acid is a strong acid, dissolves in water, and decreases the water pH. It has shown the effect on mallow building as well as crop damage, aquatic animal irritation, lack of minerals in soil, and acid soil (U.S. EPA, 2012).

Effect on health

Nitrogen oxides can dissolve in water to form nitric acid. Nitric acid has an effect on the upper respiratory system, irritating sinus and lung (Department of Employment, Australia, 2011). Moreover, patients or vulnerable person such as asthma, pulmonary and respiratory disease, elderly, and children are sensitive to the effects of nitrogen dioxide (U.S. EPA., 2011).

Hydrocarbon (HC)

Effect on the environment

Volatile organic compounds are the precursor of photochemical reactions between nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the atmosphere (National Research Council, 1991) to form ground level ozone:

$$VOCs + OH^- (aq) \rightarrow RO_2 (g) + H_2O (aq),$$

$$RO_2 (g) + NO (g) \xrightarrow{O_2} Secondary\ VOCs (g) + HO_2 (g) + NO_2 (g),$$

$$NO_2 (g) + h\upsilon \rightarrow NO (g) + O,$$

$$O + O_2 (g) + M \rightarrow O_3 (g) + M.$$

Effect on health

Hydrocarbon, including many chemicals such as benzene and toluene, has both acute and chronic effects. Benzene is carcinogen in human (U.S. National Library of Medicine, 2015). Although the emission of HC had a low effect on the environment, HC from an aircraft might affect quite high to the staffs who work in airport and travelers (Masiol and Harrison, 2014).

Effects of air pollution on environmental system and health that previously mentioned are summarized in Fig. 2.13 and Fig. 2.14

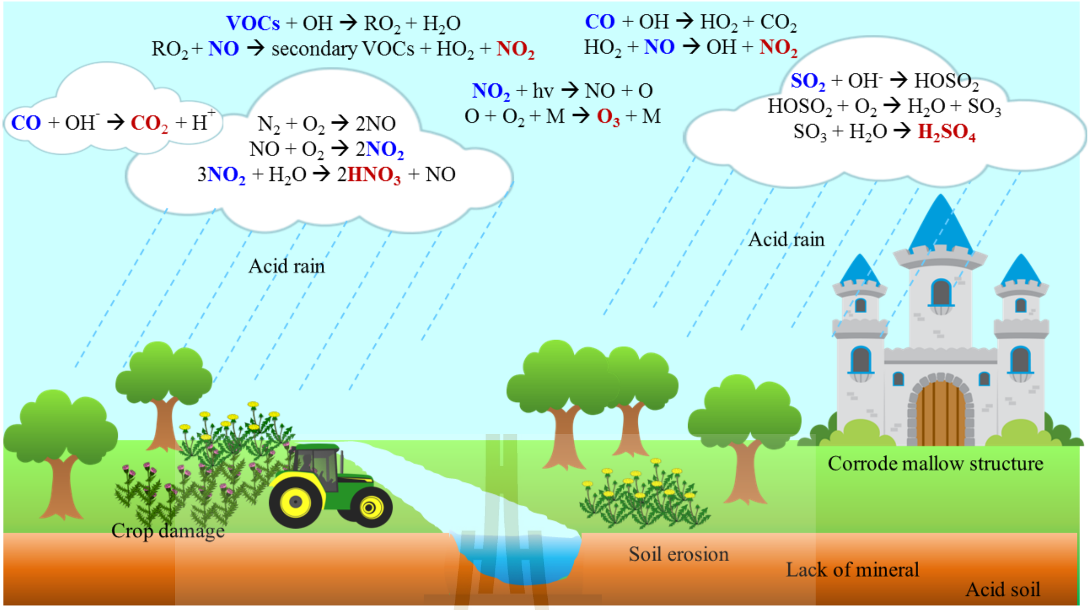


Fig. 2.12 Effects of pollution on an environmental system

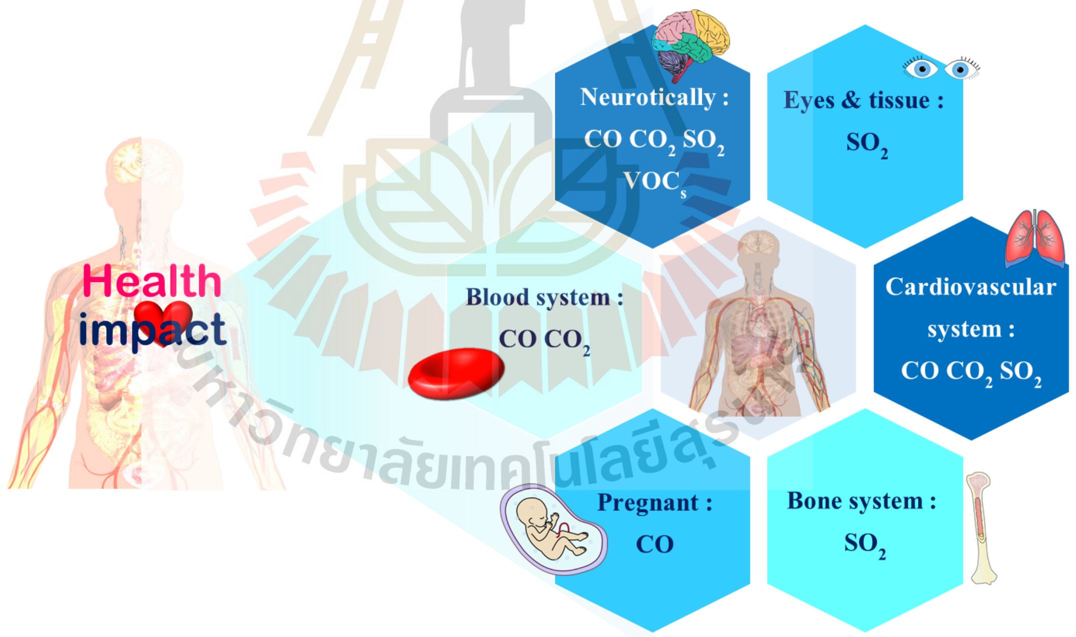


Fig. 2.13 Effects of pollution on health

CHAPTER 3

METHODOLOGY

Quantifying emissions from the commercial aircraft in land territory of Thailand have 4 steps. Briefly, data collection step collected the flight numbers from aviation agencies' websites. Emission calculation step used flight number data and numbers of flights for calculating the emissions through the mathematical equations and emission factors. Route mapping step, used the flight tracking to identify the coordination data and creating the route maps. Spatial analysis step used the emission and route map data for interpolating the spatial emissions on the satellite image. Overview of the steps is shown in Fig. 3.1.

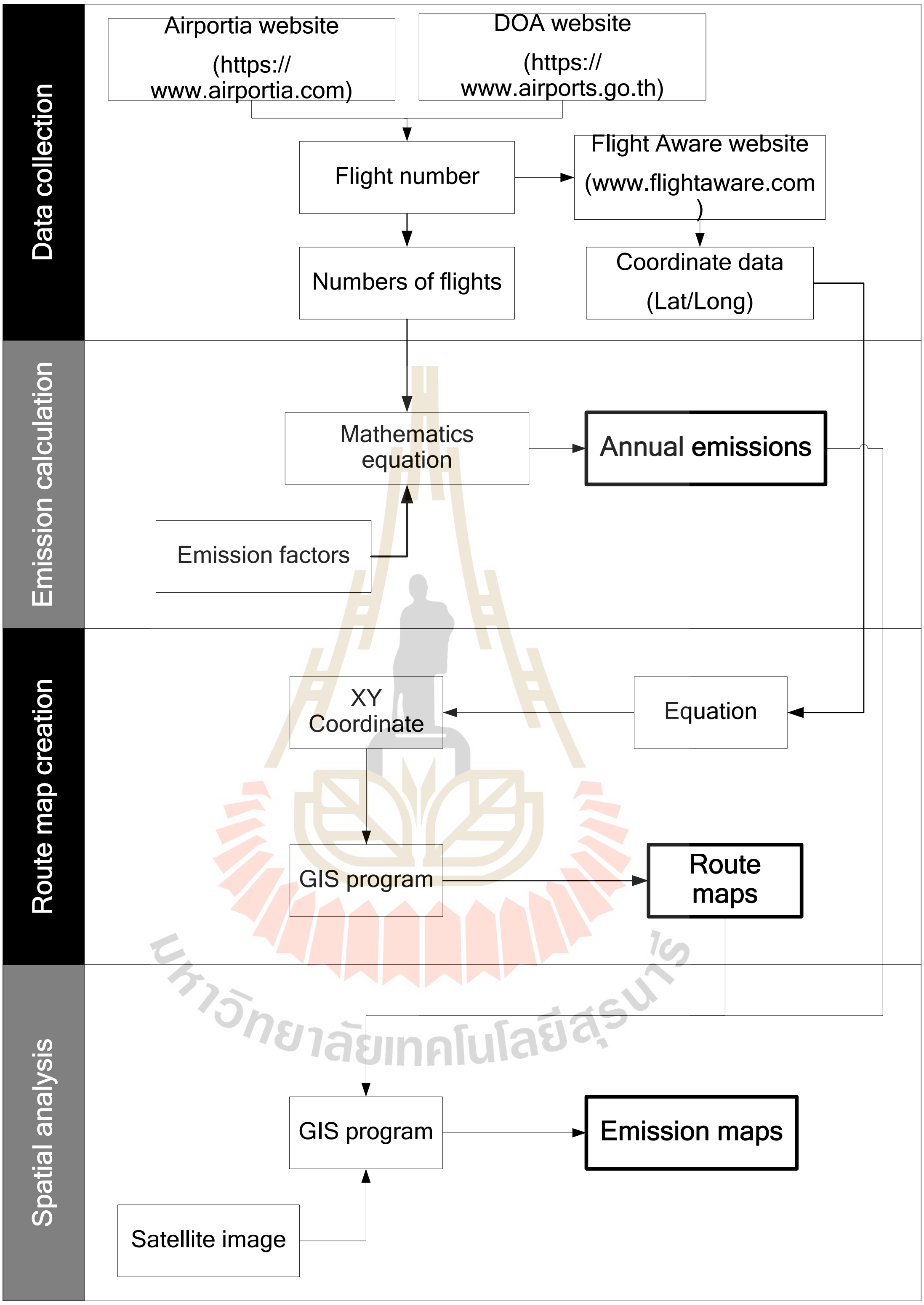


Fig. 3.1 Methodological steps

3.1 Data collection and handling

Flight numbers and numbers of each flight were collected from the aviation agency websites. These data were used as the inputs for calculating the emissions in the second step. The coordinate data were gathered based on respective flight numbers and the data were used to create the route maps in the third step. This study collected flight data daily for twelve months in 2015.

3.1.1 Flight number and numbers of flights

There are two sources of the flight data, AOT and DOA websites (Fig. 3.2 and 3.3). Both websites provide the details of flight number and their itineraries. Data collection and handling were as follows.

1. Visited the Airportia (https://www.airportia.com) and DOA (https://www.airports.go.th) websites, selected the airport of interest and gathered the details on flight numbers.

2. Counted the number of flights based on the flight number, summed the flight number into a spreadsheet program.

3. Collected the aircraft engine types for each flight number and grouped in a spreadsheet program.

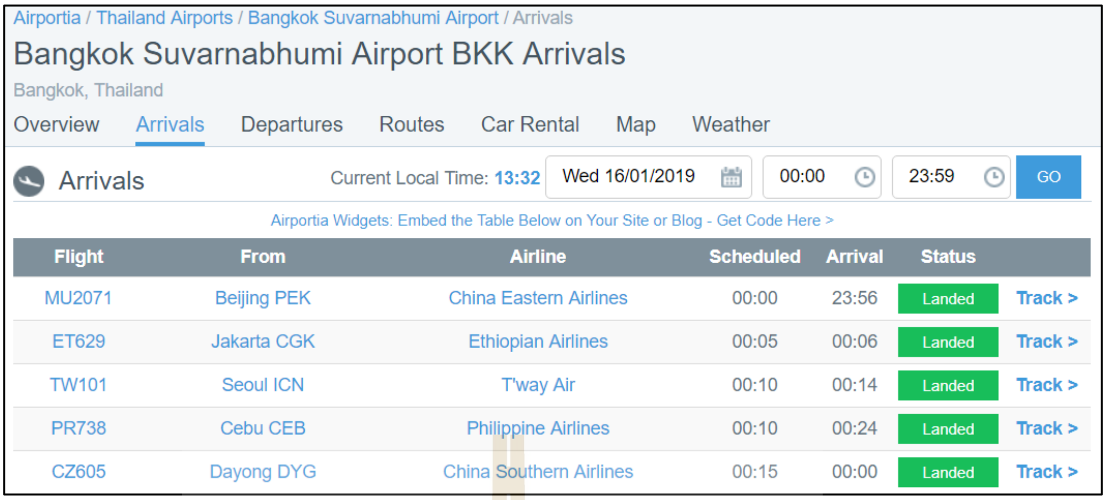


Fig. 3.2 The details of flights in Airportia website

(https://www.airportia.com)

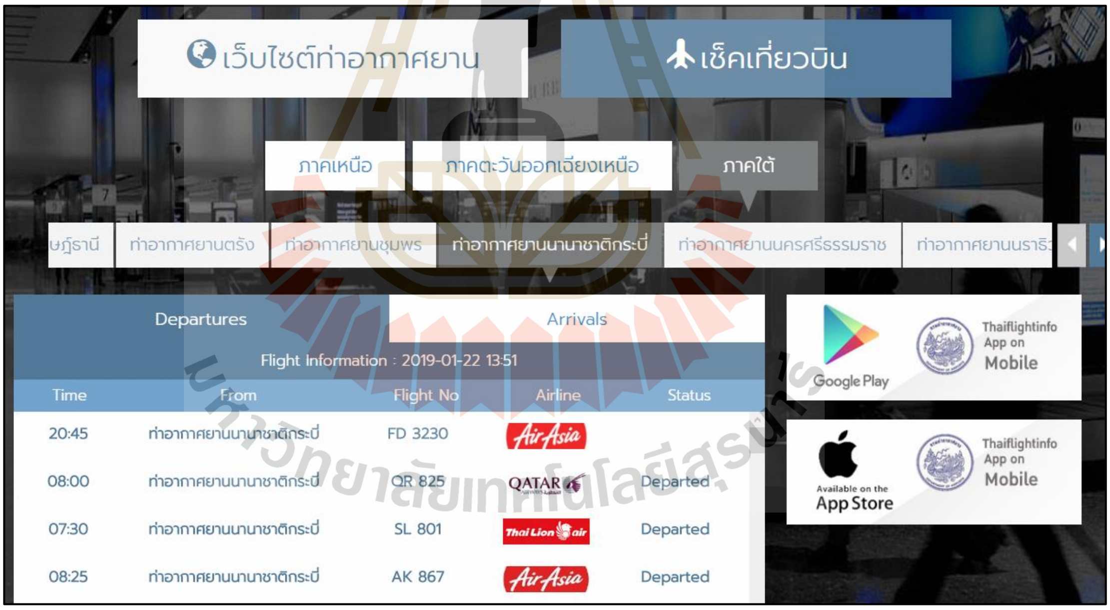


Fig. 3.3 The details of flights in the Department of Airport website

(https://www.airports.go.th/th/index.php)

Step 3.1.1 provides the number of flights as inputs for calculating the emissions in the second step, emission calculations.

3.1.2 Coordinate data

The coordinate data were used for route map creation. The data were gathered from the Flight Aware website (Fig. 3.4). In order to get the coordinate data, the flight number was the key to access the data (Fig. 3.5). The details of coordinate data gathering are as follow.

1. Visited the website "Flight Aware" (https://flightaware.com), searched for the flight number.

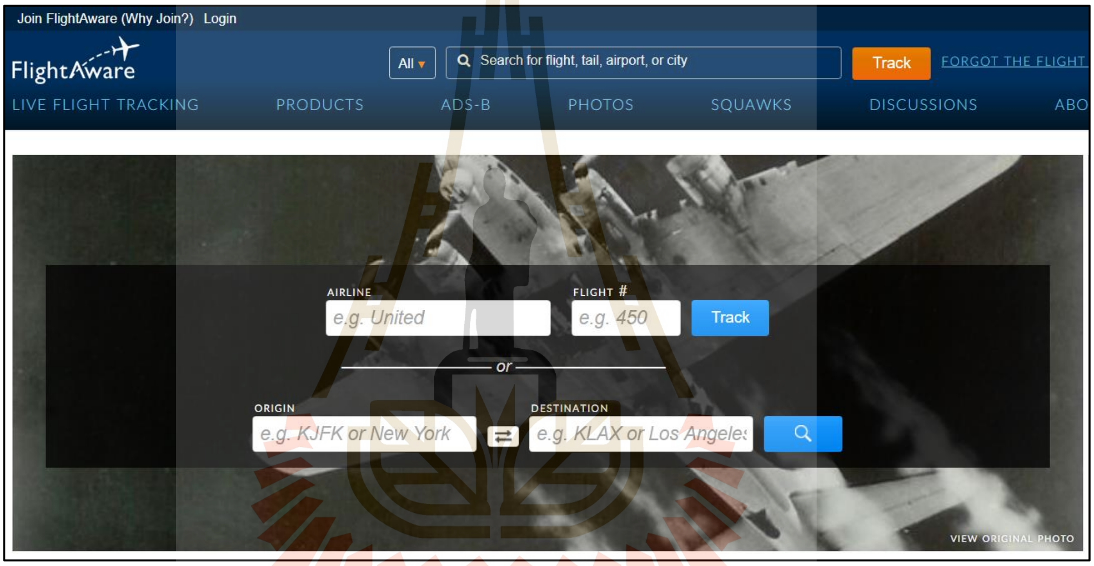
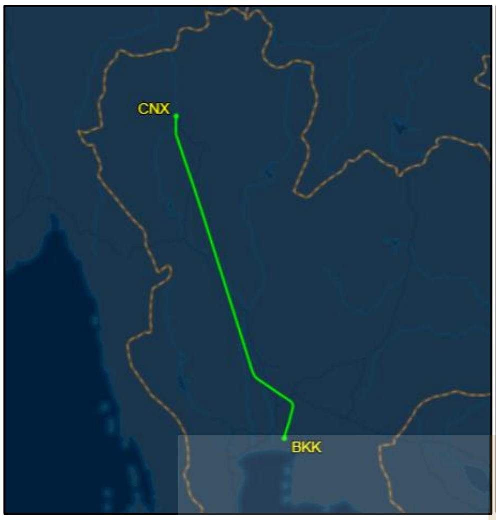


Fig. 3.4 The home page of Flight Aware website for the route tracking (https://flightaware.com)



Mon 07:24:44 AM	13.7676	100.7600
Mon 07:25:14 AM	13.8006	100.7700
Mon 07:25:44 AM	13.8366	100.7820
Mon 07:26:14 AM	13.8722	100.7940
Mon 07:26:44 AM	13.9089	100.8070
Mon 07:27:14 AM	13.9451	100.8190
Mon 07:27:44 AM	13.9860	100.8300
Mon 07:28:18 AM	14.0373	100.8430
Mon 07:28:48 AM	14.0837	100.8550
Mon 07:29:18 AM	14.1305	100.8680
Mon 07:29:48 AM	14.1838	100.8820
Mon 07:30:04 AM	14.2116	100.8840
Mon 07:30:23 AM	14.2452	100.8742
Mon 07:30:40 AM	14.2718	100.8537
Mon 07:31:01 AM	14.2937	100.8231

Fig. 3.5 The route of searching flight and its coordinate data

2. Stored the latitude and longitude coordinate data into a table with the spreadsheet program.

3. Converted latitude and longitude coordinate data to UTM (XY) coordinate as the inputs for spatial identification.

The next step was the calculation of the emissions. UTM (XY) coordinate data were used to create the route map.

3.2 Emission calculations

The annual emissions of CO, NO_x, and HC were estimated for different modes of the aircraft flying cycle. The aircraft flying cycle in this study, includes taxi, take-off, initial-climb, climb-out, cruise, approach, and landing. In taxi mode, the time used in the taxi mode was calculated by equation 3.1.

Equation 3.1 (Watterson et al., 2004) was applied to calculate the time in taxi mode for regional airports based on the longest runway length.

$$T_{a,m} = 0.1 \times R_a \tag{3.1}$$

Where:

$T_{a,m}$	is the time in mode m (Taxi-in or Taxi-out) at airport a (second)
a	is the airport
m	is the mode (Taxi-in or Taxi-out)
R_a	is the length of the longest runway at airport a (m)

The annual emissions were calculated using equation 3.2 (Watterson et al., 2004). Numbers of flights data from step 1 was used to calculate the annual emissions in this step.

$$E_{LTO_{a,m,p,s}} = N_s \times T_{a,m,s} \times F_{a,s}\left(t_{a,m,s}\right) \times I_{a,p,s}\left(t_{a,m,s}\right) \tag{3.2}$$

Where:

$E_{LTOa,m,p,s}$	is the emissions in mode m of pollutant p for a specific aircraft type s at airport type a (kg)
a	is the aircraft type
m	is the mode
p	is the pollutant
s	is the specific aircraft type s
N_s	is the number of engines on aircraft type s
$T_{a,m,s}$	is the time in mode m for a specific aircraft type s at airport type a (second)
$F_{a,s}(t)$	is the weight average fuel flow for an engine on aircraft type s at airport type a for thrust t (kg s^{-1})
$I_{a,p,s}(t)$	is the weight average emission factor of pollutant p for an

engine on aircraft type s at airport type a for thrust t (kg/kg fuel)

$t_{a,m,s}$ is the engine thrust setting during mode m for aircraft type s at airport type a (%)

In addition, the default engine thrust setting was used in equation 3.2 as showed in the Table 3.1.

Table 3.1 Default engine thrust setting for each mode in flying cycle (Watterson et al., 2004)

Mode	Default thrust setting (%)
Taxi-out, hold, and taxi-in	7
Take-off	100
Initial-climb	100
Climb-out	85
Approach	30
Landing-roll	7

In cruise mode, another equation was used for estimating emissions during cruise mode. The emissions from cruise mode was calculated using mathematics equation (Watterson et al., 2004) based on the route distance (equation 3.3).

$$E_{Cruise_{d,g,p}} = m_{g,p} \times d + c_{g,p} \tag{3.3}$$

Where:

$E_{Cruised,g,p}$	is the emissions in cruise of pollutant p for generic aircraft type g and flight distance d (kg)
d	is the flight distance
g	is the generic aircraft type
p	is the pollutant (or fuel consumption)
$m_{g,p}$	is the slope of regression for generic aircraft type g and pollutant p (kg/km)
$c_{g,p}$	is the intercept of regression for generic aircraft type g and pollutant p (kg)

In step 3.2, emission calculations yielded the annual emissions in each aircraft flying modes. These emission data were later used for spatial analysis.

3.3 Establishment of aircraft route maps

This step used the UTM coordinate data to generate the route maps. The UTM coordinate was used as the input data through the function in a GIS program.

1. Saved the UTM coordinate data and imported into the GIS program as a table file (CSV). The coordinates displayed as the aircraft route on the map 1×1 km.

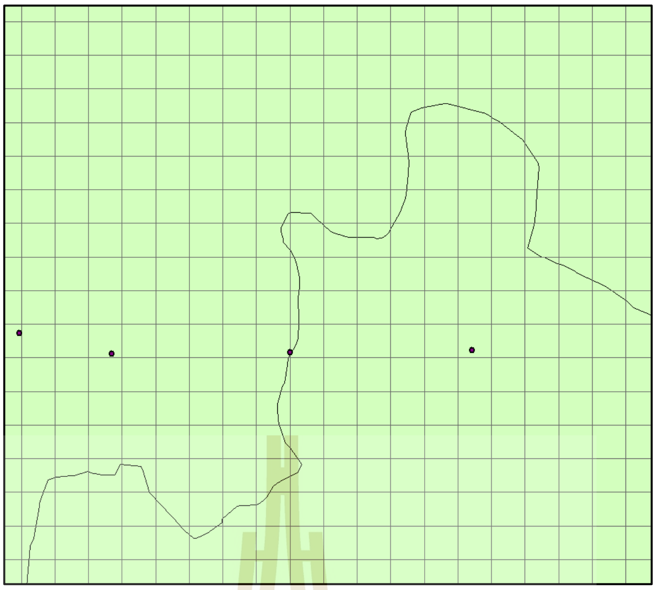


Fig. 3.6 Aircraft movement point without an adjustment

2. Digitized the new points between two points every 1 kilometer along the aircraft route map.

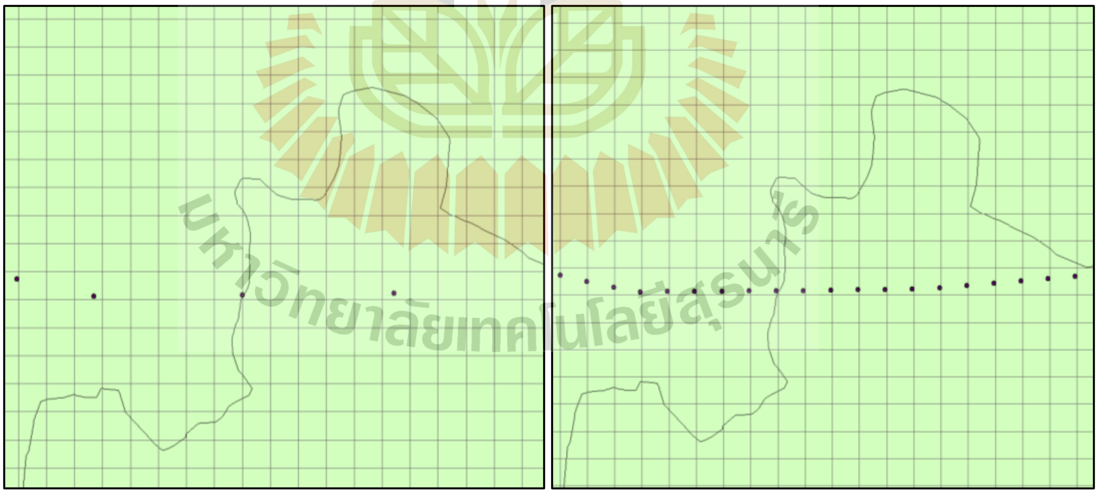


Fig. 3.7 Point of route map after an adjustment

3. Created the fields data and identified the location, mode, altitude, CO, NO_x, and HC. Added values to each field as showed in Fig. 3.8

Table

FD3568_Full

FID	Shape *	Id	Location	Mode	Altitude	CO	NOx	HC
0	Point	0	Don Mueang	Taxi	0	561.2	140.6	37.2
1	Point	0	Don Mueang	Take-off	0	44.81	1432.	6.81
2	Point	0	Don Mueang	Initial-climb	31	2.3	73.67	.35
3	Point	0	Don Mueang	Initial-climb	77	2.3	73.67	.35
4	Point	0	Don Mueang	Initial-climb	122	2.3	73.67	.35
5	Point	0	Don Mueang	Initial-climb	168	2.3	73.67	.35
6	Point	0	Don Mueang	Initial-climb	214	2.3	73.67	.35

Fig. 3.8 Attribute table of departure flight at Don Mueang airport

4. Clipped the route map with the function in the GIS program, to cut out coordinates outside of Thailand's land boundary.

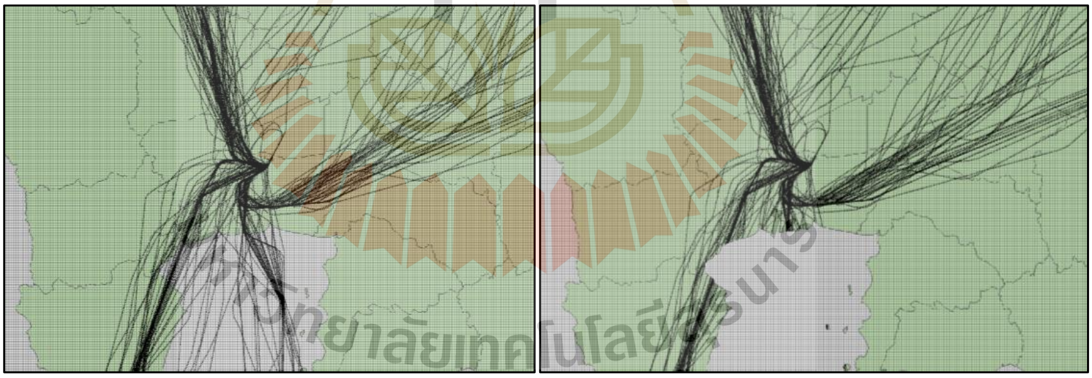


Fig. 3.9 The route maps both before (left) and after (right) map clipping

In route map creation, provides the route maps for various flights. This route map will used to interpolate the spatial analysis in the fifth step.

3.4 Creation of boundaries

The boundaries of airports were created using LTO cycle distance, covering the distance of LTO cycle.

1. Open buffer function in the GIS program.

2. Set the distance of LTO area away from the airports (5 to 10 kilometers depend on each airport)

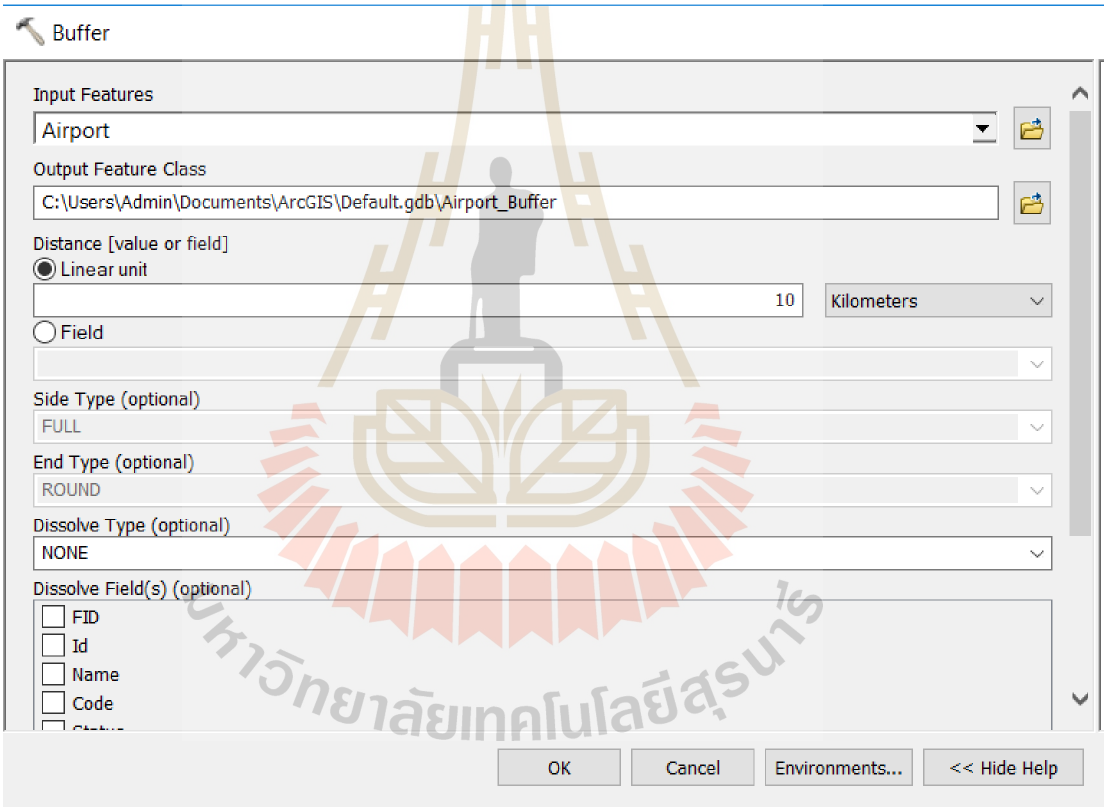


Fig. 3.10 Buffer function for creating the boundary

3. Saved the boundary shape file as new vector layer, this boundary will be used in spatial analysis step.

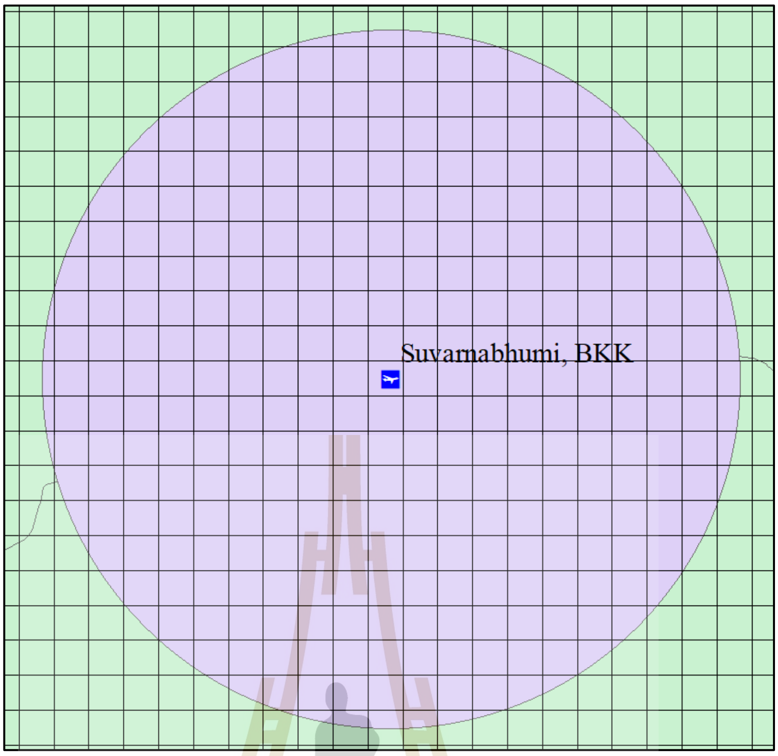


Fig. 3.11 Suvarnabhumi airport boundary

3.5 Spatial analysis

The spatial emission maps were obtained from the spatial analysis of the route maps. The points of route maps were used as an input file through the function in GIS program.

1. Opened interpolation function in the GIS program.

2. Input route map file into the GIS program. Then, selected the field for each pollutant (CO, NO_x, and HC).

3. Insert vector layer, boundary of the airport for each airport. To set the area for interpolation analysis in LTO cycle. For cruise mode, boundary layer of Thailand was used as the extent in interpolation analysis.

4. Set the cell size value to 50 meters, boundary of interpolation for interpolating

the spatial map during LTO cycle. And the cell size of 500 meters for interpolating analysis in the cruise mode.

After the emission interpolation step, the emission maps were created. The maps showed the distribution of pollution at airports.

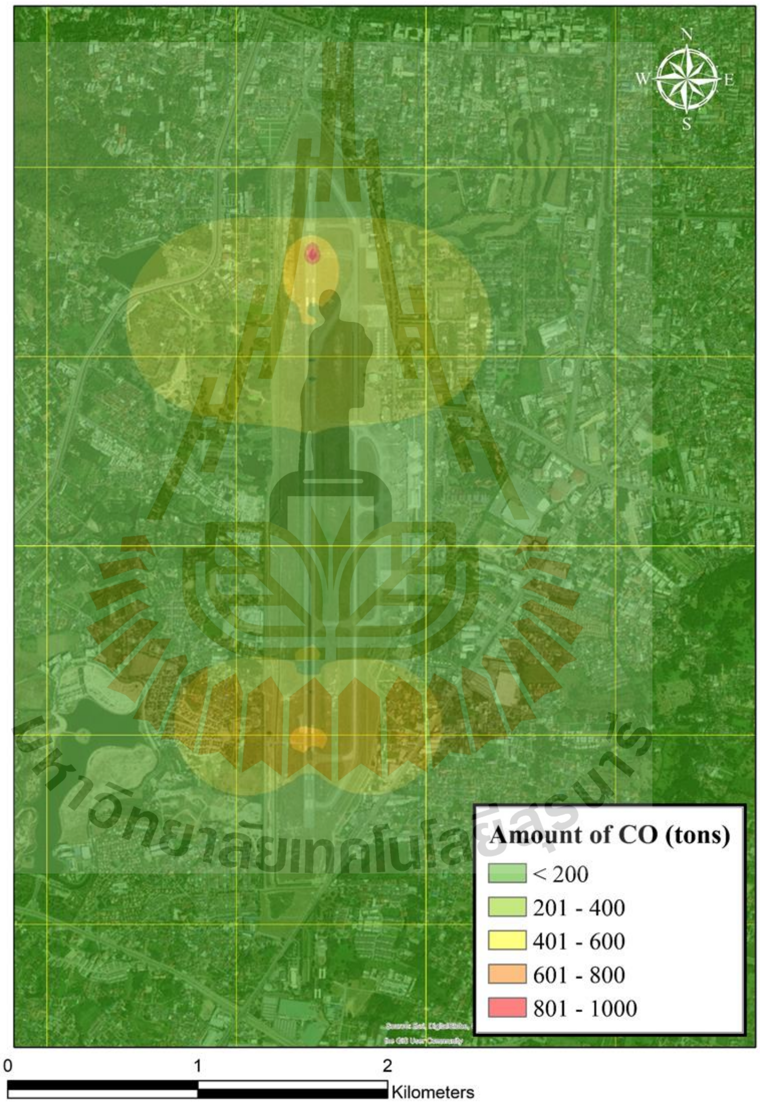


Fig. 3.12 The spatial emission map after adjustment

CHAPTER 4

RESULTS AND DISCUSSION

The results of this study are separated into 3 parts: a) aircraft routes map, displaying the movement of the commercial aircraft in different modes of flying, b) emission estimates from the commercial aircraft's flying cycle using the emission factors, and c) the spatial emissions over the land territory of Thailand.

4.1 The commercial aircraft routes tracking

Commercial aircraft flying routes over the land boundary of Thailand were created and classified into two categories based on the actual data of domestic and international flights. Both categories were later classified based on the flying cycles; taxi, take-off, initial-climb, climb-out, cruise, approach, and landing (Table 4.1).

Table 4.1 Classification of the flying cycle based on the altitude

Altitude (meters)	Aeronautical operational control	Layer
At the ground	Taxi, Take-off, and Landing	1
0 to 450	Initial-climb and Approach	1
450 to 1000	Climb-out and Approach	1
1000 up	Cruise	2

The flight data were obtained by monitoring and acquiring from the tracking and airport websites. These techniques help acquiring the data necessary for constructing the route maps. This study used the stepped described in Fig. 4.1 to perform the data collection and processing.

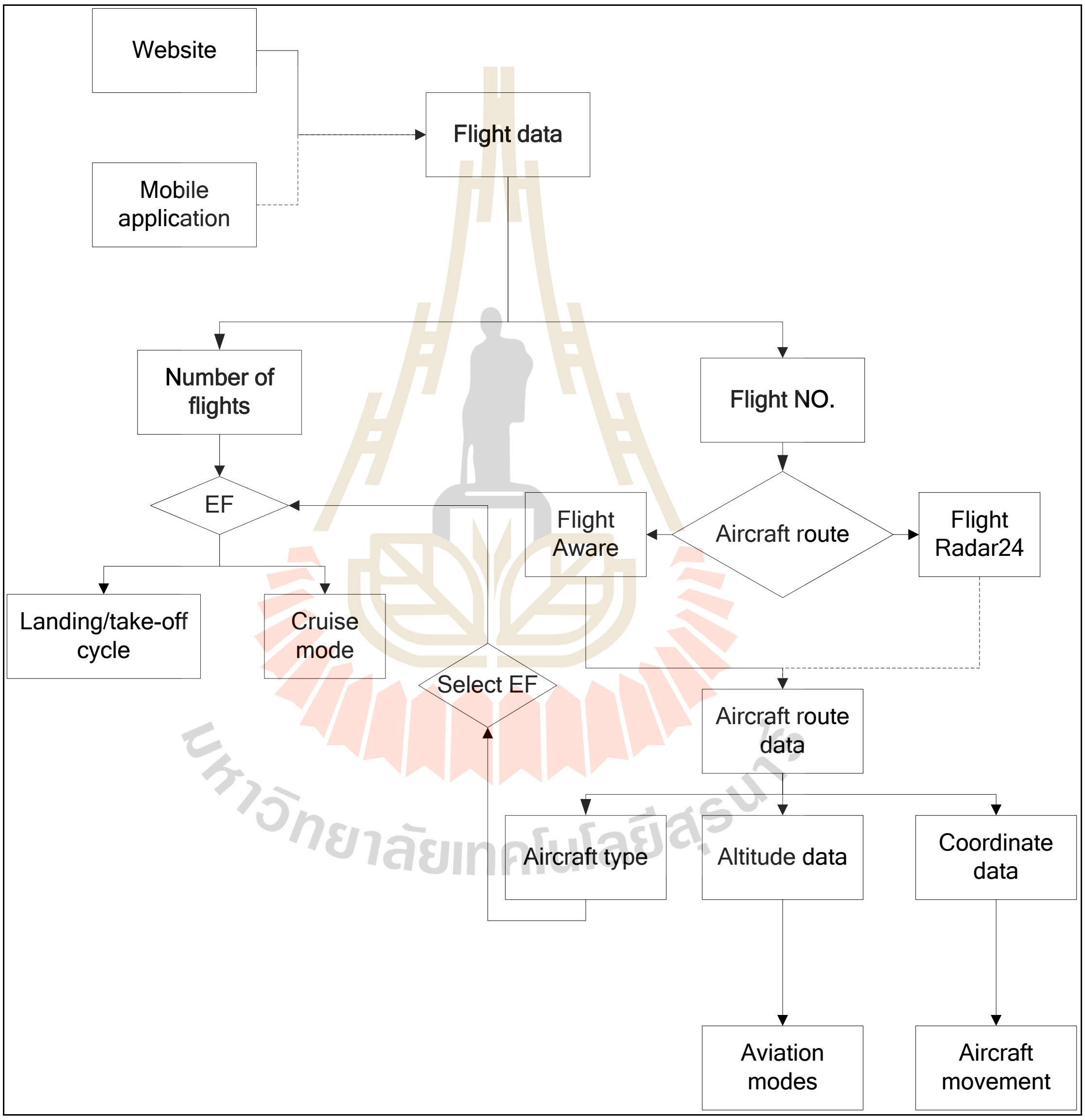


Fig. 4.1 The techniques for route tracking of the commercial aircraft.

Flight data collection

Flight data of available commercial aircrafts flying over Thailand were obtained from the websites that provided the flight data of the commercial aircrafts including the flight number of each aircraft, altitude, and real-time coordinates. Number of flights were used to calculate the emissions.

Conversion of coordinate data

Equations were used in a spreadsheet program to convert the coordinate data from latitude/longitude to the Universal Transverse Mercator (UTM). This tool helps minimizing the time-consuming process for converting more than ten thousand of coordinate data into the coordinate system used in a GIS program.

Categorization of aircraft modes

The altitude data for each movement point were used for classifying the mode of aircraft activities of the commercial aircrafts. Modes in the flying cycle from the classification were used later for interpolating the spatial emissions of the aircrafts.

Data from the flight tracking techniques were overlaid on the topography map with at least 1 km × 1 km grid.

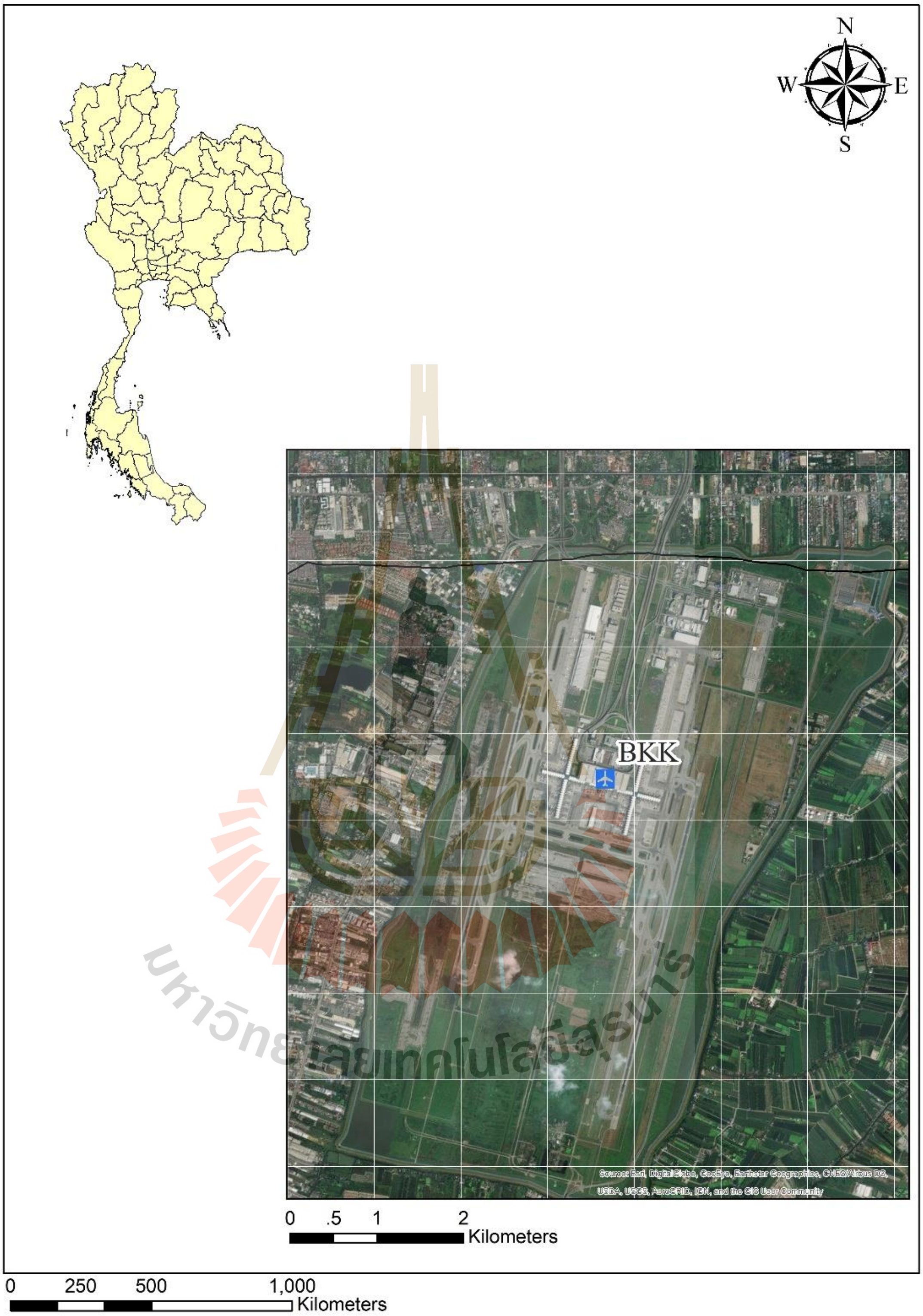


Fig. 4.2 Grid map resolution at 1 km × 1 km for digitizing point of aircraft movement

However, the flying cycle on the ground, initial-climb, climb-out, and approach occurred in the airport and nearby areas which covered less distance comparing to aircraft cruising. The coordinate data for near ground operations were sub-divided into less than 1 km × 1 km grid. Therefore, the coordinate data of the flying cycle were grouped as layers 1 and 2 (Table 4.1).

4.2 The movement of commercial aircraft

The commercial aircraft movements during LTO cycle and cruise mode were showed in layer 1 and 2, respectively.

4.2.1 LTO cycle

The movement of commercial aircraft during LTO cycle occurred at the altitude under 1,000 meters.

Parallel dual runways

Layer 1 of a route map of the commercial aircrafts in the area of Suvarnabhumi airport had higher traffic than other airports. The movement of the commercial aircrafts covered greater distant. The runways at the airport has the length of about 4,000 meters with the parallel dual runways in the north-northeast direction. The runways' length was used to calculate the aircraft emissions during taxi modes. The taxi mode occurred at the end of the runways on the north and south directions. Take-off also occurred on the runways but this mode was operated at the center of the runways. Initial-climb and climb-out occurred at the end of the runways on the north and south about 10 kilometers farther away from the runways. Landing mode occurred at the center of the runways to the end of the runways on the north. Approach mode was observed at the end of the runways to the area 10 kilometers away from the runways. The route maps for each mode in flying cycle were generated, based on the assumption of 1×1 kilometer for each point.

Don Mueang airport was operated with the dual runways. Aircraft taxi mode was founded at the end of the runways in the north. Take-off started at the center of the runways next to the taxi mode. Landing occurs at the center of the runways. Initial-climb and climb-out were founded at the end of the runways on the south to the area far from the runways at the distance about 10 kilometers. The aircraft approaching mode occurred at the end of the runways.

Single runway: flights operated at both sides of the runway

Unlike Suvarnabhumi and Don Mueang airports, the rest of the airports have a single runway (Table 4.2). Arrival and departure flights occurred at both sides of the runway. These airports included Chiang Mai (CNX), Mae Fah Luang Chiang Rai (CEI), Krabi (KBV), Trang (TST), Phitsanulok (PHS), Loei (LOE), Udon Thani (UTH), Khon Kaen (KKC), and Ubon Ratchathani (UBP).

Table 4.2 The aircraft movement occurring at both sides of the runway

Airports	The movement of commercial aircraft
CNX	Aircraft taxi mode was found at both sides to the end of the runway. Take-off mode occurred at the center of the runway. Landing mode was observed at the end of the runway nearby approach mode. This mode occurred in the range of 10 kilometers from the airport. Initial-climb and climb-out were found next to the end of the runway about 5 and 10 kilometers from the runway.

Table 4.2 The aircraft movement occurring at both sides of the runway (Continued)

Airports	The movement of commercial aircraft
CEI	The aircraft taxi mode occurred at both sides of the end of the runway. Take-off mode took up the area at the center of the runway. Aircraft landing mode was observed only one side at the end of the runway in the southwest direction. Approach mode occurred at the area near landing mode in the southwest direction. The initial-climb and climb-out occurred in the northeast direction of the runway.
KBV	Taxi mode at was found at the end of the runway. The commercial aircraft used the center of the runway for take-off mode. Landing mode occurred at the center of the runway. The aircrafts used both sides of the runway for approaching mode. The aircrafts used only one side of the runway in southeast direction during initial-climb and climb-out.
TST	The movement in taxi mode occurred at both sides at the end of the runway. Take-off mode occurred at the center of the runway. Landing mode also occurred at the center of the runway. The commercial aircraft was operated the approach mode for both sides of the runway. The movement of the commercial aircraft through initial-climb and climb-out occurred only one side of the runway in the east direction.
PHS	Aircraft taxi mode used the area at both sides of the end of the runway. The movement of the aircrafts throughout take-off and landing modes were found at the center of the runway. Approach mode was operated at the end of the runway on both sides. The operation of the commercial aircraft during initial-climb and climb-out modes were observed only one side of the end of the runway in the northwest direction.
LOE	The movement of the commercial aircraft during taxi mode occurred at both sides of the end of the runway. Take-off and landing mode occurred at the center of the runway. Approach mode occurred at both sides of the runway while the initial-climb and climb-out were observed only one side of runway in the southwest direction.

Table 4.2 The aircraft movement occurring at both sides of the runway (Continued)

Airports	The movement of commercial aircraft
UTH	The aircraft taxi mode occurred at the end of the runway, mostly at the northwest direction. Take-off and landing modes occurred at the center area of the runway. Initial-climb and climb-out were found at the end of the runway in the southeast direction. Aircraft approach mode occurred at both sides of the runway.
KKC	The commercial aircraft movement during taxi mode occurred at both sides of the end of the runway. The center of the runway was the area where take-off and landing were operated. Initial-climb and climb-out were observed at both sides of the runway, especially in southwest direction. Approach mode was found only one side of the runway.
UBP	The commercial aircraft movement during taxi mode was observed at both sides of the end of the runway. Take-off and landing were found at the center of the runway. Approach, initial-climb, and climb-out occurred at the area about 10 kilometers away from both sides of the runway.

Single runway: flights operated at only one side of the runway

There are other small airports that the commercial aircrafts in LTO cycle occur only one side of the runway. They are Mae Sot (MAQ), Nakhon Phanom (KOP), Nan Nakhon (NNT), Buriram (BFV), Phrae (PRH), Mae Hong Son (HGN), Roi Et (ROI), Ranong (UNN), Lampang (LPT), Sakon Nakhon (SNO), and Sukhothai (THS).

The movement of the commercial aircraft during taxi mode occurred at the end of the runway in the north direction for Lampang airport, northeast direction at Nan Nakhon and Buriram airports, northwest direction at Nakhon Phanom and Mae Hong Son airports, west direction at Mae Sot airport, and the southwest direction at Ranong airport. Take-off and landing occurred at the center of the runway. Approach mode occurred at the end of the runway in the east direction. Initial-climb and climb-out occurred at the area about 10 kilometers away from the runway.

At Phrae and Roi Et airports, the commercial aircraft movement during taxi mode occurred at the end of the runway in the north direction, while Sakon Nakhon airport was observed at the end of the runway in the northeast direction. Take-off mode occurred at the center of the runway. Aircraft landing mode occurred at the end of the runway. Initial-climb, climb-out, and approach modes occurred at 10 kilometers away from the end of the runway.

At Sukhothai airport, the commercial aircraft movement during taxi mode occurred at the end of the runway in the north direction. Taking off occurred at the end of the runway. Landing mode occurred at the center of the runway. Initial-climb, climb-out, and approach modes were operated 10 kilometers away from the runway.

Single runway: airports locate near the coast

The airports located near the coast are Phuket (HKT), Hat Yai (HDY), Chunphon (CJM), Nakhon Si Thammarat (NST), Narathiwat (NAW), Surat Thani (URT), Trat (TDX), U-Tapao (UTP), and Samui (USM). Some modes in the flying cycle of these airports occurred over the sea, therefore, they were not estimated. The modes of climb-out and approach were cut, emissions in these two modes were not estimated.

Table 4.3 The aircraft movement occurring near the coast

Airports	The movement of commercial aircraft
HKT	The aircraft taxi mode was found mostly at the end of the runway in the east direction. Take-off mode started at the center of the runway moving to the sea. Aircraft landing also occurred at the center of the runway. Initial-climb mode was operated at the end of the runway moving to the sea in the west direction. Mode of climb-out was cut off due to this mode occurred out of Thailand boundary. Aircraft approach mode occurred at both sides of the end of the runway.
KBV	The commercial aircraft movement during taxi mode occurred on both sides at the end of the runway. Take-off and landing mode were operated at the center of the runway. Initial-climb and climb-out were found only the nearby area away from the runway in the west direction. While approaching mode occurred at both sides of the runway, but it was found mostly at the area in the east direction of the runway.
CJM	The movement during taxi mode occurred on both sides at the end of the runway. Take-off and landing mode were operated at the center of the runway. Some parts of initial-climb's route occurred at the area near the end of the runway in the northeast direction, while climb-out mode was cut off due to this mode was operated out of Thailand boundary. The approach was found both sides at the areas away from the end of the runway.
NST	The movement of the commercial aircraft during taxi mode started mostly at the end of the runway in south direction. Aircraft take-off and landing were found at the center of the runway. Initial-climb and approach were operated at the areas both sides of the end of the runway, while climb-out mode was cut off if the coordinates were over the sea.

Table 4.3 The aircraft movement occurring near the coast (Continued)

Airports	The movement of commercial aircraft
NAW	Aircraft taxi mode occurred only the end of the runway in the southwest direction. Take-off mode started at the center of the runway as well as the landing mode. Some points of the movement during initial-climb and approach were observed only the end of the runway in the northeast direction moving to the sea. The movement in climb-out mode was not estimated when it occurred over the sea.
URT	The movement during taxi mode started both sides at the end of the runway. Take-off and landing modes occurred at the center of the runway. Approach mode was found both sides at the area about 10 kilometers away from the runway. The initial-climb and climb-out mode were observed mostly at the area away from the runway in the northeast direction moving to the sea.
TDX	Aircraft taxi mode occurred at the end of the runway. Take-off and landing mode were found at the center of the runway. Initial-climb and climb-out mode started from the end of the runway in the southwest direction to the sea. The approaching mode was observed at both sides of the end of the runway.
UTP	The movement during taxi mode was found at both sides of the end of the runway. Take-off and landing modes were found at the center of the runway. Initial-climb and climb-out were observed mostly at the end of the runway and nearby area 10 kilometers away from the runway in the north direction. Aircraft approach mode also was found similar to initial-climb and climb-out mode.
USM	Aircraft movement during taxi mode occurred at both sides of the end of the runway, while take-off and landing modes were found at the center of the runway. Initial-climb mode was observed in the south direction away from the runway. Aircraft approaching mode was found at both sides away from the runway in Samui and some area of Phangan island. Climb-out mode was not estimated when it occurred over the Gulf of Thailand.

4.2.2 Cruise mode

Layer 2 represented the movement of the commercial aircraft during cruise mode in Thailand's airspace and it was divided into 4 parts depending on the region (Fig 4.3). The movement of the commercial aircrafts on cruise mode was showed in Fig 4.4.

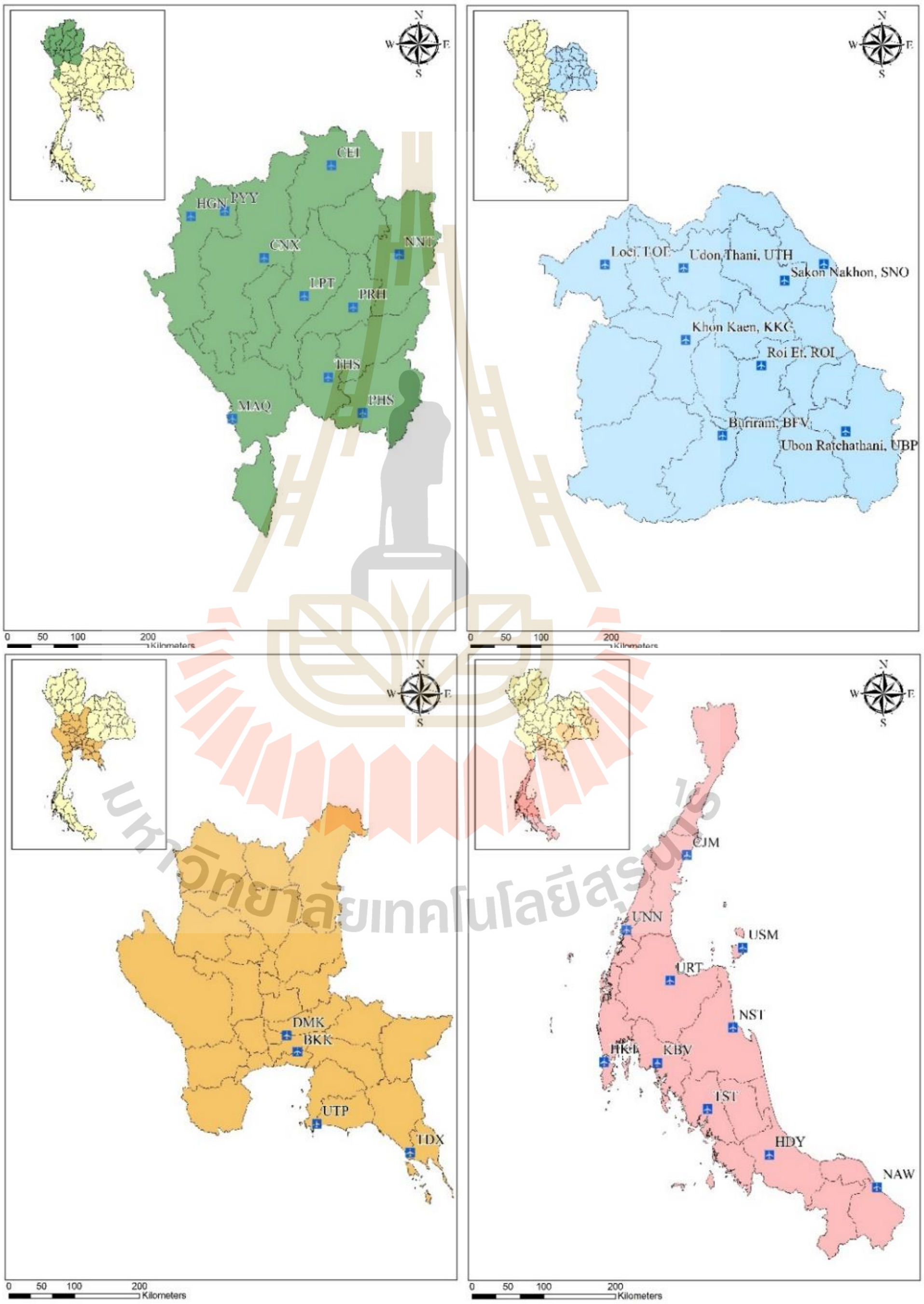


Fig. 4.3 The regions for the presentation of the commercial aircraft movement

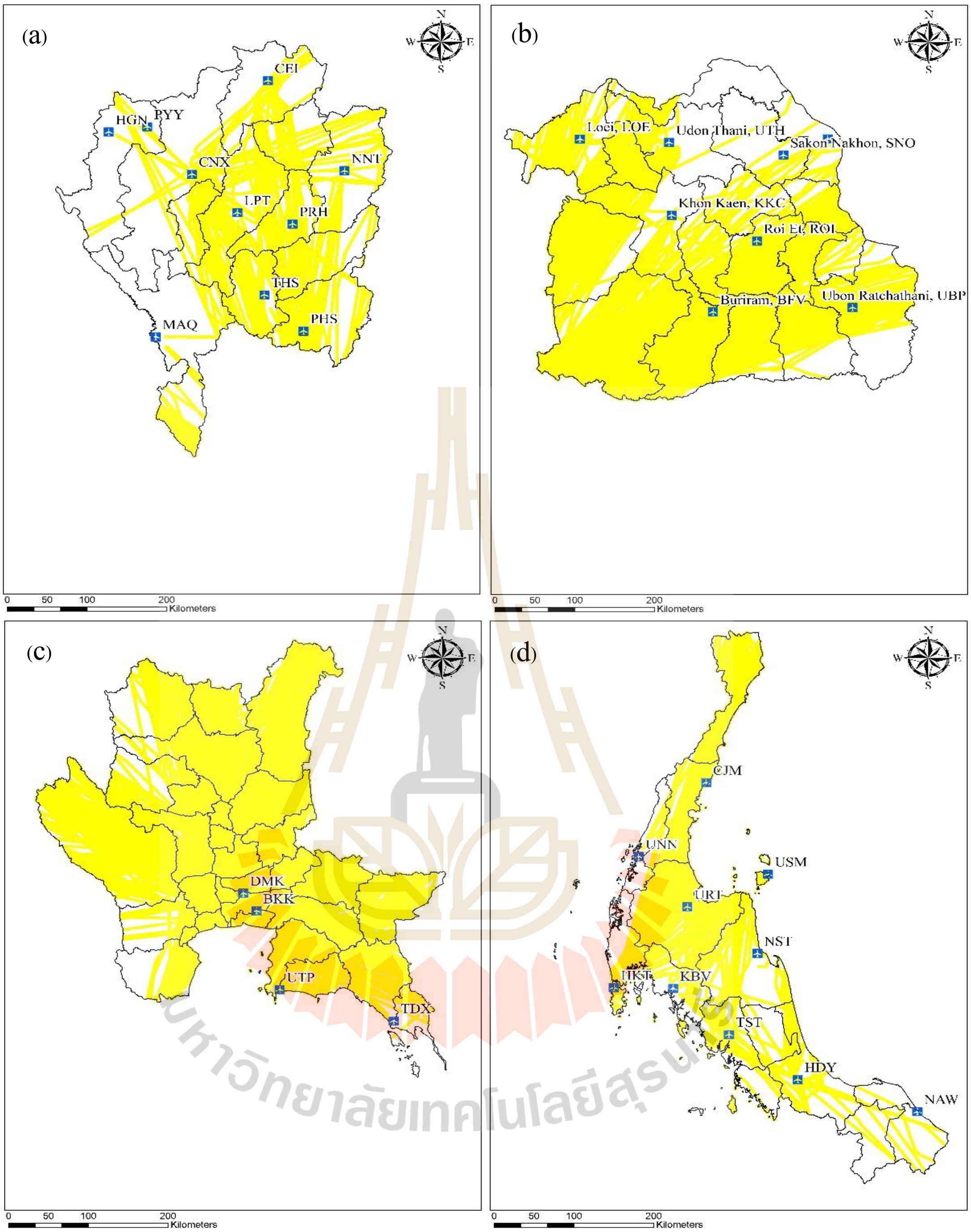


Fig. 4.4 The movement of commercial aircraft during cruise mode dividing by the region: northern (a), northeastern (b), central (c) and southern (d)

The movement of the commercial aircraft during cruise mode occurred at the altitude above 1,000 meters. The routes of the commercial aircraft covered most area of Thailand, especially the central region. In the central region, the movement of the commercial aircraft was very intensive due to the destination toward Suvarnabhumi and Don Mueang airports (Fig. 4.4 c). The routes over the northeastern region during cruise mode were heading to the central region or abroad (Fig. 4.4 b). Similar patterns were found in Chiang Mai and Phuket (Fig. 4.4 a and 4.4 d).

The movement of the commercial aircraft for all modes of flying in Thailand's airspace was presented in the Fig.4.5.

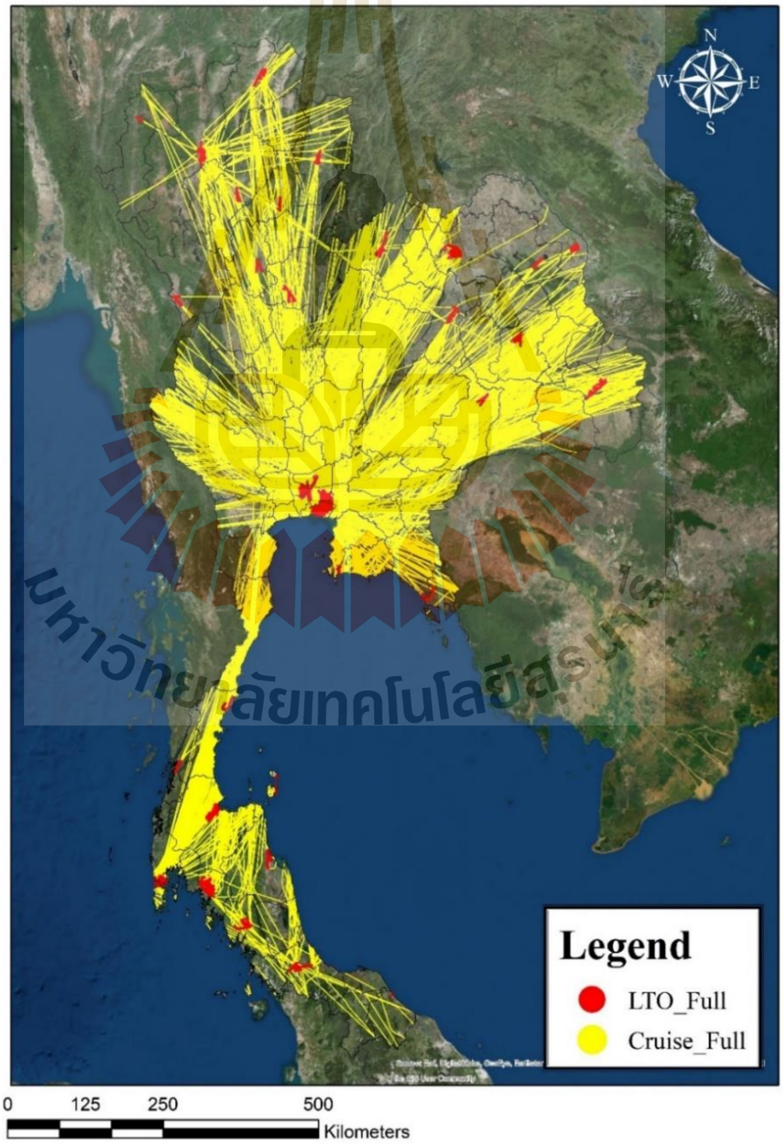


Fig. 4.5 The movement of the commercial aircraft in Thailand's airspace

The route map in Fig. 4.5 showed the movement of the commercial aircrafts during the LTO cycle (red) and cruise mode (yellow) in Thailand's land territory. The movement of the commercial aircrafts during taxi, take-off, initial-climb, climb-out, approach, and landing were represented with the red points, aircraft movements occur in the range of altitude at the ground to the level under 1,000 meters. The bounds are in the range between 5 and 10 kilometers around the airports, depending on runway's length.

The yellow points in Fig. 4.5 represented the movement of the commercial aircrafts for both domestic and international flights during cruise mode. The commercial aircraft operation occurred at the altitude over 1,000 meters within Thailand's land territory. The movement of aircraft during cruise mode covered large area of the country, especially in the central region of Thailand.

Flight description of the commercial aircraft for various routes in Thailand's land territory and number of coordinate point within Thailand's territory after excluding coordinates over the Gulf of Thailand (Table 4.4). The number of coordinates used in this study during landing/take-off and cruise mode were 48,039 and 824,050 points, respectively. The total number of coordinates was 872,089 points.

Table 4.4 Flight description of the commercial aircraft

Airports	Flights		Number of coordinates (Points)
	Domestic	International	
BKK	CNX, CEI, HDY, HKT, KBV, KKC, LPT, NAW, TDX, THS, UBP, URT, USM, and UTH	51 countries	21,205
DMK	CNX, CEI, HDY, HKT, KBV, KKC, CJM, TST, MAQ, KOP, NST, NAW, NNT, BFV, PHS, PRH, HGN, ROI, UNN, LOE, LPT, SNO TDX, UBP, URT, and UTH	11 countries	12,828
CNX	BKK, DMK, HDY, HKT, KBV, KKC, HGN, NNT, PHS, UBP, URT, USM, UTH, and UTP	8 countries	3,061
CEI	BKK and DMK	1 country	990
HKT	BKK, DMK, CNX, HDY, USM, UTH, and UTP	21 countries	1,718
HDY	BKK, DMK, CNX, HKT, PHS, UTH, and UTP	2 countries	1,267
KBV	BKK, DMK, CNX, and USM	3 countries	1,032
URT	BBK, DMK, and CNX	2 countries	684
USM	BKK, CNX, HKT, KBV, and UTP	1 country	407
UTP	CNX, HDY, HKT, UBP, USM, and UTH	2 countries	396

Table 4.4 Flight description of the commercial aircraft (Continued)

Airports	Flights		Number of coordinates (Points)
	Domestic	International	
KKC	BKK, DMK, CNX, and HDY	-	582
CJM	DMK	-	54
TST	DMK	-	216
MAQ	DMK	-	136
KOP	DMK	-	136
NST	DMK	-	307
NAW	BKK and DMK	-	20
NNT	DMK and CNX	-	216
BFV	DMK	-	114
PHS	DMK	-	254
PRH	DMK	-	68
HGN	CNX	-	84
ROI	DMK	-	170
UNN	DMK	-	68
LOE	DMK	-	146
LPT	BKK and DMK	-	226

Table 4.4 Flight description of the commercial aircraft (Continued)

Airports	Flights		Number of coordinates (Points)
	Domestic	International	
SNO	DMK	-	136
UTH	BBK, DMK, CNX, HDY, HKT, and UTP	-	752
UBP	BBK, DMK, CNX, and UTP	-	612
TDX	BKK	-	74
THS	BKK	-	80
Landing/take-off mode			48,039
Cruise			824,050
Total			**872,089**

4.3 Annual emissions of the commercial aircraft

The annual emissions were calculated using the emission factors and engine types data combined with the number of flights based on 2015 data.

4.3.1 Annual emissions for each airport during LTO cycle

Domestic airports

There are 21 domestic airports, Khon Kaen (KKC), Chumphon (CJM), Trang (TST), Mae Sot (MAQ), Nakhon Phanom (KOP), Nakhon Si Thammarat (NST), Narathiwat (NAW), Nan Nakhon (NNT), Buriram (BFV), Phitsanulok (PHS), Phrae (PRH), Mae Hong Son (HGN), Roi Et (ROI), Ranong (UNN), Loei (LOE), Lampang

(LPT), Sakon Nakhon (SNO), Udon Thani (UTH), Ubon Ratchathani (UBP), Trat (TDX), and Sukhothai (THS). The estimated annual emissions (ktons) in 2015 for each mode are in Table 4.5.

Table 4.5 The estimated annual emissions in the domestic airports

Airports		Emissions in each modes (ktons)							Emission rates (tons/flight)
		Taxi	Take-off	Initial-climb	Climb-out	Approach	Landing	Total (ktons)	
KKC	CO	20.51	0.92	0.44	0.83	7.56	1.77	35.30	2.31
	NO_x	3.45	24.99	12.20	12.78	7.20	0.29	90.24	4.39
	HC	3.05	0.20	0.09	0.12	1.33	0.24	5.50	0.36
CJM	CO	2.90	0.08	0.02	0.00	1.13	0.39	4.53	3.10
	NO_x	0.02	0.15	0.04	0.00	0.03	0.003	0.43	0.17
	HC	0.76	0.03	0.01	0.00	0.10	0.10	1.00	0.68
TST	CO	6.16	0.41	0.17	0.33	2.83	0.77	12.13	2.09
	NO_x	0.94	10.69	4.63	5.04	2.89	0.12	31.12	4.76
	HC	1.40	0.11	0.04	0.06	0.45	0.17	2.60	0.44
MAQ	CO	4.07	0.17	0.08	0.13	2.19	0.76	7.44	2.53
	NO_x	0.03	0.29	0.15	0.17	0.06	0.01	2.27	0.24
	HC	1.06	0.05	0.03	0.04	0.20	0.20	1.58	0.54
KOP	CO	4.84	0.20	0.09	0.17	2.03	0.57	8.93	2.71
	NO_x	0.48	4.54	2.11	2.25	1.14	0.05	17.83	3.62
	HC	1.07	0.05	0.02	0.03	0.28	0.11	1.77	0.54
NST	CO	13.50	0.81	0.33	0.50	3.06	1.71	21.05	2.10
	NO_x	1.91	20.12	8.38	7.39	2.90	0.24	45.48	4.31
	HC	3.39	0.22	0.09	0.11	0.57	0.43	5.08	0.51
NAW	CO	1.90	0.13	0.03	0.00	0.09	0.18	2.40	1.06
	NO_x	0.47	4.30	0.88	0.00	0.11	0.04	6.67	2.65
	HC	0.13	0.03	0.00	0.00	0.02	0.01	0.20	0.09
NNT	CO	6.37	0.26	0.15	0.23	2.99	0.89	11.39	2.48
	NO_x	0.56	3.16	1.65	1.70	2.69	0.12	16.31	2.26
	HC	1.52	0.07	0.04	0.05	0.54	0.22	2.45	0.56

Table 4.5 The estimated annual emissions in the domestic airports (Continued)

Airports		Modes (ktons)							Emission rates (tons/flight)
		Taxi	Take-off	Initial-climb	Climb-out	Approach	Landing	Total (ktons)	
BFV	CO	4.26	0.17	0.09	0.14	1.58	0.48	6.87	2.30
	NO_x	0.19	1.65	0.85	0.88	0.59	0.03	6.57	1.43
	HC	0.99	0.05	0.02	0.03	0.19	0.11	1.40	0.48
PHS	CO	11.32	0.47	0.21	0.38	2.79	0.82	17.31	2.43
	NO_x	1.15	9.31	4.13	4.47	2.29	0.10	29.00	3.27
	HC	2.71	0.12	0.05	0.08	0.48	0.20	3.96	0.56
PRH	CO	1.76	0.08	0.04	0.06	0.84	0.28	3.10	2.10
	NO_x	0.09	0.15	0.07	0.08	0.70	0.03	1.95	0.76
	HC	0.49	0.03	0.01	0.02	0.15	0.09	0.78	0.54
HGN	CO	4.82	0.21	0.19	0.24	1.12	0.39	7.03	1.91
	NO_x	0.04	0.36	0.33	0.31	0.03	0.00	1.16	0.29
	HC	1.26	0.06	0.06	0.08	0.10	0.10	1.66	0.46
ROI	CO	4.64	0.22	0.11	0.20	2.23	0.63	8.53	2.20
	NO_x	0.58	4.44	2.28	2.36	2.22	0.09	18.57	3.28
	HC	0.97	0.05	0.02	0.03	0.42	0.15	1.66	0.45
UNN	CO	2.75	0.08	0.04	0.06	1.13	0.39	4.47	3.05
	NO_x	0.02	0.15	0.07	0.08	0.03	0.00	0.85	0.24
	HC	0.72	0.03	0.01	0.02	0.10	0.10	0.98	0.67
LOE	CO	3.69	0.13	0.06	0.11	1.88	0.53	6.56	2.92
	NO_x	0.25	1.58	0.81	0.84	1.06	0.04	7.16	2.09
	HC	0.79	0.03	0.02	0.02	0.26	0.11	1.24	0.56
LPT	CO	8.68	0.25	0.17	0.24	3.82	1.32	14.72	3.31
	NO_x	0.07	0.44	0.31	0.31	0.10	0.01	2.87	0.28
	HC	2.78	0.08	0.05	0.08	0.34	0.35	3.67	0.84

Table 4.5 The estimated annual emissions in the domestic airports (Continued)

Airports		Modes (ktons)							Emission rates (tons/flight)
		Taxi	Take-off	Initial-climb	Climb-out	Approach	Landing	Total (ktons)	
SNO	CO	5.24	0.23	0.10	0.18	1.81	0.55	9.35	2.77
	NO_x	0.59	4.70	1.98	2.18	1.68	0.07	16.64	3.84
	HC	1.36	0.06	0.03	0.04	0.33	0.14	2.29	0.67
UTH	CO	29.39	1.16	0.51	0.96	10.50	2.94	51.96	2.97
	NO_x	4.45	30.22	13.58	14.61	10.49	0.44	112.34	4.81
	HC	6.55	0.29	0.12	0.17	1.98	0.68	11.08	0.64
UBP	CO	23.56	0.91	0.39	0.75	8.56	2.51	42.18	3.14
	NO_x	3.36	24.25	10.73	11.60	7.73	0.33	86.99	4.97
	HC	5.55	0.22	0.09	0.14	1.54	0.59	9.43	0.70
TDX	CO	2.68	0.12	0.11	0.11	0.81	0.19	4.09	1.84
	NO_x	0.22	0.22	0.20	0.14	1.00	0.05	1.93	0.83
	HC	0.54	0.04	0.04	0.03	0.16	0.01	0.83	0.38
THS	CO	0.22	0.22	0.20	0.14	1.00	0.05	1.93	2.68
	NO_x	0.54	0.04	0.04	0.03	0.16	0.01	0.83	0.30
	HC	1.04	0.04	0.04	0.05	0.10	0.10	1.36	0.62
Total	CO	167.00	7.13	3.46	5.77	60.06	18.46	285.36	2.48
	NO_x	18.91	145.91	65.57	67.38	44.99	2.08	497.25	2.32
	HC	38.11	1.85	0.87	1.21	9.65	4.21	60.52	0.54

The total annual emissions from domestic airports were in the range between 1.93 (Sukhothai, THS) to 51.96 ktons (Udon Thani, UTH) for CO, 0.83 (Sukhothai, THS) to 112.34 ktons (Udon Thani, UTH) for NO_x, and 0.20 (Narathiwat, NAW) to 11.08 ktons (Udon Thani, UTH) for HC, respectively. Total emissions from domestic airports accounted about 285.36 ktons of CO emission, 497.25 ktons of NO_x, and 60.52 ktons of HC annually.

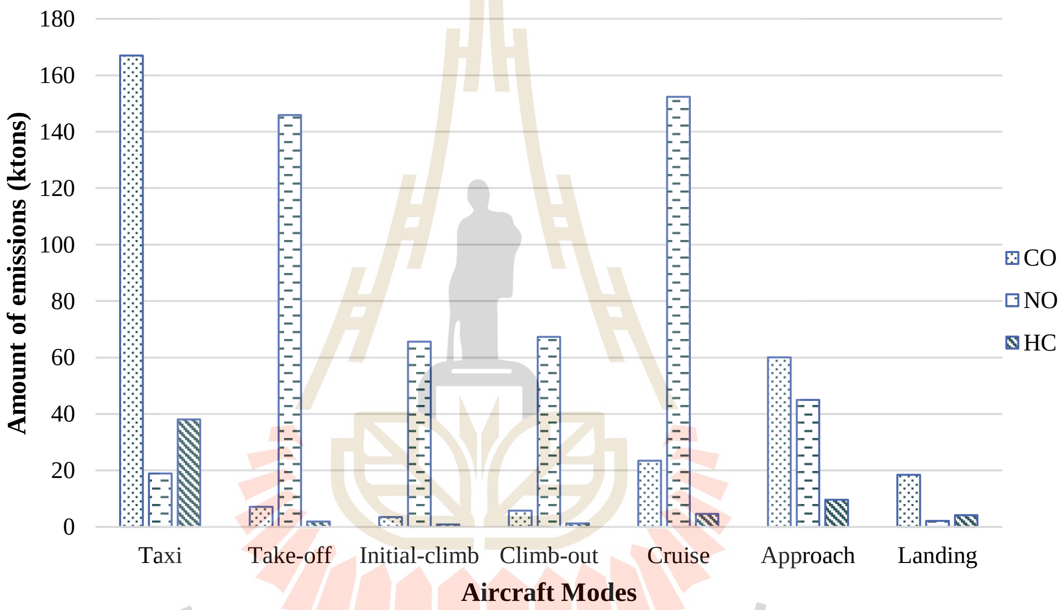


Fig. 4.6 The annual emissions occurred in different modes from domestic airport

In taxi mode, the annual emission accounted about 167.00 ktons of CO, 18.91 ktons of NO_x, and 38.11 ktons of HC. In take-off mode, the annual amount of CO was about 7.13 ktons, 145.91 ktons for NO_x, and 1.85 ktons for HC. For landing mode, the annual emissions were 18.46 ktons of CO, 2.08 ktons of NO_x, and 4.21 ktons of HC. During the initial-climb-mode, the emissions were about 3.46 ktons for CO, 65.57 ktons for NO_x, and 0.87 ktons for HC, annually. At the climb-out mode, the emission of CO was 5.77 ktons, 67.38 ktons for NO_x, and 1.21 ktons for HC. In approach mode, the annual emission of CO was 60.06 ktons, 44.99 ktons for NO_x, and 9.65 ktons for HC. The emissions of CO emitted through cruise mode was 23.48 ktons, 152.42 ktons of NO_x, and 4.61 ktons of HC annually.

When considered the annual emission data of domestic airports in each aircraft modes, high quantity of CO was found in the aircraft taxi, approach, and landing modes due to incomplete combustion, insufficient air conditions (Jacobson, 2012). The highest emission of CO occurred in the aircraft taxi mode. NO_x was high during take-off, initial-climb, climb-out, and cruise modes. High quantity of NO_x is the result of the excess air in high temperature combustion over 1,300 Celsius (US.EPA., 1999). The highest amount of NO_x occurred during cruise mode, while the emission of HC showed the highest quantity in taxi mode.

The highest emissions occurred at Udon Thani airport, the emissions were 51.96 tons for CO, 112.34 ktons for NO_x, and 11.08 ktons for HC. The highest emissions of CO and HC occurring in the taxi mode. The highest quantities of emissions were 29.39 ktons for CO and 6.55 ktons for HC. The highest emission of NO_x occurred in take-off mode when NO_x was 30.22 ktons.

Khon Kaen airport had the highest emission rate of CO about 2.31 tons per flight. For the emission rate of NO_x, the highest value was found at Ubon Ratchathani airport (4.97 tons per flight). The highest emission rate of HC was 0.84 tons per flight, this value was observed at Lampang airport.

International airports

International airports provide the services for both domestic and international flights. These consist of 10 airports namely Suvarnabhumi (BKK), Don Mueang (DMK), Chiang Mai (CNX), Mae Fah Luang Chiang Rai (CEI), Phuket (HKT), Hat Yai (HDY), Krabi (KBV), Surat Thani (URT), U-Tapao (UTP), and Samui airport (USM). The annual emissions from 10 international airports are in Table 4.6.

Table 4.6 The annual emissions from the international airports

Airports		Modes (ktons)							Emission rates
		Taxi	Take-off	Initial-climb	Climb-out	Approach	Landing	Total	(tons/flight)
BKK	CO	1123.72	24.37	11.72	17.11	199.79	94.37	2233.20	4.69
	NO_x	225.42	2200.23	990.22	925.55	600.36	20.06	6224.27	15.82
	HC	187.83	5.68	3.05	3.34	33.69	14.18	814.40	0.79
DMK	CO	536.94	17.37	7.63	14.20	148.05	43.92	889.61	3.34
	NO_x	81.39	531.52	235.73	247.38	159.42	10.74	1852.24	5.51
	HC	111.76	30.30	1.75	2.57	26.28	8.91	222.31	0.79
CNX	CO	136.84	4.66	2.28	4.07	41.69	11.81	247.37	3.18
	NO_x	23.53	170.11	78.09	79.83	59.83	5.36	623.62	6.59
	HC	24.25	1.06	0.51	0.71	7.55	1.95	56.79	0.57
CEI	CO	34.25	2.09	1.00	1.91	8.90	2.31	64.37	1.63
	NO_x	6.63	62.11	30.31	31.75	8.98	0.38	265.57	4.52
	HC	5.45	0.43	0.18	0.25	2.18	0.47	10.90	0.29
HKT	CO	239.54	11.75	1.09	0.00	12.35	21.07	344.16	1.80
	NO_x	48.81	493.08	45.20	0.00	27.12	7.65	1057.99	3.91
	HC	36.71	2.40	0.21	0.00	2.21	3.04	55.94	0.28
HDY	CO	46.88	1.88	0.81	1.55	17.25	4.68	78.14	3.02
	NO_x	7.44	49.97	22.12	23.92	17.69	0.74	147.91	5.04
	HC	10.23	0.48	0.31	0.28	3.28	1.02	16.81	0.64
KBV	CO	36.85	1.55	0.75	1.38	13.32	3.85	65.17	2.55
	NO_x	7.21	50.73	24.01	24.59	19.44	0.76	186.76	5.60
	HC	5.48	0.30	0.14	0.19	2.47	0.56	10.18	0.40
URT	CO	25.91	1.23	0.54	1.03	8.60	2.29	42.57	2.47
	NO_x	4.28	33.18	14.88	16.02	9.05	0.38	99.83	4.84
	HC	5.38	0.32	0.12	0.18	1.65	0.46	8.65	0.51

Table 4.6 The annual emissions from the international airports (Continued)

Airports		**Modes (ktons)**							**Emission rates**
		Taxi	Take-off	Initial-climb	Climb-out	Approach	Landing	Total	**(tons/flight)**
UTP	CO	34.41	1.22	0.33	0.28	9.52	2.84	61.76	2.83
	NO_x	5.26	31.56	8.50	4.35	9.84	0.44	123.98	3.49
	HC	7.09	0.28	0.08	0.05	1.80	0.59	13.13	0.58
USM	CO	39.51	2.09	0.44	0.10	3.87	5.43	53.15	1.53
	NO_x	6.80	58.06	11.38	0.12	4.10	0.86	93.27	2.42
	HC	5.51	0.41	0.08	0.03	0.72	0.82	7.71	0.23
								(Mtons)	
Total (Mtons)	CO	2.25	0.07	0.03	0.04	0.46	0.19	4.08	2.70
	NO_x	0.42	3.68	1.46	1.35	0.92	0.05	10.68	5.77
	HC	0.40	0.04	0.01	0.01	0.08	0.03	1.22	0.51

The annual emissions occurred from the international airports are in Table 4.6. The emissions were in the ranges of 42.57 (Surat Thani, URT) to 2,233.20 ktons (Suvarnabhumi, BKK) for CO, 93.27 (Samui, USM) to 6,224.27 ktons (Suvarnabhumi, BKK) for NO_x, and 7.71 (Samui, USM) to 814.40 ktons (Suvarnabhumi, BKK) for HC. Total emissions from international airports were accounted about 4.08 Mtons of CO emission, 10.68 Mtons of NO_x, and 1.22 Mtons of HC annually. The annual emissions for different modes of international airport are showed in Fig. 4.7.

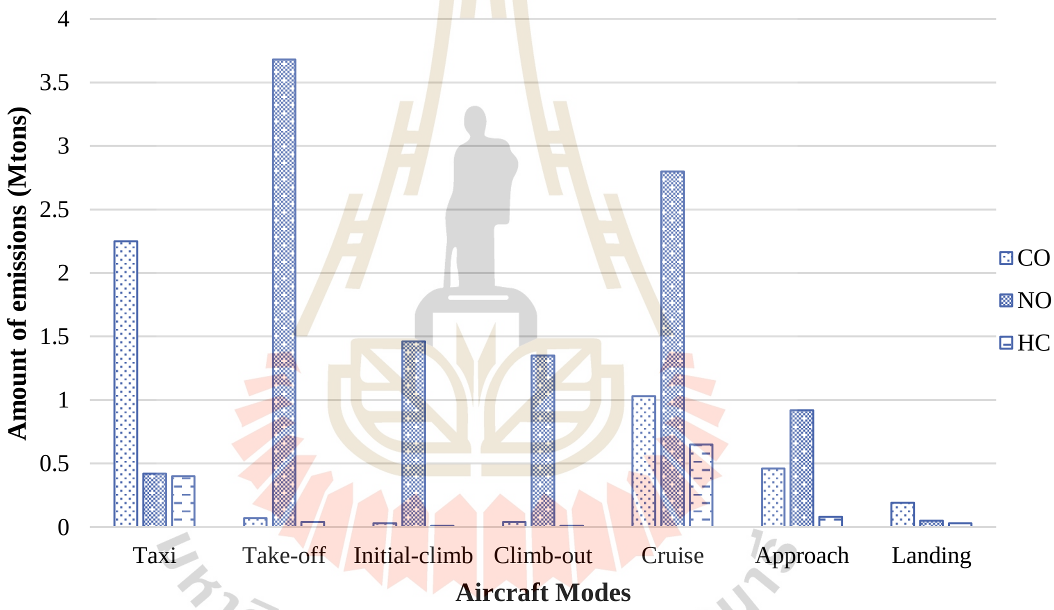


Fig. 4.7 The annual emissions of different modes from international airports

The annual emission was 2.25 Mtons of CO, 0.42 Mtons of NO_x, and 0.40 Mtons of HC for aircraft taxi mode. Take-off mode emitted about 0.07 Mtons for CO, 3.68 Mtons for NO_x, and 0.04 Mtons for HC annually. For landing mode, the annual emissions were 0.19 Mtons for CO, 0.05 Mtons for NO_x, and 0.03 Mtons for HC, respectively. The annual emissions during initial-climb mode were 0.03 Mtons for CO, 1.46 Mtons for NO_x, and 0.01 Mtons for HC. The emissions in climb-out mode were 0.04 Mtons for CO, 1.35 Mtons for NO_x, and 0.01 Mtons for HC. The emissions in approach mode accounted about 0.46 Mtons for CO, 0.92 Mtons for NO_x, and 0.08 Mtons for HC, respectively. The annual emissions during cruise mode were about 1.03 Mtons for CO, 2.80 Mtons for NO_x, and 0.65 Mtons for HC.

The emissions were different in each aircraft modes. When considers the emissions of international airport, high emission of CO occurred during taxi, approach, and cruise modes. The highest quantity of CO was found in taxi mode due to incomplete combustion (Jacobson, 2012). High quantity of NO_x was found during take-off, initial-climb, climb-out, approach, and cruise. High amount of NO_x is the result of the high temperature combustion over 1,300 Celsius (US.EPA., 1999). The highest emission of NO_x occurred during take-off mode while the highest quantity of HC occurred in the taxi mode. Resitoglu et al. (2014) reported that HC was high during taxi mode.

The annual emissions were low during climb-out, approach, and cruise because some flight tracking was outside of Thailand's land boundary. The annual emissions of the airports located next to the coastline were not included the emission over the sea. Only the flight tracks that got back over land were included in the estimation.

The highest emissions in international airports occurred at Suvarnabhumi airport. The highest emission of CO was 2233.20 ktons, 6224.27 ktons for NO_x, and 814.40 ktons for HC. The highest CO and HC occurred in taxi mode at Suvarnabhumi airport. The highest emissions of CO and HC were 1123.72 and 187.83 ktons, respectively. The highest amount of NO_x occurred during take-off mode at

Suvarnabhumi airport similar to CO and HC. The emission of NO_x was 2200.23 ktons.

When the emissions were calculated per flight to normalize the number of flights found at large airport, the highest rates of CO and NO_x occurred at Suvarnabhumi airport, 4.69 and 15.82 tons per flight, respectively. The highest emission rate of NO_x had the influence by the emission factor of B747 during take-off mode, this emission factor was the highest value during take-off. The B747 airplane was used to fly in and from Suvarnabhumi airport only. The highest emission rate of HC was 0.79 tons per flight, Suvarnabhumi and Don Mueang airports had the highest emission rate of HC.

4.3.2 Annual emissions during the cruise mode

The annual emissions from the commercial aircraft during the cruise mode for both domestic and international flights were showed in the Table 4.7.

Table 4.7 The annual emissions during the cruise mode

Airports	**Annual emissions (ktons)**		
	CO	**NO_x**	**HC**
Domestic airports			
KKC	3.27	29.33	0.47
CJM	0.01	0.18	0.00
TST	1.47	6.81	0.37
MAQ	0.05	1.58	0.00
KOP	1.03	7.26	0.20
NST	1.13	4.54	0.28

Table 4.7 The annual emissions during the cruise mode (Continued)

Airports	**Annual emissions (ktons)**		
	CO	**NO_x**	**HC**
Domestic airports			
NAW	0.07	0.85	<0.01
NNT	0.50	6.43	0.02
BFV	0.15	2.39	0.01
PHS	1.32	7.55	0.31
PRH	0.03	0.83	0.00
HGN	0.06	0.09	0.00
ROI	0.50	6.59	0.03
UNN	0.02	0.50	0.00
LOE	0.17	2.57	0.01
LPT	0.23	1.64	0.00
SNO	1.25	5.43	0.33
UTH	6.49	38.55	1.29
UBP	5.51	28.98	1.30
TDX	0.07	0.11	0.00
THS	0.14	0.21	0.00
Total (ktons)	**23.48**	**152.42**	**4.61**
International airports			
BKK	762.12	1262.43	566.63
DMK	121.51	586.06	40.75
CNX	46.01	206.86	20.76
CEI	13.90	125.42	1.94
HKT	58.36	436.13	11.37

Table 4.7 The annual emissions during the cruise mode (Continued)

Airports	Annual emissions (ktons)		
	CO	NO_x	HC
International airports			
HKT	58.36	436.13	11.37
HDY	5.09	26.02	1.22
KBV	7.47	60.01	1.03
URT	2.98	22.04	0.54
UTP	13.16	64.03	3.23
USM	1.72	11.94	0.12
Total (Mtons)	**1.03**	**2.80**	**0.65**

For domestic airports, the annual emissions during cruise mode were found in the range of 0.01 to 6.49 ktons for CO, 0.09 to 38.55 ktons for NO_x, and less than 0.01 (0.003 for Narathiwat airport) to 1.30 ktons for HC. The emissions at international airports were in the range of 1.72 to 762.12 ktons of CO, 11.94 to 1262.34 ktons of NO_x, and 0.12 to 566.63 ktons of HC, annually.

From the emission data in Table 4.7, the emission of HC was zero due to complete combustion following the emission factors for AT72 and DASH8 airplanes. Such cases occurred at small airports, where a few flights were scheduled each day, including Chumphon (CJM), Mae Sot (MAQ), Phrae (PRH), Mae Hong Son (HGN), Ranong (UNN), Lampang (LPT), Trat (TDX), and Sukhothai (THS) airports.

4.3.3 Annual emissions during flights

Annual emissions in this section were divided into 2 parts: domestic and international flight (Table 4.8).

The annual emissions of domestic flight from the commercial aircraft during taxi mode were 167.00 ktons of CO, 18.91 ktons of NO_x, and 38.11 ktons of HC, respectively. The annual emissions for take-off mode accounted about 7.13 ktons of CO, 145.91 ktons of NO_x, and 1.85 ktons of HC. The annual emissions of landing mode were 18.46, 2.08, and 4.21 ktons per year for CO, NO_x, and HC, respectively.

Table 4.8 The annual emissions of domestic and international flights

Flights		Modes (ktons)							Total (Mtons)
		Taxi	Take-off	Initial-climb	Climb-out	Approach	Landing	Cruise	
Domestic	CO	167.00	7.13	3.46	5.77	60.06	18.46	23.48	0.29
	NO_x	18.91	145.91	65.57	67.38	44.99	2.08	152.42	0.50
	HC	38.11	1.85	0.87	1.21	9.65	4.21	4.61	0.06
International	CO	2,254.84	68.22	26.59	41.63	463.35	192.57	1,032.30	4.08
	NO_x	416.77	3,680.54	1,460.44	1,353.51	915.84	47.39	2,800.94	10.68
	HC	399.70	41.65	6.43	7.61	81.83	32.01	647.59	1.22

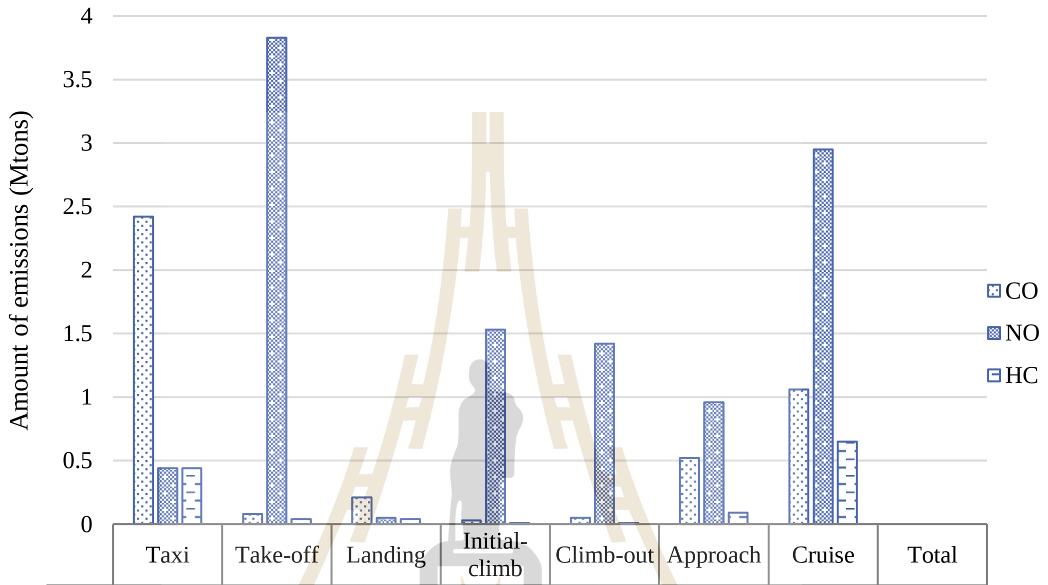
The annual emissions of initial-climb were 3.46 ktons of CO, 65.57 ktons of NO_x, and 0.87 ktons of HC. Climb-out mode accounted about were 5.77 ktons of CO, 67.38 ktons of NO_x, and 1.21 ktons of HC, annually. Aircraft approach mode emitted about 60.06 ktons of CO, 44.99 ktons of NO_x, and 9.65 ktons of HC, annually. Cruise mode released 23.48 ktons of CO, 152.42 ktons of NO_x, and 4.61 ktons of HC, annually. The total annual emissions through domestic flight were 0.29 Mtons of CO, 0.50 Mtons of NO_x, and 0.06 Mtons of HC.

The annual emissions from international flight during aircraft taxi mode were 2,254.48 ktons of CO, 416.77 ktons of NO_x, and 399.70 ktons of HC, respectively. Aircraft taking-off released 68.22 ktons of CO, 3,680.54 ktons of NO_x, and 41.65 ktons of HC, annually. Aircraft landing mode emitted about 192.57 ktons of CO, 47.39 ktons of NO_x, and 32.01 ktons of HC, annually. Initial-climb mode accounted about 26.59 ktons of CO, 1,460.44 ktons of NO_x, and 6.43 ktons of HC, respectively. The annual emissions for climb-out mode accounted about 41.63 ktons of CO, 1,353.51 ktons of NO_x, and 7.61 ktons of HC. The annual emissions during aircraft approach were about 463.35 ktons of CO, 915.84 ktons of NO_x, and 81.83 ktons of HC.

The annual emissions during cruise mode were 1,032.30 ktons of CO, 2,800.94 ktons of NO_x, and 647.59 ktons of HC. The total annual emissions of international flight were 4.08 Mtons of CO, 10.68 Mtons of NO_x, and 1.22 Mtons of HC.

4.3.4 Total annual emissions

Total annual emissions were the combination of domestic and international emission data. The emissions from the commercial aircrafts in Thailand's land territory based on the year 2015 was showed in Fig. 4.8.



	Taxi	Take-off	Landing	Initial-climb	Climb-out	Approach	Cruise	Total
CO	2.42	0.08	0.21	0.03	0.05	0.52	1.06	4.36
NO	0.44	3.83	0.05	1.53	1.42	0.96	2.95	11.17
HC	0.44	0.04	0.04	0.01	0.01	0.09	0.65	1.28

Fig. 4.8 Total annual emissions from aviation activities in airports of Thailand

The annual emissions from the commercial aircraft for different modes of the flying cycle are discussed separately.

Aircraft Taxi Mode

Emissions from the commercial aircraft during taxi mode were estimated from the aircraft activities on the ground. This mode accounted for the move out of the boarding gate at terminal building, the move from runway to the terminal building as well as parking idle at the terminal.

The total annual emissions from the commercial aircraft during aircraft taxi mode accounted about 2.42 Mtons for CO, 0.44 Mtons for NO_x, and 0.44 Mtons for HC. CO had the highest emission in this mode. High emission of CO in taxi mode was the result of incomplete combustion from the idle status that affected the air loading in the aircraft's engine, the condition of low oxygen and low pressure (Sutkus, Baughcum, and DuBois, 2001; Masiol and Harrison, 2014).

Take-off

In take-off mode, the emissions of the commercial aircraft were calculated when the aircraft accelerated into the air, only for the departure flight. The amount of CO during take-off mode was 0.08 Mtons, 3.83 Mtons for NO_x, and 0.04 Mtons for HC annually. In take-off mode, the quantity of NO_x was the highest caused by the combustion conditions in the aircraft's engine with excess air and high temperature within the engine's chamber (Masiol and Harrison, 2014).

Landing

The emissions from this mode occur with the arrival flight coming to the runway. This mode represents the activities of the aircraft arriving on the runway prior to taxi to the terminal.

The annual emission was 0.21 Mtons of CO, 0.05 Mtons of NO_x, and 0.04 Mtons of HC, respectively. CO was the highest emissions in this mode, similar to emissions during taxi mode due to incomplete combustion from the speed reduction.

It is important to note that taxi, take-off, and landing are modes in the LTO cycle that occur at the ground level. The emissions from these modes were usually found in high quantities. Emissions of CO and NO_x were obvious during taxi and take-off modes.

Initial-climb and climb-out

The emissions of initial-climb and climb-out modes were estimated while the aircrafts were above ground level. The initial-climb accounted for the altitude less than 450 meters. Continuous climb at altitude between 450 and 1,000 meters was considered as the climb-out mode.

The annual emissions during initial-climb accounted about 0.03 Mtons for CO, 1.53 Mtons for NO_x, and 0.01 Mtons for HC, while the annual emissions during climb-out mode were 0.05, 1.42 and 0.01 Mtons for CO, NO_x, and HC, respectively. Emissions of NO_x were the highest in these modes. The aircraft engine demands more power to lift itself from the ground. As a result, the excess air in high temperature combustion conditions emits NO_x.

Approach

The emissions from the approach mode accounted when the aircrafts fly at the altitude below 1,000 meters, changing from cruise mode and prior to the landing mode.

The annual emissions during approach mode were 0.52 Mtons for CO, 0.96 Mtons for NO_x, and 0.09 Mtons for HC, respectively. NO_x emissions were the highest in this mode. The aircrafts' engines need power to control the route during landing preparation.

Cruise

The cruise mode occurs when an aircraft was operated at the altitude over 1,000 meters. The annual emissions were about 1.06 Mtons of CO, 2.96 Mtons of NO_x, and 0.65 Mtons of HC. Normally, the emissions during cruise mode was less than LTO cycle due to relatively constant combustion. However, the emissions from cruise mode depend on the traveling distances.

Although the emissions from cruise mode were high for all parameters, but the emissions at the altitude above 1,000 meters are not directly influence the emissions under 1,000 meters layer and at ground level (Wayson and Fleming, 2000).

Overall, the total annual emissions from the commercial aircraft in Thailand's land territory during taxi mode was 2.42 Mtons for CO, 0.44 Mtons for NO_x, and 0.44 Mtons for HC. CO in take-off mode was 0.08 Mtons, 3.83 Mtons for NO_x, and 0.04 Mtons for HC. For landing mode, the annual emission was 0.21 Mtons of CO, 0.05 Mtons of NO_x, and 0.04 Mtons of HC, respectively. The emissions during the initial-climb were about 0.03 Mtons for CO, 1.53 Mtons for NO_x, and 0.01 Mtons for HC. In climb-out mode, the annual emissions were 0.05, 1.42, and 0.01 Mtons for CO, NO_x, and HC, respectively. The annual emissions during approach mode were 0.52 Mtons for CO, 0.96 Mtons for NO_x, and 0.09 Mtons for HC. In cruise mode, the annual emissions were 1.06 Mtons of CO, 2.96 Mtons of NO_x, and 0.65 Mtons of HC. The highest quantities of CO and NO_x occurred during taxi and take-off modes due to incomplete combustion. The excess air and high temperature combustion conditions emitted high NO_x.

The total emissions from commercial aircraft activities based on the year 2015 were about 4.36 Mtons of CO, 11.17 Mtons of NO_x, and 1.28 Mtons of HC. The emissions of NO_x were higher than CO and HC, resulting from high amount of NO_x during take-off, initial-climb, climb-out, approach, and cruise modes.

4.4 Spatial emissions

The spatial emissions were created based on the annual emission data, route map of the commercial aircraft movement data, and the satellite image through the function in a GIS program. The annual emission data based on the year 2015. The spatial emission map revealed the distribution of CO, NO_x, and HC in various modes of the flying cycle. The spatial emissions were computed based on the cell size of 0.5 kilometer for LTO mode, while the cruise mode was interpolated based on the cell size of 1 kilometer.

Suvarnabhumi airport

With dual parallel runways, most aircrafts usually operate on the east runway resulting in high emissions in the area. High spatial emissions of CO and HC were in the range of 1,100 to 1,380 and 324 to 405 tons, respectively. The spatial emissions during taxi mode were at the end of the east runway in the north direction and the area near the terminals. High spatial emission of NO_x was 6,001 to 7,500 tons, occurred during take-off mode at the center of the areas.

Don Mueang airport

The spatial emissions of CO and HC were 801 to 1,000 and 201 to 250 tons, respectively. High emissions appeared at the end of the east and west runways in the south direction. High emission of HC occurred at the center of east runway. Spatial emission of NO_x was in the range of 1,601 to 2,000 tons. High spatial emission of NO_x occurred at the center of the east runway.

The airports with a single runway tend to have the arrival and departure flights at both sides of the runway. The spatial emissions at each airport are discussed and grouped in Table 4.9 to avoid redundancy due to resemble patterns of these smaller airports.

Table 4.9 The spatial emissions at airports operating both sides of the runway

Airports	**The movement of commercial aircraft**
CNX	High spatial emissions of CO and HC were at both ends of the runway with the range of 800 to 1,000 and 141 to 170 tons for CO and HC, respectively. High spatial emission of NO_x ranged from 1,751 to 2,200 tons, occurred at the center of the runway.
CEI	The high spatial emissions of CO and HC were 601 to 750 and 181 to 225 tons, respectively. These emissions occurred at both sides of the end of the runway. High spatial emissions of NO_x were in the range of 1,101 to 1,375 tons. High spatial emission of NO_x was found at the center of the runway and some area at the aircraft parking stand.
KBV	High spatial emissions of CO and HC were in the range 641 to 800 and 161 to 200 tons, respectively. The highest emissions appeared at the end of the runway in the northwest direction. The spatial emission of NO_x occurred at the center of the runway in the range between 1,801 and 2,250 tons.

Table 4.9 The spatial emissions at airports operating both sides of the runway (Continued)

Airports	The movement of commercial aircraft
TST	Large quantities of CO and HC occurred at the end of the runway in the west direction with the highest emissions in the ranges 501 to 625 tons of CO and 141 to 175 tons of HC. The highest spatial emission of NO_x ranged from 1,201 to 1,500 tons, observed at the center of the runway.
PHS	The spatial emissions of CO, NO_x, and HC were in the ranges 801 to ,1000 tons of CO, 1,001 to 1,250 tons of NO_x, and 201 to 250 tons of HC. Large quantities of CO and HC occurred at the end of the run way. The spatial emission of NO_x was found at the center of the runway.
LOE	Highest spatial emissions of CO and HC were in the ranges of 601 to 750 tons for CO and 141 to 175 tons for HC. Large quantities were found at the end of the runway in the north direction. Large emission of NO_x was found at the center of the runway with the emission in the range between 1,001 and 1,250 tons.
UTH	The highest emissions of CO and HC were 681 to 850 tons of CO and 181 to 225 tons of HC. These emissions were observed at the end of the runway in the northwest direction. NO_x was found at the center of the runway with the highest emission in the range of 1,141 to 1,425 tons.
KKC	The spatial emissions of CO and HC had high quantities around 601 to 750 tons of CO and 141 to 175 tons of HC. Large quantities occurred at the end of the runway in the northeast direction. NO_x was in the range between 1,001 and 1,250 tons, around the center of the runway.
UBP	The spatial emissions of CO, NO_x, and HC were in the ranges of 601 to 750 tons for CO, 1,201 to 1,500 tons for NO_x, and 181 to 225 tons for HC. Large quantities of CO and HC appeared at the end of the runway. NO_x occurred at the center of the runway.

The airports where the movement of the commercial aircrafts occurred only one direction are Mae Sot, Nakhon Phanom, Nan Nakhon, Buriram, Phrae, Mae Hong Son, Roi Et, Ranong, Lampang, Sakon Nakhon, and Sukhothai airports. The spatial emissions at each airport are collectively discussed in Table 4.10.

Table 4.10 The spatial emissions at airports operating one side of the runway

Airports	The movement of commercial aircraft
MAQ	Large emissions of CO and HC occurred at the end of the runway in the west direction, about 401 to 500 and 101 to 125 tons of CO and HC, respectively. The highest spatial emission of NO_x was in the range 61 to 75 tons, observed at center of the runway on the east.
KOP	Highest spatial emissions were 701 to 875 tons for CO, 801 to 1,000 tons for NO_x, and 181 to 225 tons for HC. The spatial emission of CO occurred at the end of the runway on the northwest, similar to the spatial emission of HC. NO_x was high at the center of the runway.
NNT	The highest spatial emissions were 501 to 625 tons for CO, 501 to 625 tons for NO_x, and 121 to 150 tons for HC. Large spatial emissions of CO and HC occurred at the center of the runway in the north direction. NO_x was observed at the center of the runway.
BFV	The spatial emissions of CO and HC were 601 to 750 and 141 to 175 tons, respectively. The emissions occurred at the end of the runway in the northeast direction. The highest spatial emission of NO_x was in the range 401 to 500 tons, high at the center of the runway.
PRH	Highest spatial emissions of CO and HC were 401 to 500 tons and 101 to 125 tons, respectively. These emissions occurred at large quantities at the end of the runway in the north direction. High spatial emission of NO_x occurred at the center of the runway near the south direction, with the emission in the range of 61 to 75 tons.

Table 4.10 The spatial emissions at airports operating one side of the runway (Continued)

Airports	**The movement of commercial aircraft**
HGN	The spatial emissions of CO, NO_x, and HC were 601 to 750, 61 to 75, and 141 to 175 tons, respectively. High spatial emissions of CO and HC occurred at the end of the runway in the west direction. NO_x was high at the center of the runway in the east direction.
ROI	High spatial emissions were 401 to 500 tons for CO, 1,001 to 1,250 tons for NO_x, and 121 to 150 tons for HC. CO and HC were high at the center and at the end of the runway in the north. NO_x was high quantity at the end of the runway in the south direction.
UNN	The spatial emissions were 601 to 750 tons of CO, 61 to 75 tons of NO_x, and 141 to 175 tons of HC. High spatial emissions of CO and HC occurred at the end of the runway on the south. NO_x was high at the center of the runway in the north.
LPT	High emissions of CO and HC were 601 to 750 and 201 to 250 tons, respectively. The spatial emissions occurred at the end of the runway in the north direction. High emission of NO_x occurred at the center of the runway in the south, with 61 to 75 tons of NO_x.
SNO	The spatial emissions were 601 to 750 tons of CO, 1,081 to 1,350 tons of NO_x, and 161 to 200 tons of HC. High emissions of CO and HC occurred at the area between the center and the end of the runway in the northeast direction. NO_x was found at the end of the runway in the southwest direction.
THS	The highest spatial emissions of CO and HC were 601 to 750 and 161 to 200 tons, respectively. These were found at the end of the runway on the north. High NO_x, was observed at the end of the runway in the south, with 41 to 50 tons of NO_x.

Overall, high emission of CO was founded at the end of the runway for all airports where the movement of the commercial aircraft occurred only one side of the runway. The spatial emission of HC was similar to CO, with high emissions at the end of the runway. High NO_x was founded at the center of the runway for 3 airports including Nakhon Phanom, Nan Nakhon, and Buriram. At other airports, namely Mae Sot, Phrae, Mae Hong Son, Roi Et, Ranong, Lampang, Sakon Nakhon, and Sukhothai, high emission was founded at the end of the runway, opposite to the spatial emissions of CO and HC.

The airports that located near the coast, Phuket, Hat Yai, Chumphon, Nakhon Si Thammarat, Narathiwat, Surat Thani, Trat, U-Tapao, and Samui airports, had some emissions cutoff after the interpolation. Some modes in flying cycle were not accounted for the spatial emission. The spatial emissions at each airport are discussed in Table 4.11.

Table 4.11 The spatial emissions at airports near the coast

Airports	The movement of commercial aircraft
HKT	The emissions of CO and HC were the highest at around 501 to 625 tons of CO and 101 to 125 tons of HC at the end of the runway in the east direction. High NO_x was appeared at the center of the runway, with 1,251 to 1,575 tons of NO_x.
HDY	The emissions of CO and HC were 541 to 675 and 141 to 175 tons, respectively. High emissions occurred at the end of the runways. High NO_x occurred at the center of the runway with highest emission of 791 to 985 tons.

Table 4.11 The spatial emissions at airports near the coast (Continued)

Airports	The movement of commercial aircraft
CJM	The high emissions of CO and HC were found on both sides at the end of the runway, 581 to 725 tons of CO and 141 to 175 tons of HC. NO_x emission was in the range of 41 to 50 tons, high emission at the center of the runway.
NST	High emissions of CO and HC occurred on both side at the end of the runway, 501 to 625 tons of CO and 141 to 175 tons of HC. NO_x was in the range of 1,201 to 1,500 tons, the high at the center of the runway.
NAW	Highest emissions were 281 to 350 tons for CO and 21 to 25 tons for HC. High emissions of CO and HC occurred at the end of the runway in the southwest direction. High NO_x was found at the center of the runway with the emission of 1,201 to 1,500 tons of NO_x.
URT	The emissions were 601 to 750 tons of CO, 1,001 to 1,250 tons of NO_x, and 181 to 225 tons of HC. High emissions of CO and HC were found at the end of the runway on both sides. High NO_x occurred at the center of the runway in the northeast direction.
TDX	The emissions were 501 to 625 tons of CO, 61 to 75 tons of NO_x, and 121 to 150 tons of HC. CO was high at the end of the runway in the northeast direction similar to HC. High NO_x was observed at end of the runway in the southwest direction.
UTP	The emissions were 801 to 1,000 tons of CO, 1,201 to 1,500 tons of NO_x, and 201 to 250 tons of HC. The emissions of CO and HC were found at the end of the runway on both sides. High NO_x was observed at the center of the runway.
USM	High emission of CO was in the range 401 to 500 tons at the end of the runway on both sides in the north direction, as well as HC. The emissions of HC were 101 to 125 tons. High NO_x was 1,001 to 1,250 tons at the center of the runway.

The overall patterns found that the highest emission of CO was frequently found at the end of the runways on one or both sides. The spatial emissions of HC were similar to CO. The high spatial emissions of CO and HC during flying cycle was the result of incomplete combustion of the aircraft's engines, usually during the aircraft taxi mode. The highest spatial emission of NO_x was usually observed at the center of the runways when the aircrafts use high thrust. However, the high bound of NO_x also occurred at the area from the center to the end of the runways in some airports. In the flying cycle, large amount of NO_x was emitted during take-off mode.

Estimated spatial emissions during LTO cycle at all airports showed the affected areas based on the inverse distant weighting algorithm in the GIS program without the data on meteorology. Real measurement would help to confirm the emission distributions.

In addition, cruise mode occurs at the altitude more than 1,000 meters. The spatial emissions form the commercial aircrafts during cruise mode in Thailand's land territory were interpolated with the cell size 1×1 kilometer through the function in GIS program (Fig. 4.9).

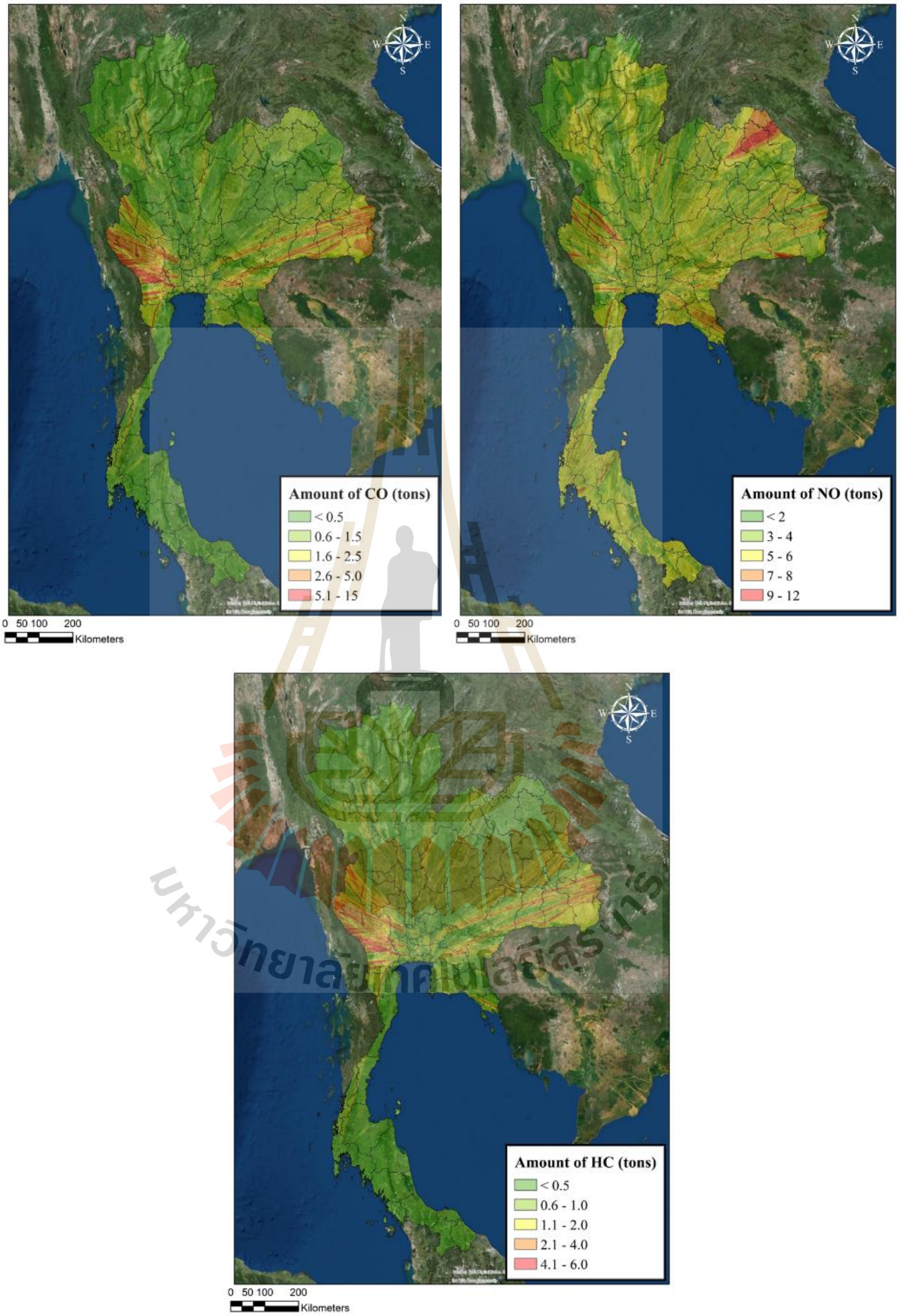


Fig. 4.9 The spatial emissions during cruise mode

Regional emissions during cruise mode showed that high emissions of CO and HC occurred in the lower area of the northeastern and the western of Thailand due to flight routes. The highest spatial emissions of CO and HC were in the ranges of 5.1 to 15 and 4.1 to 6.0 tons, respectively. The spatial emission of NO_x was in the range 9 to 12 tons. High emissions occurred across the upper area of the northeastern and the western of Thailand.

It is important to note that the spatial emissions during cruise mode occurred at the altitude above 1,000 meters, the quantities of emitted pollutants at the altitude are not the effect on the amount of pollutants at the ground level.

4.5 Uncertainty

In this study, there were two parts of uncertainty, calculation of annual emissions and computing of spatial emissions. Descriptive uncertainty is discussed in this section.

4.5.1 Annual emissions

The annual emissions were estimated with the available emission factors. In this study, there are the emission factors for various aircraft's engine types but the emission factor for the aircraft's engine types of A350, A380, and B787 were unavailable. Therefore, the calculated emissions were less than usual due to the lack of specificity emission factors for these aircrafts. However, the number of flights of these aircrafts' engine were small.

4.5.2 Spatial emissions

The spatial emissions were created using a function in GIS program. The function used input data (emission data and satellite image) to interpolate the spatial emissions. The function processing based on mathematics algorithm. As a result, the obtain spatial emissions were computed without meteorological data. Thus, the spatial emissions were illustrated as the distribution of pollutants as points in grids.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The afford on a year-long flight data tracking and analysis of the commercial aircraft emissions have shown that actual data along with the emission factors could be a proven estimated methods to provide a clear picture of the emissions from commercial aircraft operations in an emission inventory study.

5.1 Emissions estimates using aircraft tracking techniques

The techniques used in this study could help establishing the emission data from the commercial aircrafts on a country basis. The techniques require flight data, vital for tracking the aircraft movement along the routes or certain regions that can be retrieved from the official and unofficial websites of the airport operators or aviation services. Information on flight tracking provide additional coordinates and altitude data to determine the state of flying cycle. These procedures are, however, time consuming and require continuous monitoring on flight tracking. If calculation of emissions for each flying cycle are crucial, these techniques can deliver the reasonable estimates. Annual emission estimates can be simplified if routine flight schedules were observed at certain airports or areas. Spatial distributions over the areas require coordinate data of the aircrafts.

The coordinate data of the commercial aircraft movement are used for route creation, to create trajectory of the commercial aircrafts along flights over the entire periods. Route maps were created to visualize the distribution of the emissions from different modes.

5.2 Annual emissions of commercial aircraft

The annual emissions from the commercial aircrafts in Thailand accounted about 4.36 Mtons of CO, 11.17 Mtons of NO_x, and 1.28 Mtons of HC in 2015. The highest emissions of CO and HC were in taxi mode, while the highest emission of NO_x occurred in take-off mode. The emissions in each mode during the flying cycle are summarized in Figure 5.1.

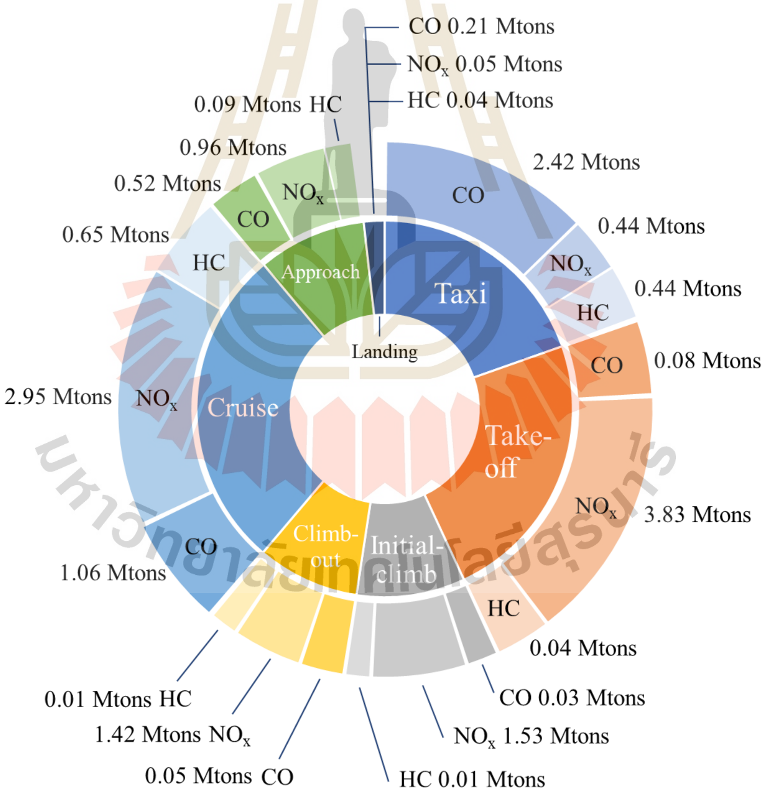


Fig. 5.1 Proportion of the annual emissions during flying cycle

Taxi: Total annual emissions were 2.42 Mtons of CO, 0.44 Mtons of NO_x, and 0.44 Mtons of HC.

Take-off: Annual emissions occurring in this mode about 0.08 Mtons for CO, 3.83

Mtons for NO_x, and 0.04 Mtons for HC.

Initial-climb: The annual emissions of CO, NO_x, and HC during initial-clime were 0.03, 1.53, and 0.01 Mtons, respectively.

Climb-out: Total emissions of CO was 0.05 Mtons, 1.42 Mtons of NO_x, and 0.01 Mtons of HC, annually.

Cruise: The annual emissions through cruise mode were accounted 1.06, 2.95, and 0.65 Mtons for CO, NO_x, and HC, respectively.

Approach: Total emissions during approach were 0.52 Mtons of CO, 0.96 Mtons of NO_x, and 0.09 Mtons of HC, annually.

Landing: Total emissions of CO, NO_x, and HC were accounted based on aircraft landing were 0.21, 0.05, and 0.04 Mtons per year, respectively.

The emission rates were in the range 1.06 – 4.69 tons per flight of CO, 0.17 – 15.82 tons per flight of NO_x, and 0.09 – 0.84 tons per flight of HC.

The comparison of the annual emissions between domestic and international flights showed that the annual emissions of international flights were more than domestic flights due to the high number of international flights as showed in the Figure 5.2. The annual emissions from international flight accounted about 95 percent when compared to domestic flight.

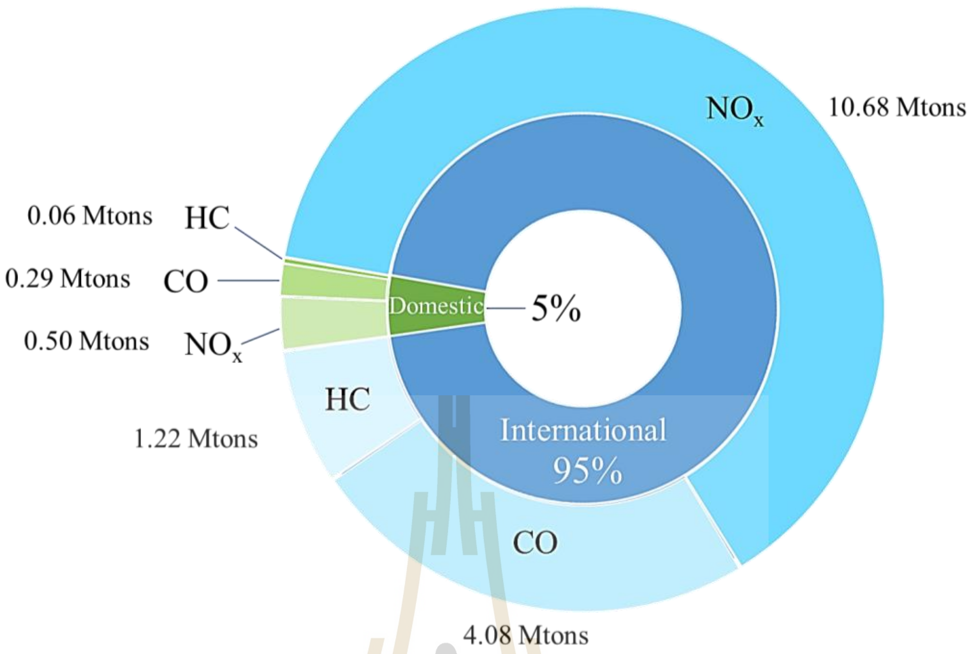


Fig. 5.2 Proportion of the annual emissions between domestic and international flights

Suvarnabhumi airport had the highest emissions, accounted about 44 percent of CO, 60 percent of NO_x, and 40 percent of HC overall (Figure 5.3). The emissions from other airports were much less, except Don Mueang airport having the second largest emissions.

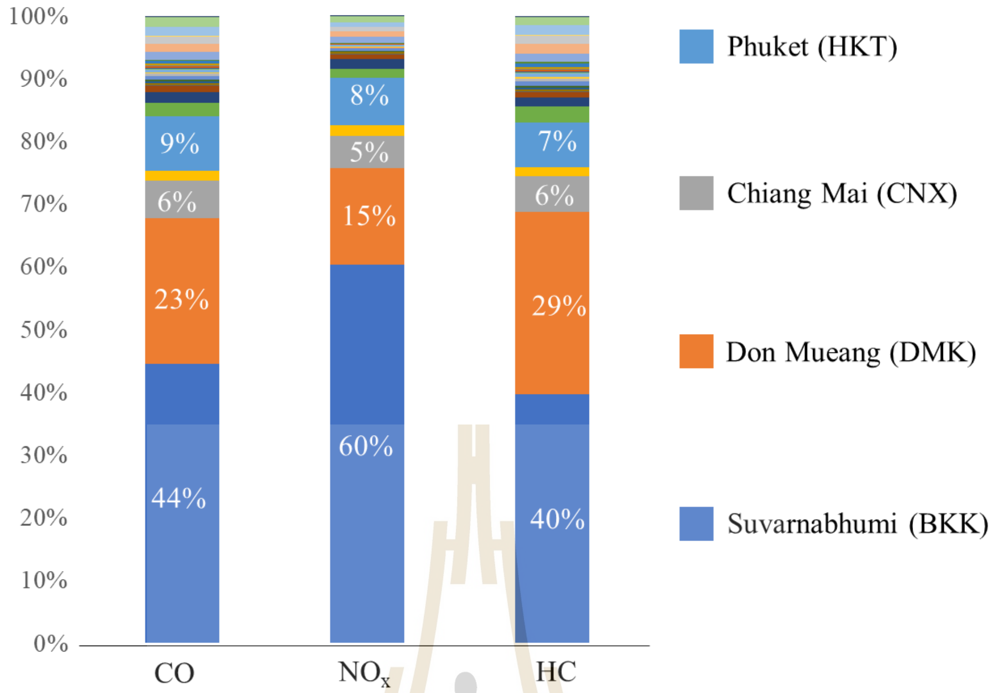


Fig. 5.3 Percentage of the high annual emissions

5.3 Spatial emissions of commercial aircraft

The spatial emissions from data interpolation showed that Suvarnabhumi and Don Mueang airport had high CO and HC emissions at the end of both runways, while high NO_x emission occurred at the center of both runways. Other single runway airports that operated on both directions of the runway had high CO and HC emissions at both sides of the end of the runway, Chiang Mai, Mae Fah Laung Chiang Rai, Phitsanulok, and Ubon Ratchathani airports. The highest spatial emissions of CO and HC at Krabi, Trang, Loei, Udon Thani, and Khon Kaen airports occurred on one side at the end of the runway, while NO_x emission was found at the center of the runway and the area between the center and the end of the runway.

The single runway airports that operated only one direction of the runway had high emissions of CO and HC at the end of the runway, while the highest spatial emission of

NO_x was found at the center of the runway for Nakhon Phanom, Nan Nakhon, and Buriram airports. Only Mae Sot, Phrae, Mae Hong Son, Roi Et, Ranong, Lampang, Sakon Nakhon, and Sukhothai airports showed high emission of NO_x at the end of the runway.

The single runway airports located near the coast, including Phuket, Hat Yai, Chumphon, Nakhon Si Thammarat, Narathiwat, Surat Thani, Trat, U-Tapao, and Samui, had high CO and HC emissions at the end of the runway, while NO_x emission was observed at the center of the runway and the area between the center and the end of the runway. Some parts of flying mode especially initial-climb, climb-out, and approach were operated out of Thailand territory. Therefore, the emissions during these modes were not accounted.

The uncertainty for this study may occurred from emissions calculation, the annual emissions may under estimate due to lack of emission factor for some aircraft types. The spatial emissions were created using GIS program, the results were obtained from algorithm in the program without the meteorological date. The spatial maps showed ideal distribution may not similar to the actual situation.

5.4 Recommendations

The recommendations of this study include the emissions from the commercial aircraft for further study and the study on exposure to workers in the air-side area.

- The emissions from the commercial aircraft should extend to cover not only land territory but also marine territory to accurately account for the emissions of a country.

- Exposure assessment may help investigate potential health effect on workers in the area with high emissions. From the spatial emissions, the area of high emissions occurred near the parking and terminal building.

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APPENDICES

APPENDIX A

EMISSION FACTORS USED TO ESTIMATE THE EMISSIONS

Table A.1 Emission factors used to estimate the emissions during taxi mode

NO.	Type	N_s	Taxi - out, Hold and Taxi - in								
			$T_{a,m,s}$ (s)	$F_{a,s}$ (kg s^{-1})	$t_{a,m,s}$ (%)	$I_{a,p,s}$ (kg/kg fuel)			CO (kg)	NO_x (kg)	HC (kg)
						CO	NO_x	HC			
1	A320	2	256.49	0.1170	7	17.76	4.45	1.18	74.62	18.70	4.96
2	A330	2	338.11	0.2736	7	18.49	4.65	1.64	239.46	60.22	21.24
3	A340	4	338.11	0.1240	7	30.93	4.28	5.00	363.09	50.24	58.70
4	ATR42-320	2	331.13	0.0517	7	91.40	0.70	23.90	219.06	1.68	57.28
5	ATR72-200	2	320.09	0.0517	7	91.40	0.70	23.90	211.76	1.62	55.37
6	B737 100	2	256.49	0.1445	7	27.91	3.04	8.39	144.82	15.77	43.53
7	B747 100-300	4	338.11	0.2320	7	68.60	3.20	25.90	1506.70	70.28	568.86
8	B757	4	270.48	0.1851	7	19.93	4.14	0.60	279.39	58.04	8.41
9	B767 300 ER	2	273.37	0.2141	7	22.06	4.42	2.61	180.76	36.22	21.39
10	B777	2	273.37	0.2750	7	15.78	5.18	1.33	166.08	54.52	14.00
11	Beech Super King Air 350	2	335.53	0.0185	7	115.30	1.97	101.63	100.20	1.71	88.32
12	Dash 8 Q400	2	320.09	0.0517	7	91.40	0.70	23.90	211.76	1.62	55.37

Table A.2 Emission factors used to estimate the emissions during take-off mode

NO.	Type	N_s	Take-off								
			$T_{a,m,s}$ (s)	$F_{a,s}$ (kg s^{-1})	$t_{a,m,s}$ (%)	$I_{a,p,s}$ (kg/kg fuel)			CO (kg)	NO_x (kg)	HC (kg)
						CO	NO_x	HC			
1	A320	2	72.23	1.0758	100	0.79	25.25	0.12	122.77	3924.10	18.65
2	A330	2	100	3.1606	100	0.25	35.18	0.00	158.03	22237.98	0.00
3	A340	4	100	1.4560	100	1.00	37.67	0.01	582.40	21939.01	5.82
4	ATR42-320	2	100	0.1780	100	3.20	5.60	1.00	113.92	199.36	35.60
5	ATR72-200	2	100	0.1780	100	3.20	5.60	1.00	113.92	199.36	35.60
6	B737 100	2	100	1.1619	100	0.82	18.85	0.25	190.55	4380.36	58.10
7	B747 100-300	4	100	2.1610	100	0.90	41.70	0.00	777.96	36045.48	0.00
8	B757	4	100	1.8340	100	0.38	25.48	0.09	278.77	18692.13	66.02
9	B767 300 ER	2	93.42	2.5960	100	0.29	33.66	0.08	140.66	16326.33	38.80
10	B777	2	100	3.3871	100	0.15	46.76	0.06	101.61	31676.16	40.65
11	Beech Super King Air 350	2	100	0.0643	100	5.10	7.98	1.75	65.59	102.62	22.51
12	Dash 8 Q400	2	100	0.1780	100	3.20	5.60	1.00	113.92	199.36	35.60

Table A.3 Emission factors used to estimate the emissions during initial-climb mode

NO.	Type	N_s	Initial-climb								
			$T_{a,m,s}$ (s)	$F_{a,s}$ (kg s^{-1})	$t_{a,m,s}$ (%)	$I_{a,p,s}$ (kg/kg fuel)			CO (kg)	NO_x (kg)	HC (kg)
						CO	NO_x	HC			
1	A320	2	37.15	1.0758	100	0.79	25.25	0.12	63.15	2018.28	9.59
2	A330	2	41.65	3.1606	100	0.25	35.18	0.00	65.82	9262.12	0.00
3	A340	4	41.65	1.4560	100	1.00	37.67	0.01	242.57	9137.60	2.43
4	ATR42-320	2	90.00	0.1780	100	3.20	5.60	1.00	102.53	179.42	32.04
5	ATR72-200	2	90.00	0.1780	100	3.20	5.60	1.00	102.53	179.42	32.04
6	B737 100	2	37.78	1.1619	100	0.82	18.85	0.25	71.99	1654.90	21.95
7	B747 100-300	4	57.01	2.1610	100	0.90	41.70	0.00	443.51	20549.53	0.00
8	B757	4	33.02	1.8340	100	0.38	25.48	0.09	92.05	6172.14	21.80
9	B767 300 ER	2	41.65	2.5960	100	0.29	33.66	0.08	62.71	7278.87	17.30
10	B777	2	44.23	3.3871	100	0.15	46.76	0.06	44.94	14010.37	17.98
11	Beech Super King Air 350	2	90.00	0.0643	100	5.10	7.98	1.75	59.03	92.36	20.25
12	Dash 8 Q400	2	50.00	0.1780	100	3.20	5.60	1.00	56.96	99.68	17.80

Table A.4 Emission factors used to estimate the emissions during climb-out mode

NO.	Type	N_s	Climb-out								
			$T_{a,m,s}$ (s)	$F_{a,s}$ (kg s^{-1})	$t_{a,m,s}$ (%)	$I_{a,p,s}$ (kg/kg fuel)			CO (kg)	NO_x (kg)	HC (kg)
						CO	NO_x	HC			
1	A320	2	56.27	0.8920	85	1.20	20.72	0.12	102.39	1767.99	10.24
2	A330	2	57.70	2.5524	85	0.22	27.19	0.00	55.08	6807.42	0.00
3	A340	4	57.70	1.1950	85	0.85	29.05	0.01	199.27	6810.34	2.34
4	ATR42-320	2	120.00	0.1570	85	3.50	4.50	1.10	112.10	144.13	35.23
5	ATR72-200	2	120.00	0.1570	85	3.50	4.50	1.10	112.10	144.13	35.23
6	B737 100	2	69.20	0.9318	85	1.06	14.67	0.27	116.19	1608.08	29.60
7	B747 100-300	4	77.62	1.7790	85	0.90	31.50	0.00	422.54	14789.01	0.00
8	B757	4	48.48	1.4902	85	0.29	19.62	0.04	71.23	4819.31	9.83
9	B767 300 ER	2	57.70	2.0807	85	0.31	25.37	0.08	63.27	5177.91	16.33
10	B777	2	68.66	2.7108	85	0.14	35.54	0.05	44.30	11245.21	15.82
11	Beech Super King Air 350	2	120.00	0.0596	85	6.50	7.57	2.03	79.03	92.04	24.68
12	Dash 8 Q400	2	80.00	0.1570	85	3.50	4.50	1.10	74.73	96.08	23.49

Table A.5 Emission factors used to estimate the emissions during approach mode

NO.	Type	N_s	Approach								
			$T_{a,m,s}$ (s)	$F_{a,s}$ (kg s^{-1})	$t_{a,m,s}$ (%)	$I_{a,p,s}$ (kg/kg fuel)			CO (kg)	NO_x (kg)	HC (kg)
						CO	NO_x	HC			
1	A320	2	286.00	0.3126	30	6.90	8.54	1.40	370.13	458.10	75.10
2	A330	2	286.00	0.8440	30	0.98	10.76	0.02	141.93	1558.38	2.90
3	A340	4	286.00	0.3860	30	1.40	10.67	0.06	185.47	1413.51	7.95
4	ATR42-320	2	312.00	0.0814	30	33.30	0.90	3.00	507.43	13.71	45.71
5	ATR72-200	2	286.00	0.0814	30	33.30	0.90	3.00	465.14	12.57	41.90
6	B737 100	2	286.00	0.3325	30	7.42	6.14	1.32	423.36	350.33	75.32
7	B747 100-300	4	286.00	0.6240	30	5.80	9.10	0.60	1242.11	1948.83	128.49
8	B757	4	286.00	0.5248	30	2.10	7.85	0.15	378.23	1413.87	27.02
9	B767 300 ER	2	286.00	0.6805	30	1.78	12.37	0.15	207.86	1444.49	17.52
10	B777	2	286.00	0.8852	30	0.83	13.91	0.10	126.08	2112.93	15.19
11	Beech Super King Air 350	2	312.00	0.0344	30	6.50	7.57	2.03	41.86	48.75	13.07
12	Dash 8 Q400	2	286.00	0.0814	30	33.30	0.90	3.00	465.14	12.57	41.90

Table A.6 Emission factors used to estimate the emissions during landing mode

NO.	Type	N_s	Landing								
			$T_{a,m,s}$ (s)	$F_{a,s}$ (kg s^{-1})	$t_{a,m,s}$ (%)	$I_{a,p,s}$ (kg/kg fuel)			CO (kg)	NO_x (kg)	HC (kg)
						CO	NO_x	HC			
1	A320	2	59.14	0.1170	7	17.76	4.45	1.18	17.20	4.31	1.14
2	A330	2	70.38	0.2736	7	18.49	4.65	1.64	49.85	12.54	4.42
3	A340	4	70.38	0.1240	7	30.93	4.28	5.00	75.58	10.46	12.22
4	ATR42-320	2	56.12	0.0517	7	91.40	0.70	23.90	37.13	0.28	9.71
5	ATR72-200	2	56.89	0.0517	7	91.40	0.70	23.90	37.64	0.29	9.84
6	B737 100	2	59.14	0.1445	7	27.91	3.04	8.39	33.39	3.64	10.04
7	B747 100-300	4	68.81	0.2320	7	68.60	3.20	25.90	306.63	14.30	115.77
8	B757	4	65.84	0.1851	7	19.93	4.14	0.60	68.01	14.13	2.05
9	B767 300 ER	2	68.81	0.2141	7	22.06	4.42	2.61	45.50	9.12	5.38
10	B777	2	70.38	0.2750	7	15.78	5.18	1.33	42.76	14.04	3.60
11	Beech Super King Air 350	2	56.07	0.0185	7	115.30	1.97	101.63	16.74	0.29	14.76
12	Dash 8 Q400	2	56.89	0.0517	7	91.40	0.70	23.90	37.64	0.29	9.84

Table A.7 Emission factors used to estimate the emissions during cruise mode

NO.	Type	N_s	Cruise									
			$m_{g,p}$ (kg/km)			d (km)	$c_{g,p}$ (kg)			CO (kg/km)	NO_x (kg/km)	HC (kg/km)
			CO	NO_x	HC		CO	NO_x	HC			
1	A320	2	1.86E-03	3.17E-02	4.58E-04	1	9.99E-01	1.25E+01	5.60E-02	1.00	12.53	0.06
2	A330	2	8.07E-03	8.00E-02	6.09E-03	1	3.81E+00	2.98E+01	6.52E-01	3.82	29.88	0.66
3	A340	4	5.19E-03	1.20E-01	3.18E-03	1	1.67E+01	1.96E+01	1.75E+01	16.71	19.72	17.50
4	ATR42-320	2	7.70E-03	6.68E-03	0.00E+00	1	3.98E-01	3.65E-01	0.00E+00	0.41	0.37	0.00
5	ATR72-200	2	4.89E-03	8.68E-03	0.00E+00	1	3.02E-01	4.33E-01	0.00E+00	0.31	0.44	0.00
6	B737 100	2	2.89E-03	2.05E-02	1.47E-03	1	2.65E+00	6.33E+00	8.26E-01	2.65	6.35	0.83
7	B747 100-300	4	8.06E-03	2.20E-01	2.33E-03	1	1.41E+01	3.56E+01	6.07E+00	14.11	35.82	6.07
8	B757	4	4.71E-03	4.59E-02	3.54E-03	1	1.94E+00	2.47E+01	5.10E-01	1.94	24.75	0.51
9	B767 300 ER	2	5.38E-03	6.95E-02	2.76E-03	1	3.32E+00	7.77E-01	1.07E+00	3.33	0.85	1.07
10	B777	2	6.01E-03	1.20E-01	4.17E-03	1	1.83E+01	3.19E+00	1.60E+01	18.31	3.31	16.00
11	Beech Super King Air 350	2	1.90E-02	1.59E-03	2.13E-03	1	1.76E-01	8.04E-02	5.61E-02	0.20	0.08	0.06
12	Dash 8 Q400	2	7.55E-03	1.99E-02	0.00E+00	1	7.04E-02	2.46E+00	0.00E+00	0.08	2.48	0.00

APPENDIX B

PERCENTAGE OF AIRCRAFT TYPES

Table B.1 Percentage of aircraft types

Airports	Percentage of aircraft types										
	A310	A320	A330	A340	AT72	B737	B747	B757	B767	B777	DASH8
BKK	0.1	35.3	14.6	3.1	5.4	14.3	2.1	0.2	0.2	24.8	-
DMK	-	49.2	1.9	-	-	40.7	-	-	0.8	1.2	6.2
CNX	-	55.8	1.2	-	10.0	28.2	-	-	-	5.0	-
CEI	-	82.4	-	-	-	17.6	-	-	-	-	-
HKT	-	69.7	4.7	0.1	0.3	21.0	-	-	0.2	4.0	-
HDY	-	56.7	0	-	0	43.3	-	-	-	-	-
KBV	-	77.4	0	-	3.2	19.4	-	-	-	-	-
KKC	-	73.7	0	-	0-	15.8	-	-	-	-	10.5
CJM	-	-	-	-	-	-	-	-	-	-	100.0
TST	-	42.9	-	-	-	57.1	-	-	-	-	-
MAQ	-	-	-	-	-	-	-	-	-	-	100
KOP	-	50.0	-	-	-	25.0	-	-	-	-	25.0
NST	-	30.8	-	-	-	69.2	-	-	-	-	-
NAW	-	100.0	-	-	-	-	-	-	-	-	-
NNT	-	33.3	-	-	16.7	-	-	-	-	-	50.0
BFV	-	25.0	-	-	-	-	-	-	-	-	75.0

Table B.1 Percentage of aircraft types (Continued)

Airports	Percentage of aircraft types										
	A310	A320	A330	A340	AT72	B737	B747	B757	B767	B777	DASH8
PHS	-	33.3	-	-	-	33.3	-	-	-	-	33.3
PRH	-	-	-	-	-	-	-	-	-	-	100
HGN	-	-	-	-	100	-	-	-	-	-	-
ROI	-	60.0	-	-	-	-	-	-	-	-	40.0
UNN	-	-	-	-	-	-	-	-	-	-	100.0
LOE	-	33.3	-	-	-	-	-	-	-	-	66.7
LPT	-	-	-	-	50.0	-	-	-	-	-	50.0
SNO	-	25.0	-	-	-	50.0	-	-	-	-	25.0
URT	-	54.5	-	-	-	45.5	-	-	-	-	-
UTH	-	52.4	-	-	-	42.9	-	-	-	-	4.7
UBP	-	50.0	-	-	-	50.0	-	-	-	-	-
TDX	-	-	-	-	100.0	-	-	-	-	-	-
UTP	-	55.3	-	-	8.5	36.2	-	-	-	-	-
USM	-	82.6	-	-	13.0	4.3	-	-	-	-	-
THS	-	-	-	-	100.0	-	-	-	-	-	-
Total	> 0.1	50.7	5.8	1.0	4.1	25.0	0.6	0.1	0.3	8.9	3.6

APPENDIX C

EMISSION CALCULATIONS

Time in taxi mode used to estimate the emissions. These values were calculated using follow equation.

$$T_{a,m} = 0.1 \times R_a$$

Where:

$T_{a,m}$ is the time in mode m (Taxi-in or Taxi-out) at airport a (second)

a is the airport

m is the mode (Taxi-in or Taxi-out)

R_a is the length of the longest runway at airport a (m)

The time in taxi mode from calculation was shown in the Table C.1

Table C.1 Distance of runways using for calculation of time in taxi mode

NO.	Airports	Runway distance (m)	Time in mode (s)
1	Suvarnabhumi	4,000	400
2	Don Mueang	3,700	370
3	Chiang Mai	3,400	340
4	Mae Fah Luang Chiang Rai	3,000	300
5	Phuket	3,000	300
6	Hat Yai	3,150	315
7	Krabi	3,000	300
8	Khon Kaen	3,050	305
9	Chumphon	2,100	210
10	Trang	2,100	210
11	Mae Sot	1,500	150
12	Nakhon Phanom	2,500	250
13	Nakhon Si Thammarat	2,100	210
14	Narathiwat	2,500	250
15	Nan Nakhon	2,000	200
16	Buriram	2,100	210
17	Phitsanulok	3,000	300
18	Phrae	1,500	150
19	Mae Hong Son	2,000	200
20	Roi Et	2,100	210
21	Ranong	2,000	200
22	Loei	2,100	210
23	Lampang	1,975	198
24	Sakon Nakhon	2,600	260
25	Surat Thani	3,000	300
26	Udon Thani	3,050	305
27	Ubon Ratchathani	3,002	300
28	Trat	1,800	180
29	U-Tapao	3,505	350
30	Samui	2,100	210
31	Sukhothai	2,300	230

Time in taxi mode in Table C.1 were used to estimate the emissions from the commercial aircraft through the equation below

$$E_{LTO_{a,m,p,s}} = N_s \times T_{a,m,s} \times F_{a,s}\left(t_{a,m,s}\right) \times I_{a,p,s}\left(t_{a,m,s}\right)$$

Where:

$E_{LTOa,m,p,s}$	is the emissions in mode *m* of pollutant *p* for a specific aircraft type *s* at airport type *a* (kg)
a	is the aircraft type
m	is the mode
p	is the pollutant
s	is the specific aircraft type *s*
N_s	is the number of engines on aircraft type *s*
$T_{a,m,s}$	is the time in mode *m* for a specific aircraft type *s* at airport type *a* (second)
$F_{a,s}(t)$	is the weight average fuel flow for an engine on aircraft type *s* at airport type *a* for thrust *t* (kg s^{-1})
$I_{a,p,s}(t)$	is the weight average emission factor of pollutant *p* for an engine on aircraft type *s* at airport type *a* for thrust *t* (kg/kg fuel)
$t_{a,m,s}$	is the engine thrust setting during mode *m* for aircraft type *s* at airport type *a* (%)

Example of CO emission calculations of A320 engine at Suvarnabhumi airport

Taxi mode;

- Number of engines (N_s): 2
- Time in taxi mode ($T_{a, m, s}$): 210 s
- Default thrust setting ($t_{a, m, s}$): 7 %
- Weight average fuel flow ($F_{a, s}$): 0.1170 kg. s^{-1}
- Weight average emission factor ($I_{a, p, s}$): 17.76 kg. fuel kg^{-1}

$$E_{Taxi} = 2 \times 210 \text{ s} \times 0.1170 \text{ kg. s}^{-1}(0.07) \times 17.76 \text{ kg. fuel kg}^{-1}(0.07)$$

$$= 872.73 \text{ kg per flight}$$

Take-off mode;

- Number of engines (N_s): 2
- Time in taxi mode ($T_{a, m, s}$): 72.33 s
- Default thrust setting ($t_{a, m, s}$): 100 %
- Weight average fuel flow ($F_{a, s}$): 1.0758 kg. s^{-1}
- Weight average emission factor ($I_{a, p, s}$): 0.79 kg. fuel kg^{-1}

$$E_{Take\text{-}off} = 2 \times 72.33 \text{ s} \times 1.0758 \text{ kg. s}^{-1}(1) \times 0.79 \text{ kg. fuel kg}^{-1}(1)$$

$$= 122.77 \text{ kg per flight}$$

Initial-climb mode;

- Number of engines (N_s): 2
- Time in taxi mode ($T_{a, m, s}$): 37.15 s
- Default thrust setting ($t_{a, m, s}$): 100 %
- Weight average fuel flow ($F_{a, s}$): 1.0758 kg. s^{-1}
- Weight average emission factor ($I_{a, p, s}$): 0.79 kg. fuel kg^{-1}

$$E_{Initial\text{-}climb} = 2 \times 37.15 \text{ s} \times 1.0758 \text{ kg. s}^{-1}(1) \times 0.79 \text{ kg. fuel kg}^{-1}(1)$$

$$= 63.15 \text{ kg per flight}$$

Climb-out mode;

- Number of engines (N_s): 2
- Time in taxi mode ($T_{a, m, s}$): 56.27 s
- Default thrust setting ($t_{a, m, s}$): 85 %
- Weight average fuel flow ($F_{a, s}$): 0.8920 kg. s^{-1}
- Weight average emission factor ($I_{a, p, s}$): 1.20 kg. fuel kg^{-1}

$$E_{Climb\text{-}out} = 2 \times 56.27 \text{ s} \times 0.8920 \text{ kg. s}^{-1}(0.85) \times 1.20 \text{ kg. fuel kg}^{-1}(0.85)$$

$$= 120.46 \text{ kg per flight}$$

Approach mode;

- Number of engines (N_s): 2
- Time in taxi mode ($T_{a, m, s}$): 286.00 s
- Default thrust setting ($t_{a, m, s}$): 30 %
- Weight average fuel flow ($F_{a, s}$): 0.3126 kg. s^{-1}
- Weight average emission factor ($I_{a, p, s}$): 6.90 kg. fuel kg^{-1}

$E_{Approach}$ = 2 × 286.00 s × 0.3126 kg. s^{-1}(0.30) × 6.90 kg. fuel kg^{-1}(0.30)

= 1,233.77 kg per flight

Landing mode;

- Number of engines (N_s): 2
- Time in taxi mode ($T_{a, m, s}$): 59.14 s
- Default thrust setting ($t_{a, m, s}$): 7 %
- Weight average fuel flow ($F_{a, s}$): 0.1170 kg. s^{-1}
- Weight average emission factor ($I_{a, p, s}$): 17.76 kg. fuel kg^{-1}

$E_{Approach}$ = 2 × 59.14 s × 0.1170 kg. s^{-1}(0.07) × 17.76 kg. fuel kg^{-1}(0.07)

= 245.78 kg per flight

Cruise mode;

The emissions during cruise mode were estimate using the equation as shown below;

$$E_{Cruise_{d,g,p}} = m_{g,p} \times d + c_{g,p}$$

Where:

$E_{Cruised,g,p}$	is the emissions in cruise of pollutant *p* for generic aircraft type *g* and flight distance *d* (kg)
d	is the flight distance
g	is the generic aircraft type
p	is the pollutant (or fuel consumption)
$m_{g,p}$	is the slope of regression for generic aircraft type *g* and pollutant *p* (kg/km)
$c_{g,p}$	is the intercept of regression for generic aircraft type *g* and pollutant *p* (kg)

- Slope of regression ($m_{g,}$ p): 1.86E-03 kg. km^{-1}

- Flight distance (d): 1 km

- Intercept of regression ($c_{g,}$ p): 9.99E-01 kg

E_{Cruise} = 1.86E-03 kg. km^{-1} × 1 km × 9.99E-01 kg

= 1.00 kg. km^{-1} per flight

Table C.2 Emission of CO for each mode in flying cycle

NO.	Aviation modes	Emissions per flight
1	Taxi	872.73 kg
2	Take-off	122.77 kg
3	Initial-climb	63.15 kg
4	Climb-out	120.46 kg
5	Approach	1,233.77 kg
6	Landing	245.78 kg
7	Cruise	1.00 kg. km^{-1}

APPENDIX D

THE MOVEMENT OF THE COMMERCIAL AIRCRAFT

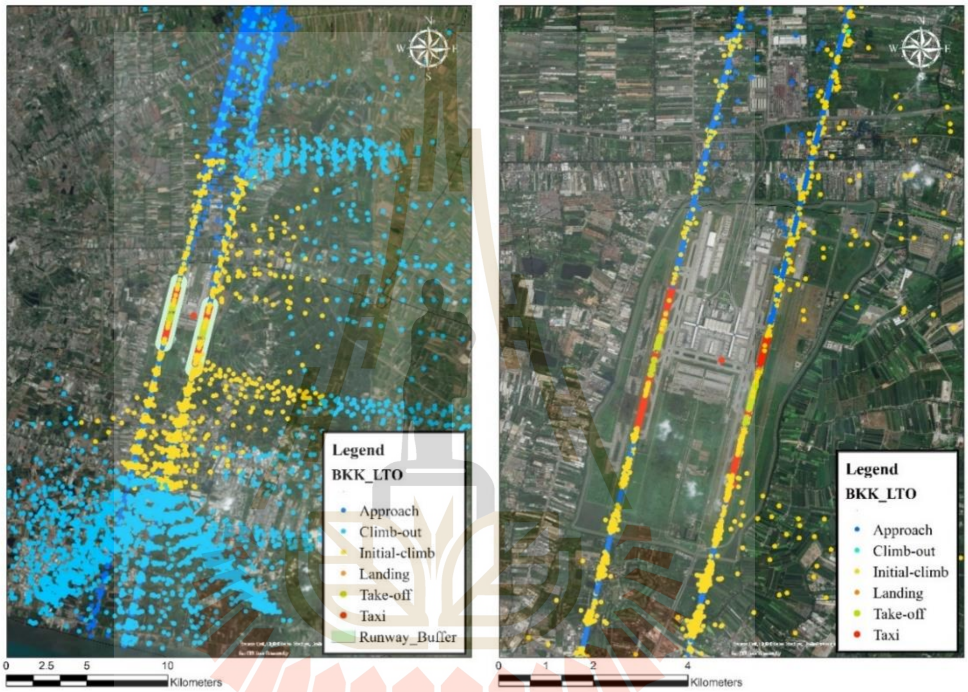


Fig. D.1 The commercial aircraft movement at Suvarnabhumi airport

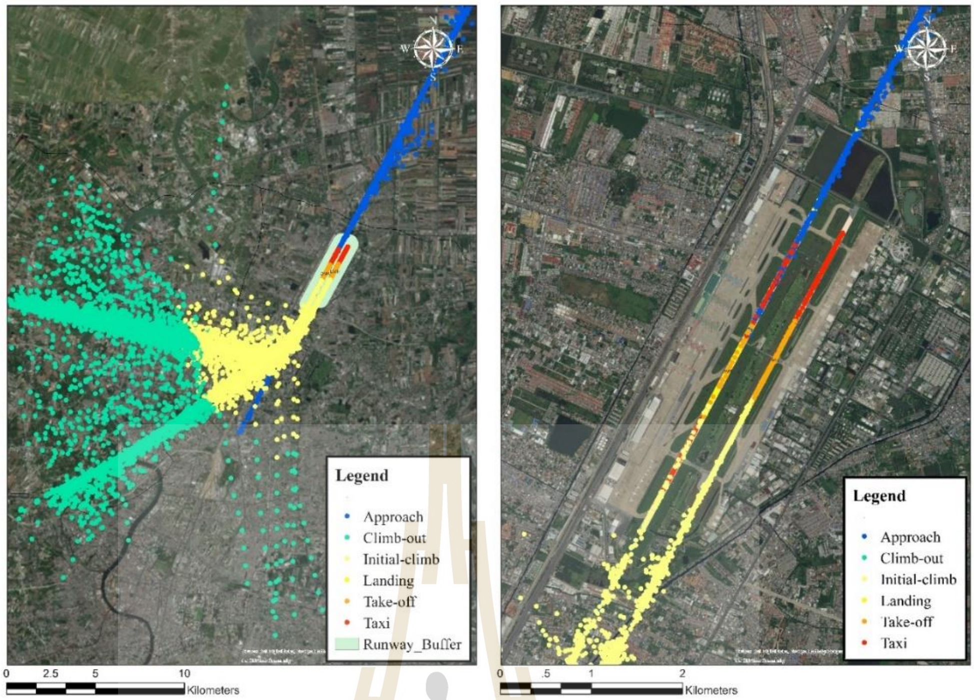


Fig. D.2 The commercial aircraft movement at Don Mueang airport

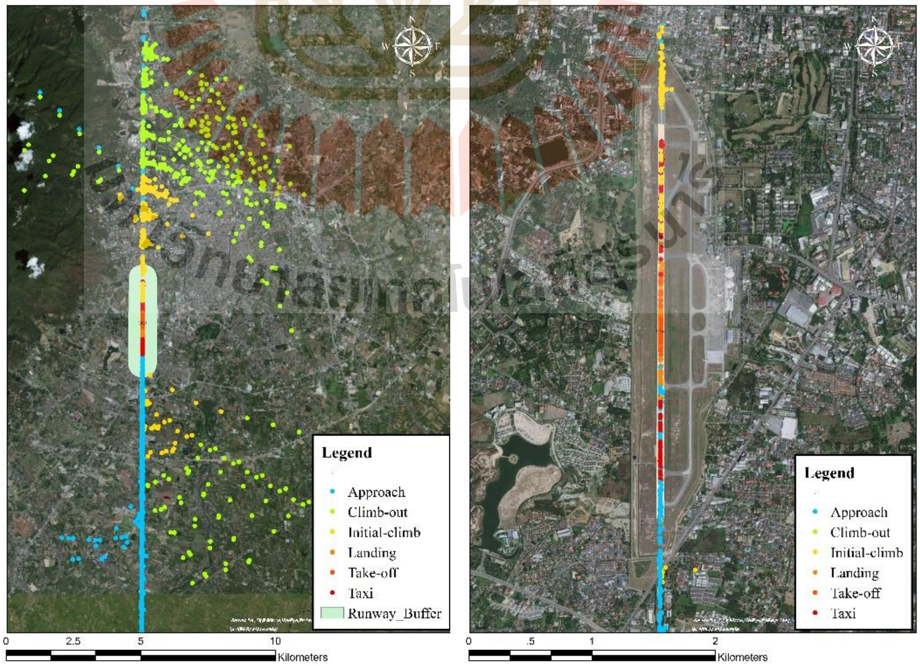


Fig. D.3 The commercial aircraft movement at Chiang Mai airport

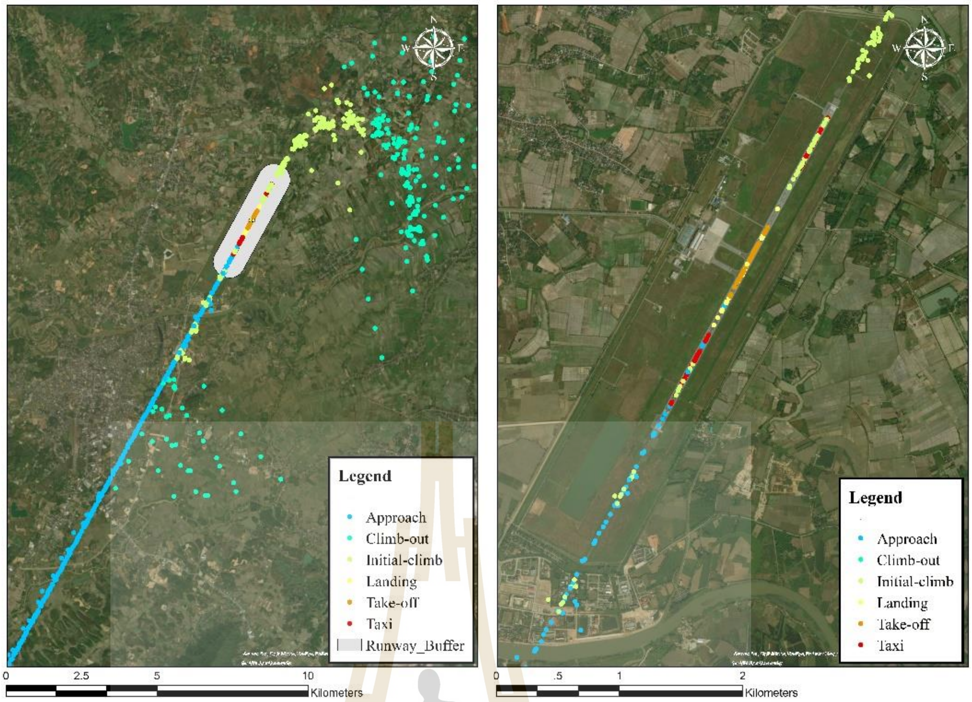


Fig. D.4 The commercial aircraft movement at Mae Fah Luang Chiang Rai airport

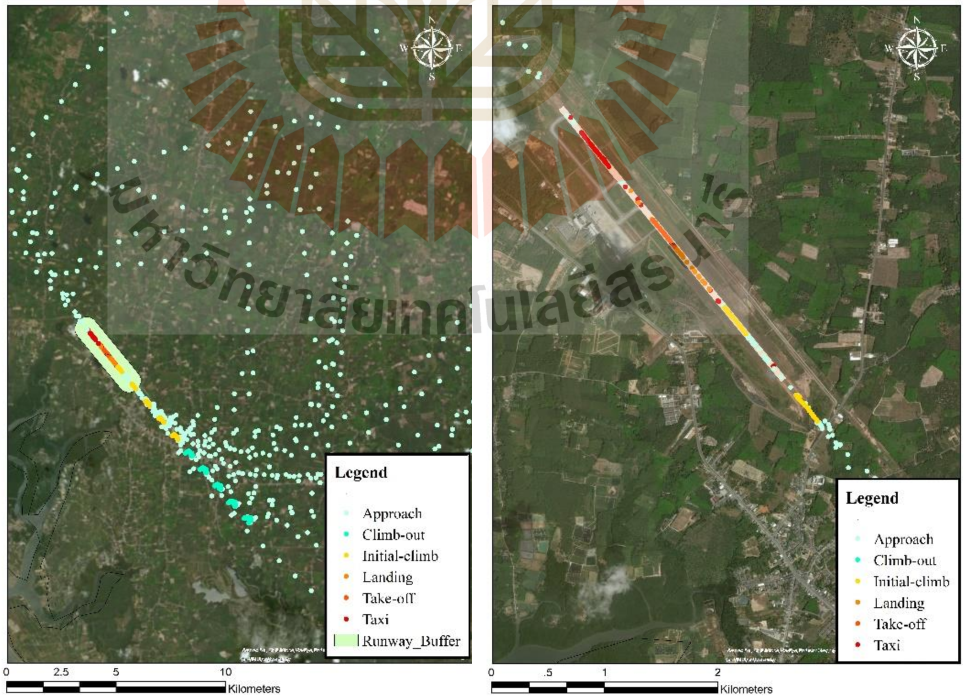


Fig. D.5 The commercial aircraft movement at Krabi airport

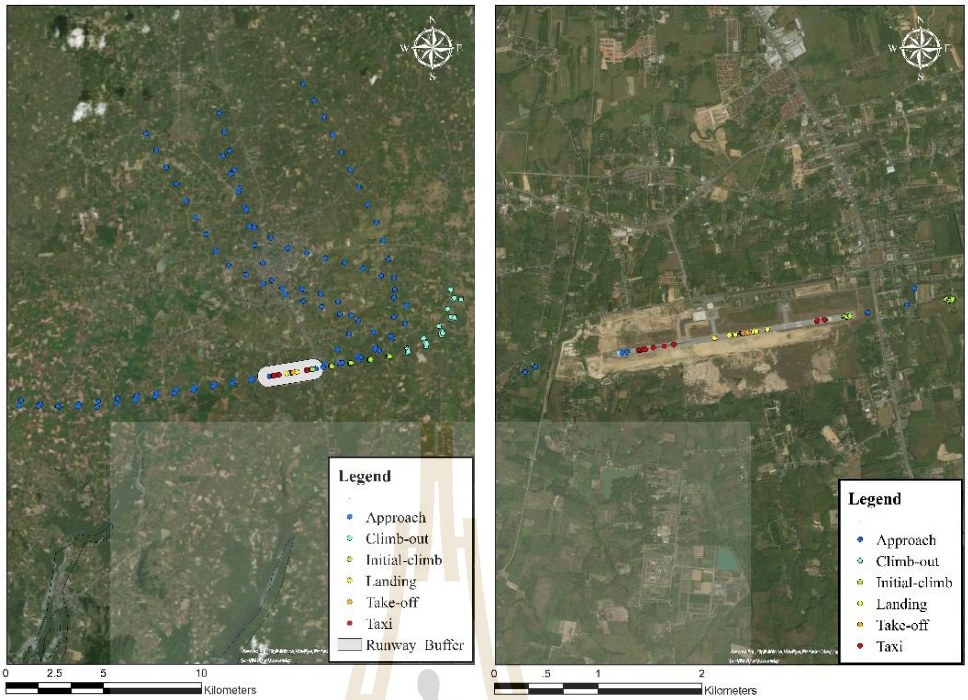


Fig. D.6 The commercial aircraft movement at Trang airport

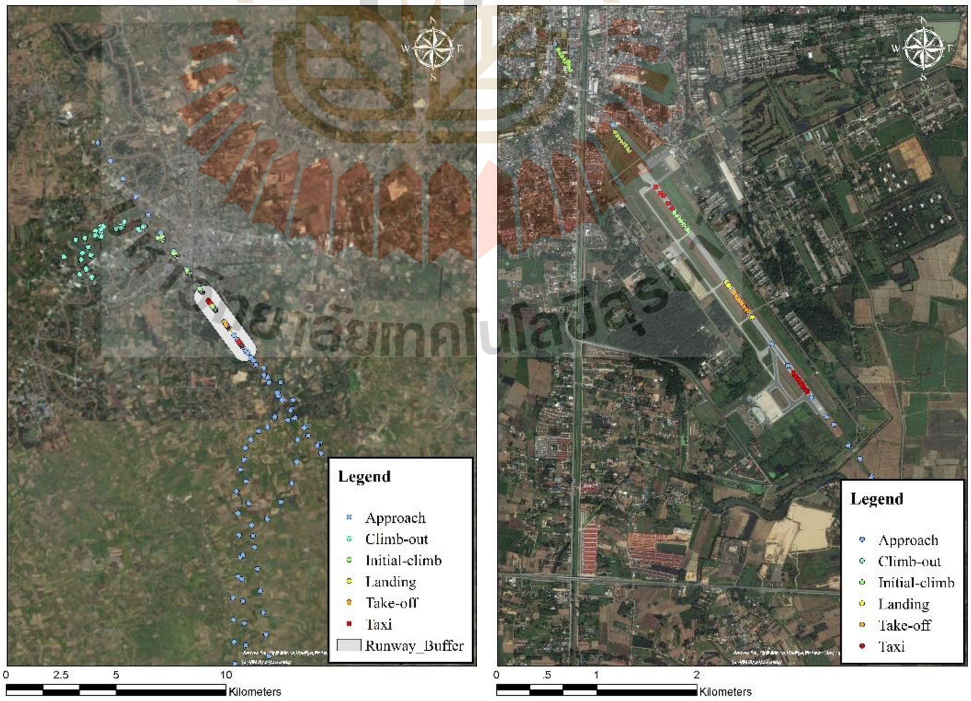


Fig. D.7 The commercial aircraft movement at Phitsanulok airport

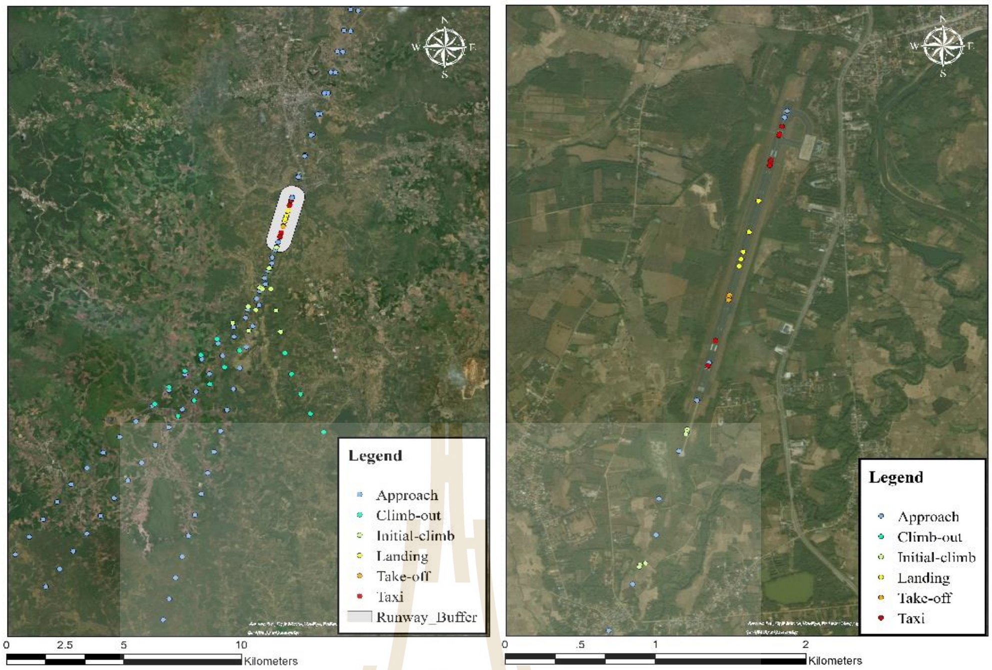


Fig. D.8 The commercial aircraft movement at Loei airport

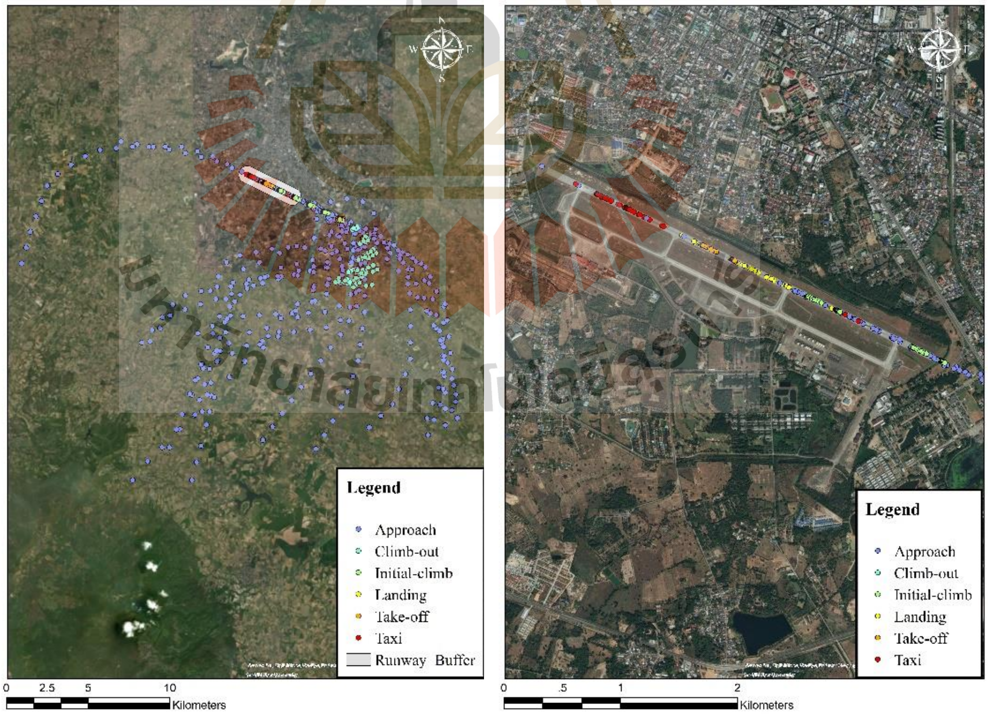


Fig. D.9 The commercial aircraft movement at Udon Thani airport

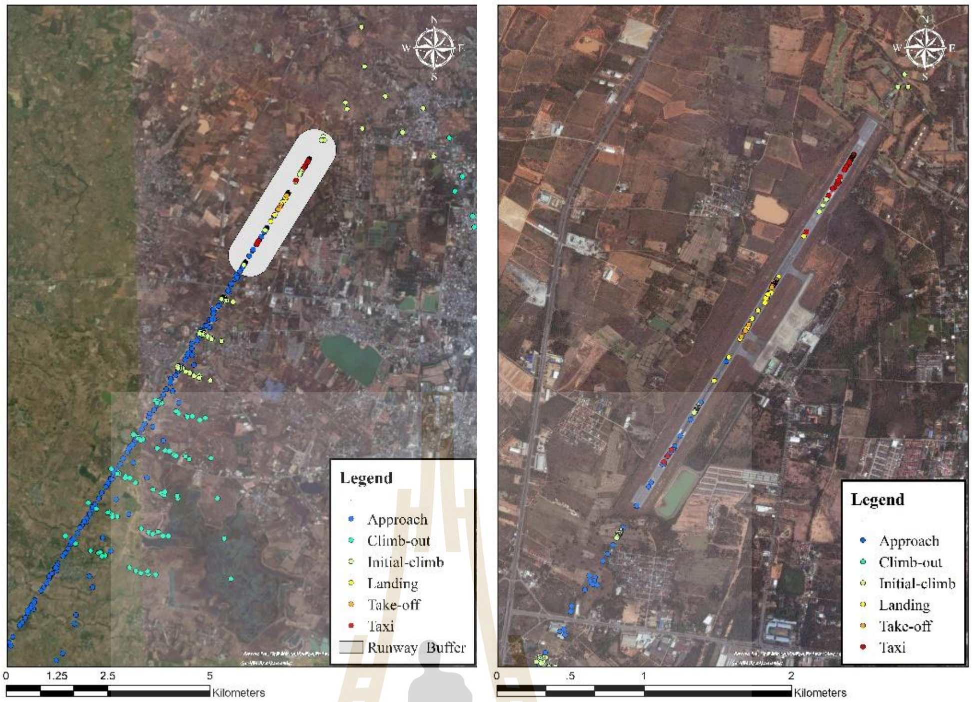


Fig. D.10 The commercial aircraft movement at Khon Kaen airport

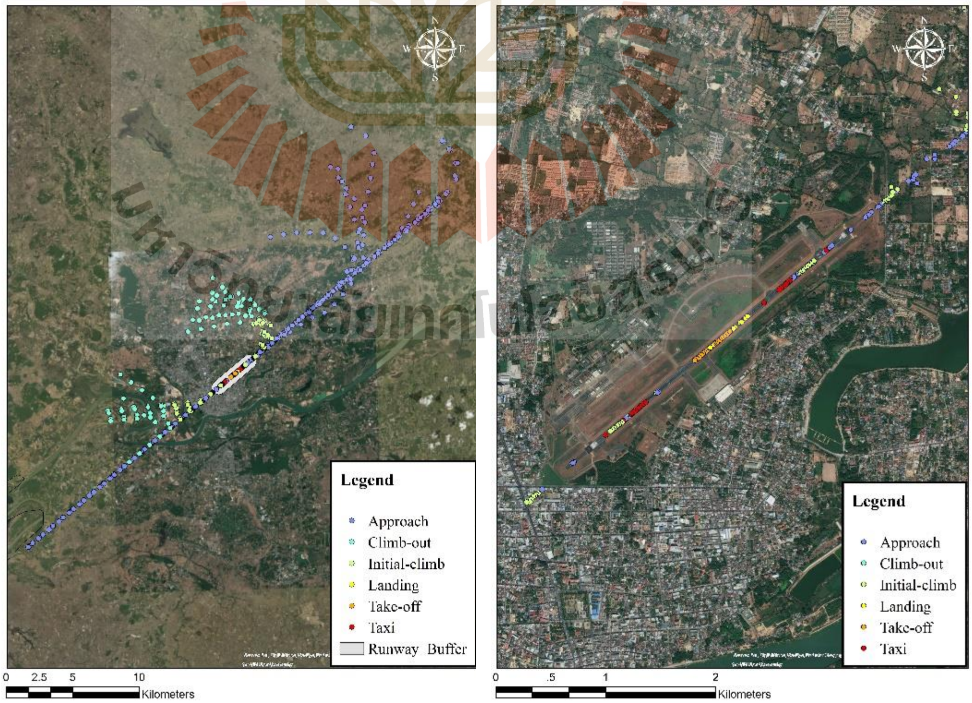


Fig. D.11 The commercial aircraft movement at Ubon Ratchathani airport

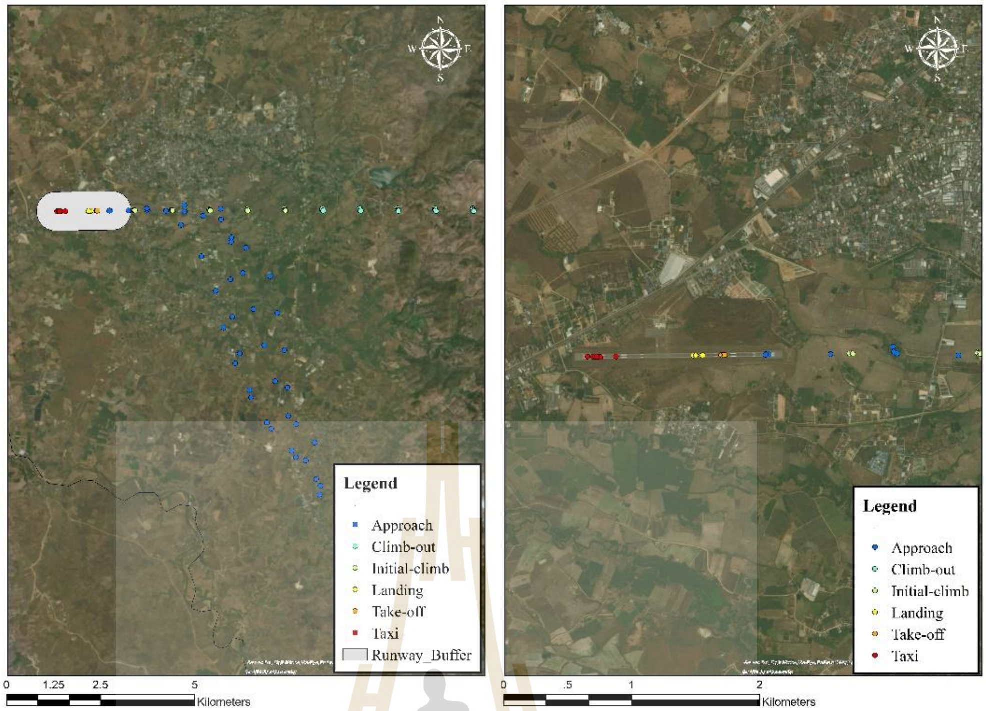


Fig. D.12 The commercial aircraft movement at Mae Sot airport

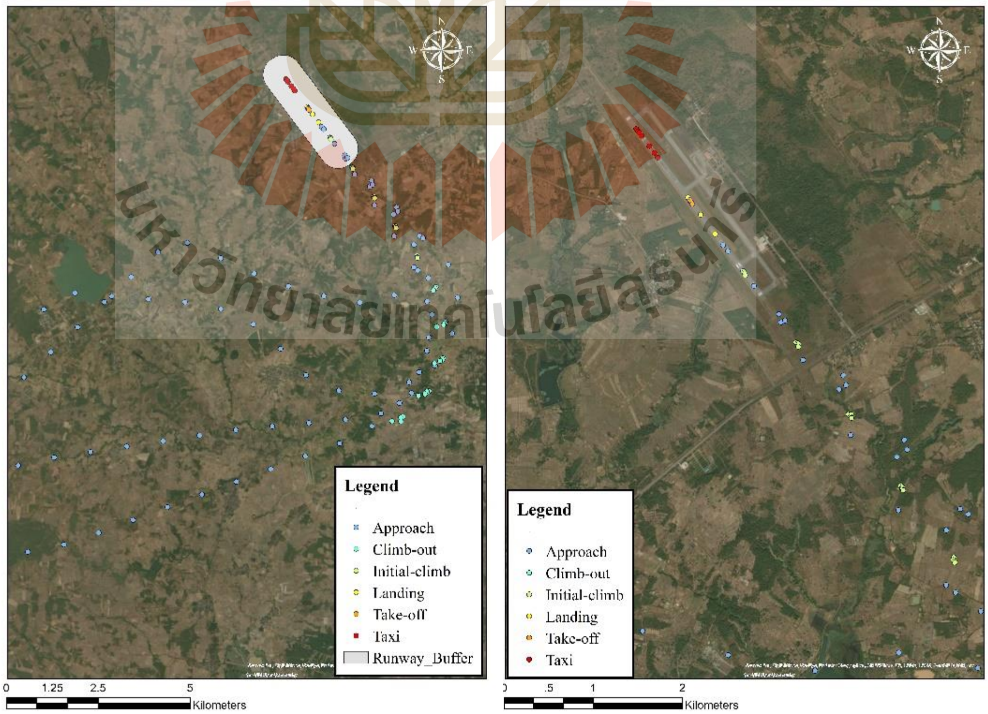


Fig. D.13 The commercial aircraft movement at Nakhon Phanom airport

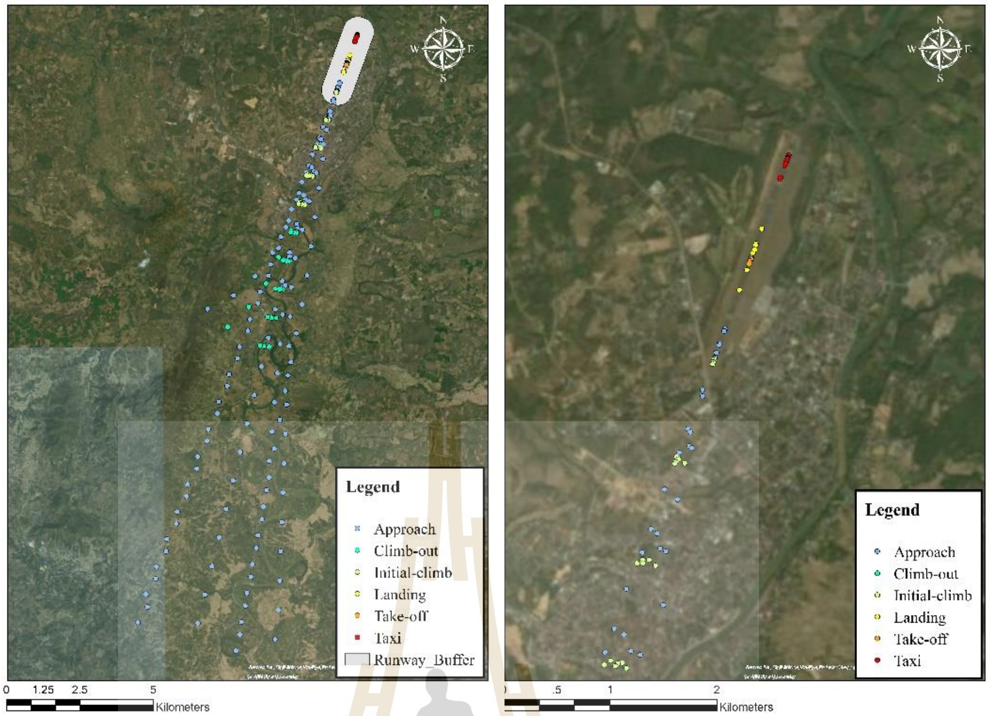


Fig. D.14 The commercial aircraft movement at Nan Nakhon airport

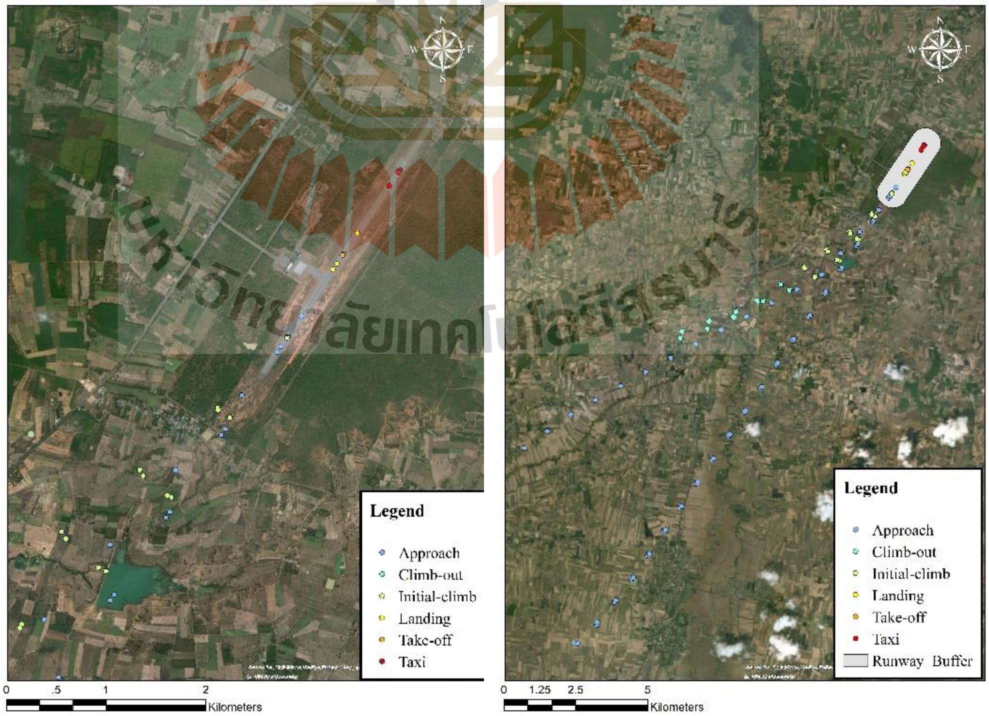


Fig. D.15 The commercial aircraft movement at Buriram airport

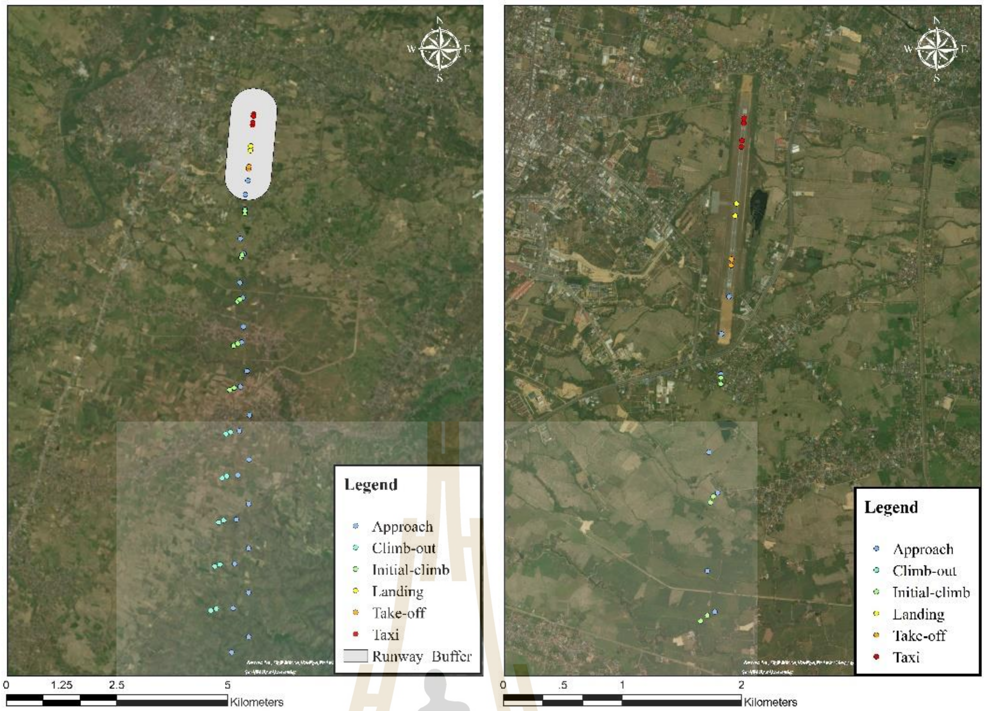


Fig. D.16 The commercial aircraft movement at Phrae airport

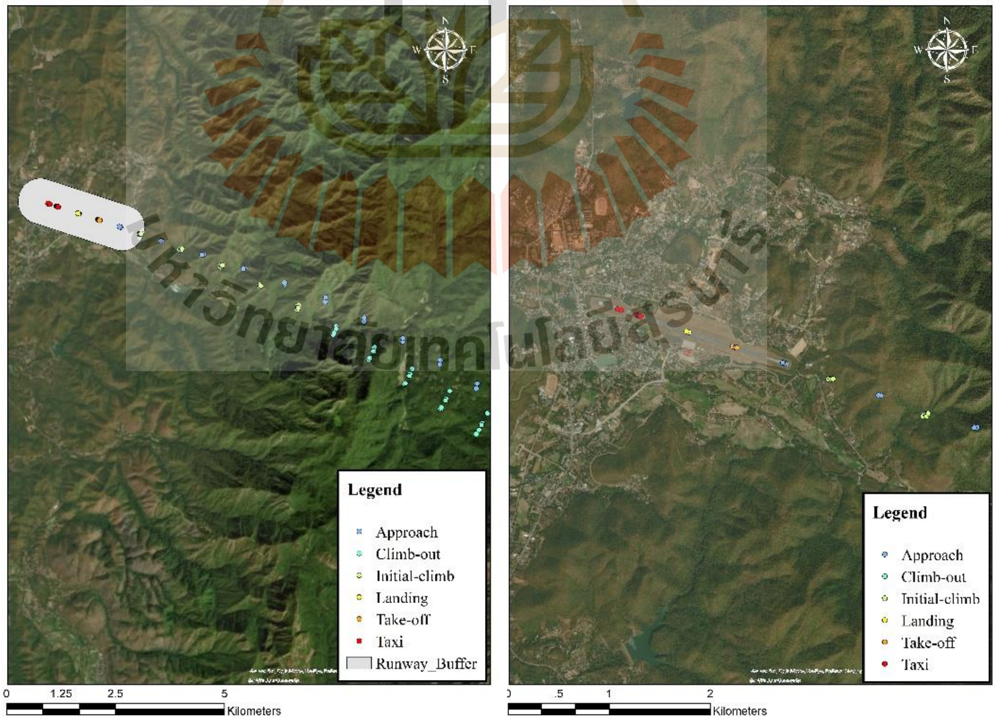


Fig. D.17 The commercial aircraft movement at Mae Hong Son airport

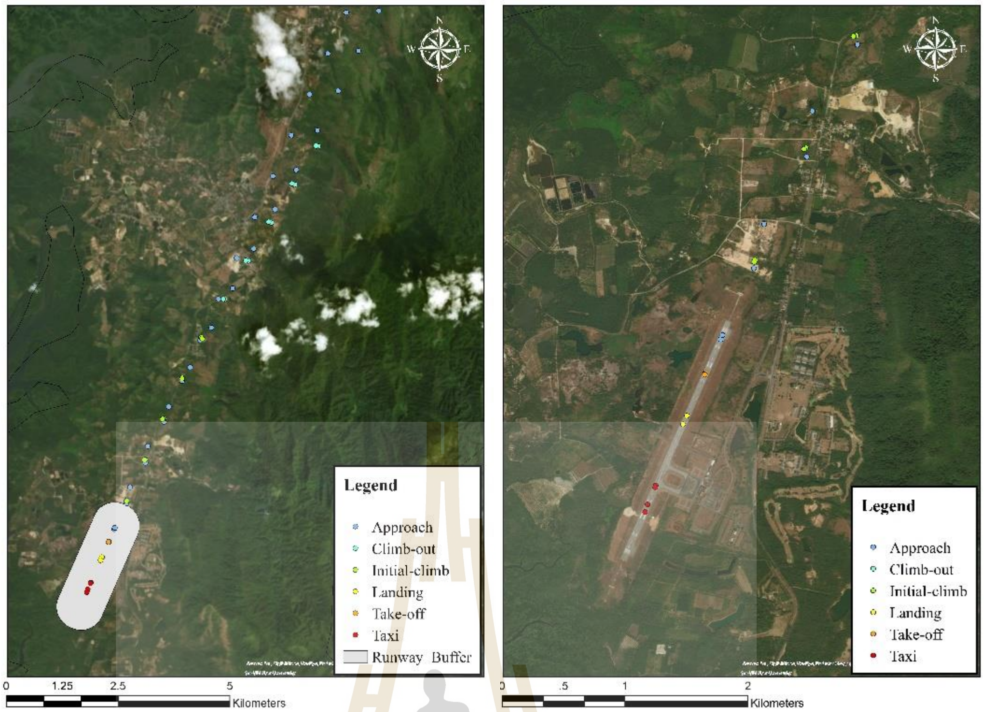


Fig. D.18 The commercial aircraft movement at Ranong airport

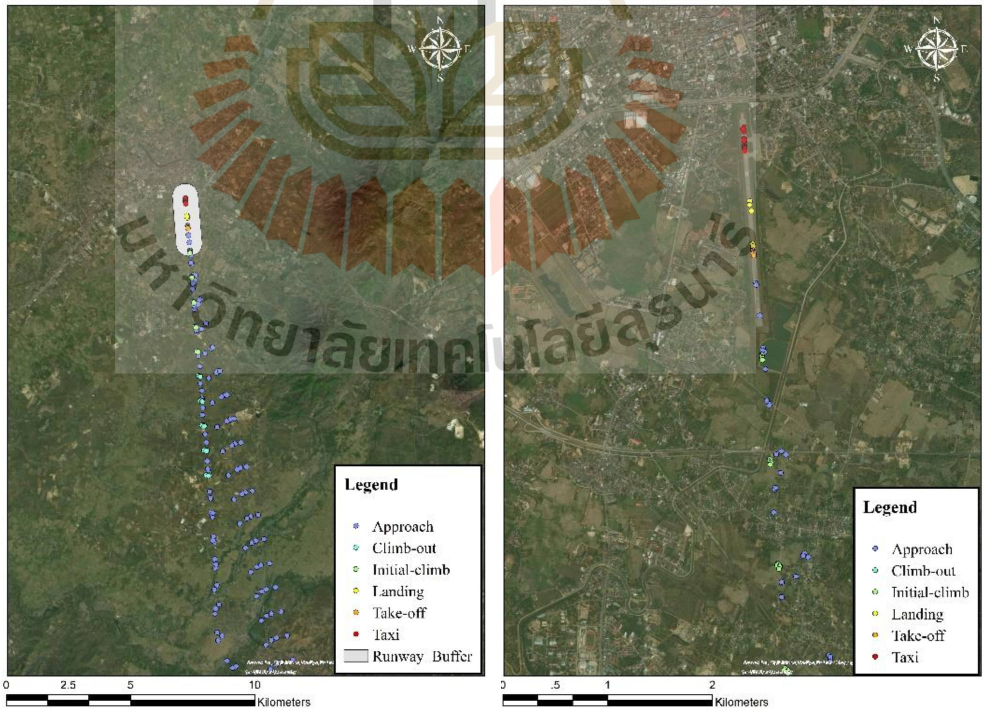


Fig. D.19 The commercial aircraft movement at Lampang airport

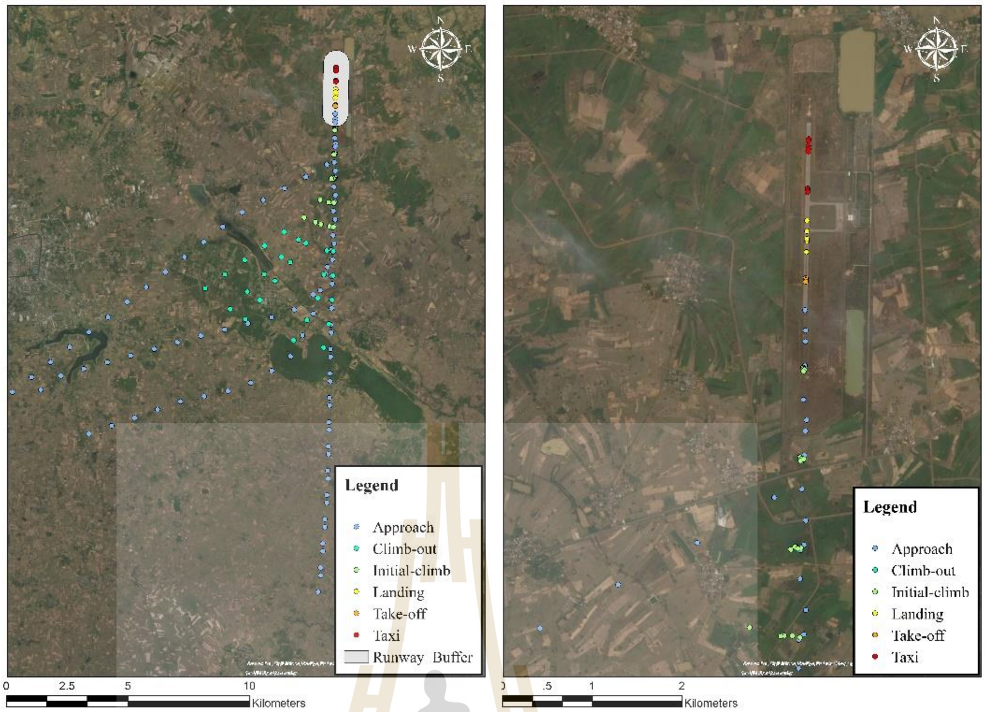


Fig. D.20 The commercial aircraft movement at Roi Et airport

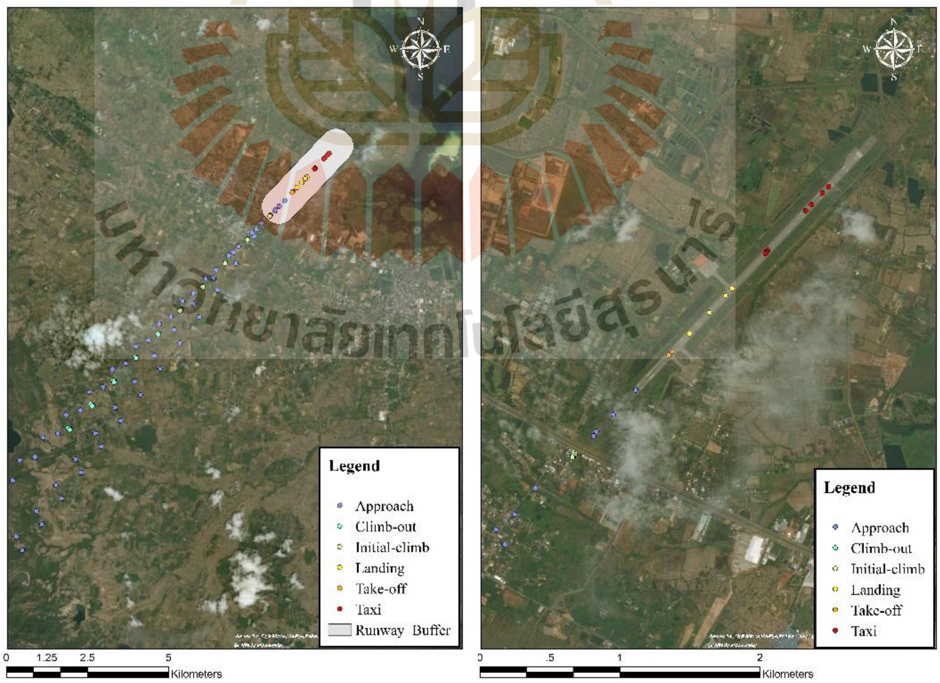


Fig. D.21 The commercial aircraft movement at Sakon Nakhon airport

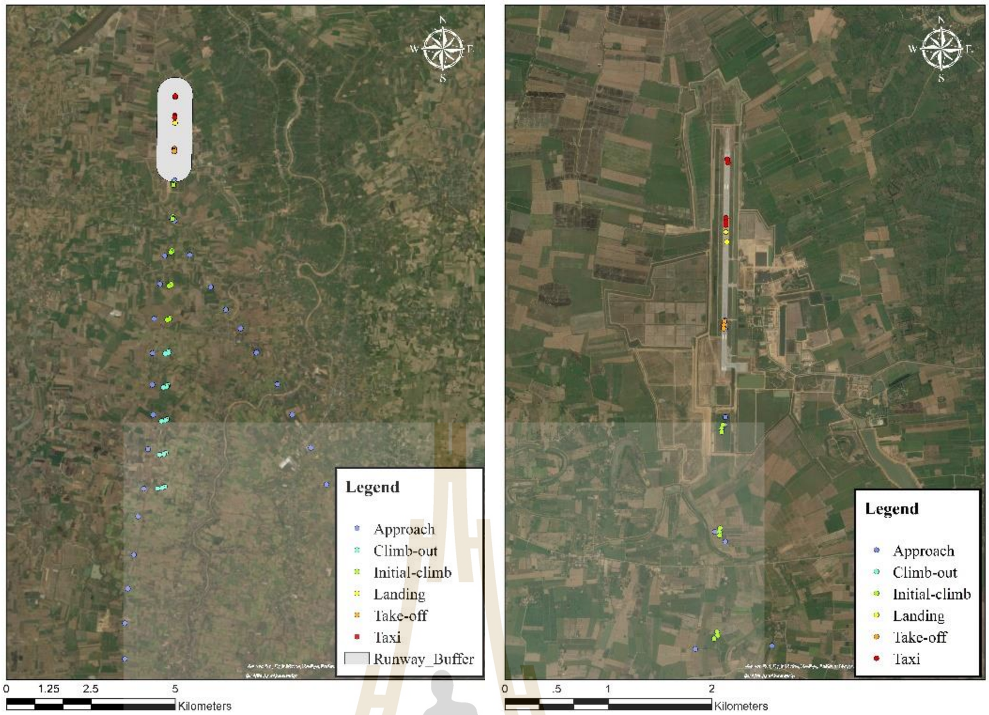


Fig. D.22 The commercial aircraft movement at Sukhothai airport

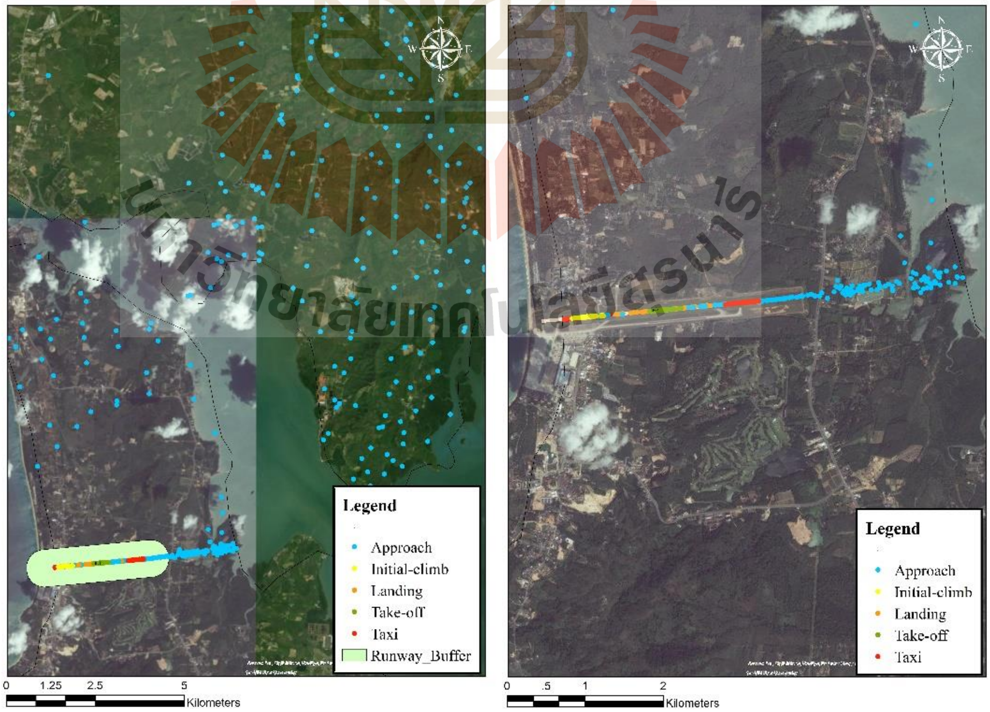


Fig. D.23 The commercial aircraft movement at Phuket airport

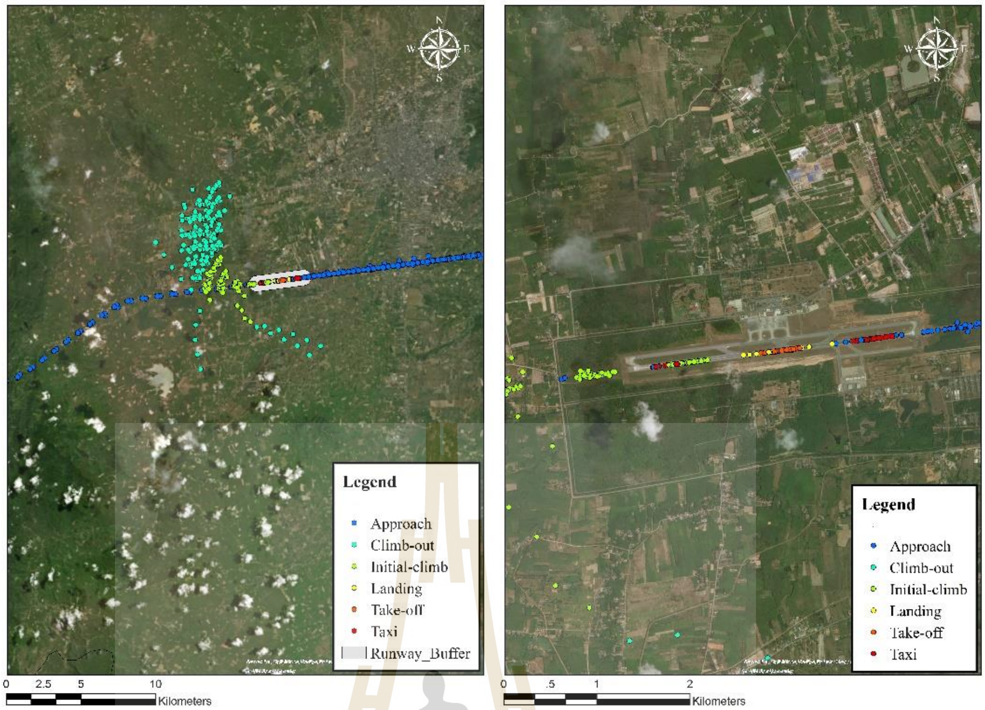


Fig. D.24 The commercial aircraft movement at Hat Yai airport

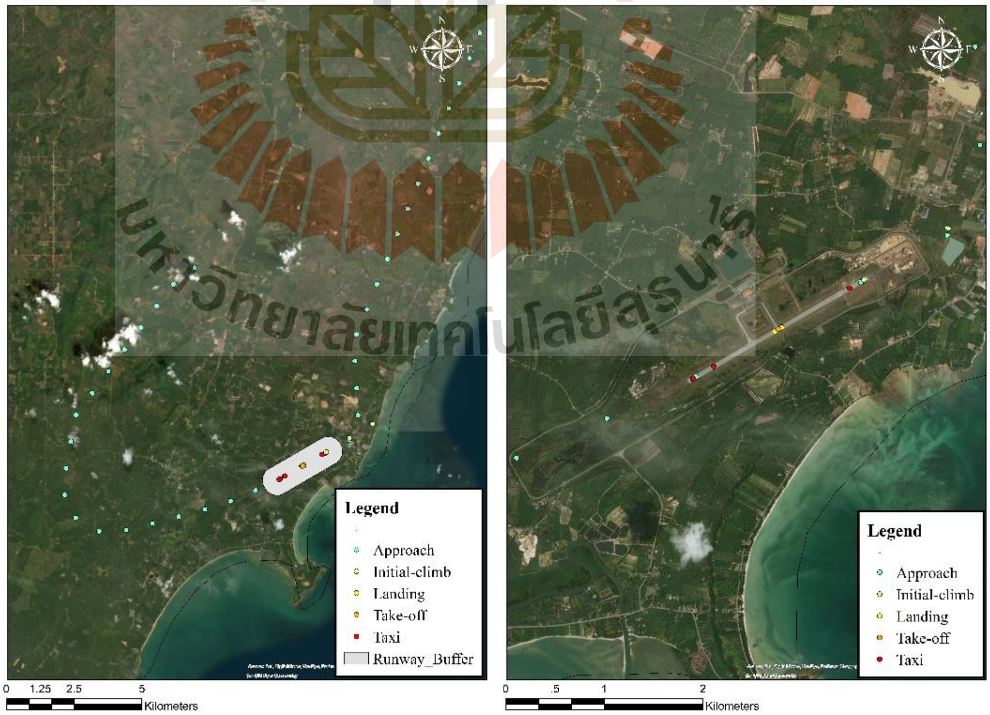


Fig. D.25 The commercial aircraft movement at Chumphon airport

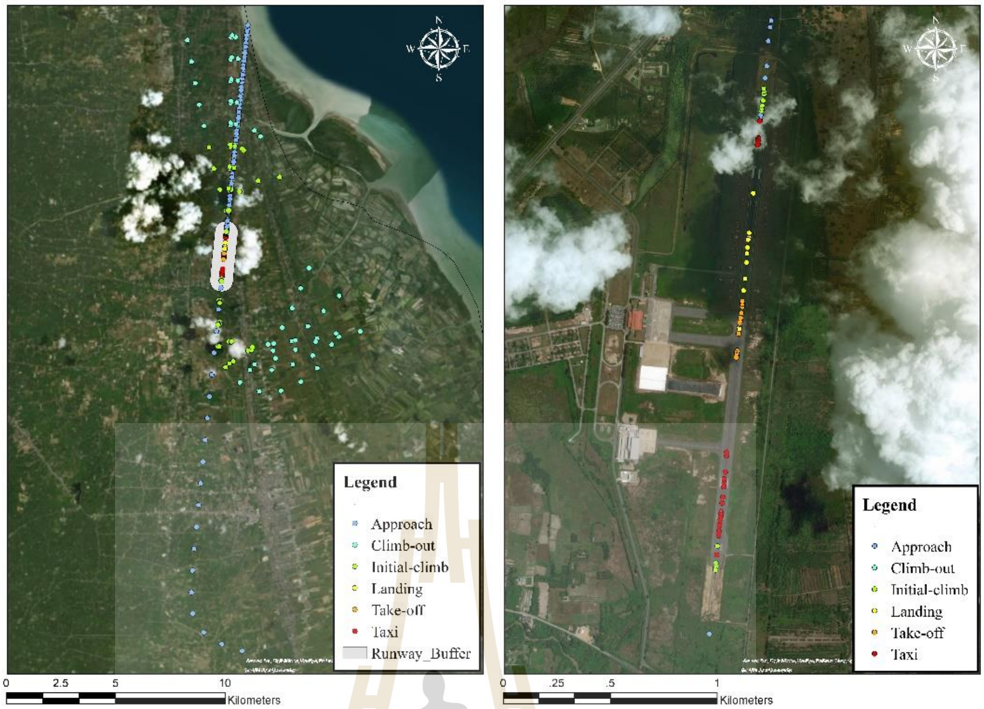


Fig. D.26 The commercial aircraft movement at Nakhon Si Thammarat airport

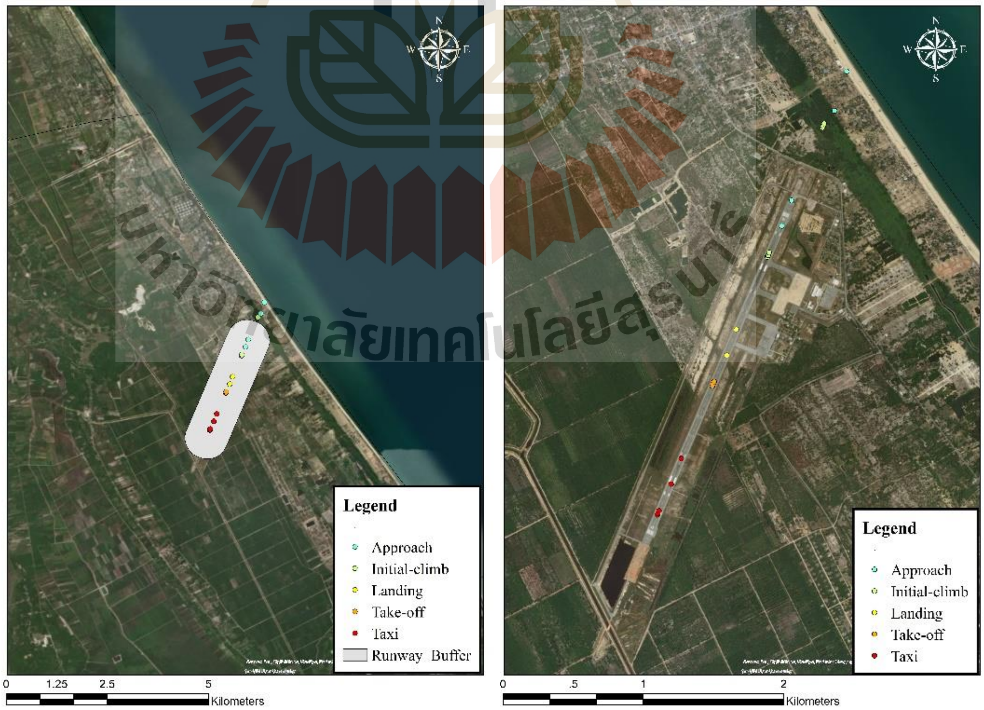


Fig. D.27 The commercial aircraft movement at Narathiwat airport

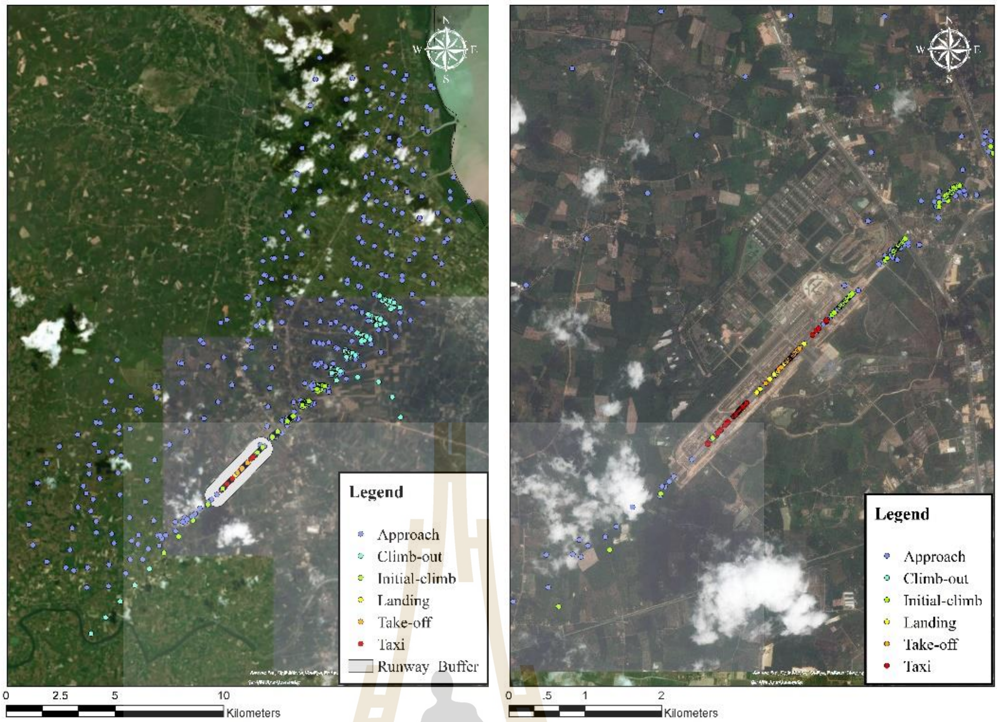


Fig. D.28 The commercial aircraft movement at Surat Thani airport

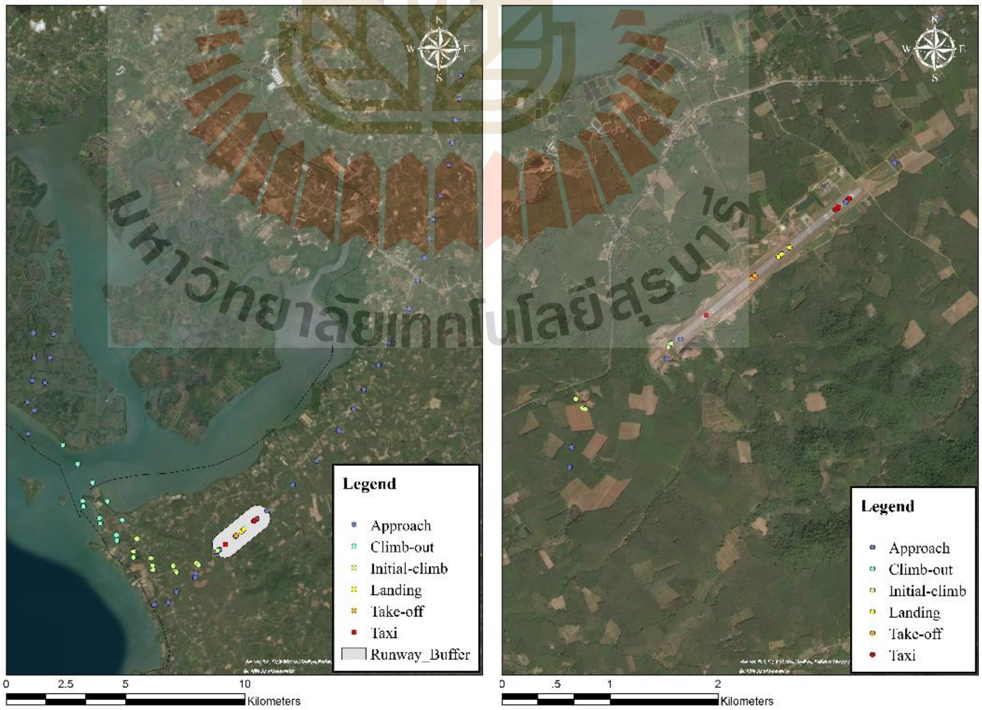


Fig. D.29 The commercial aircraft movement at Trat airport

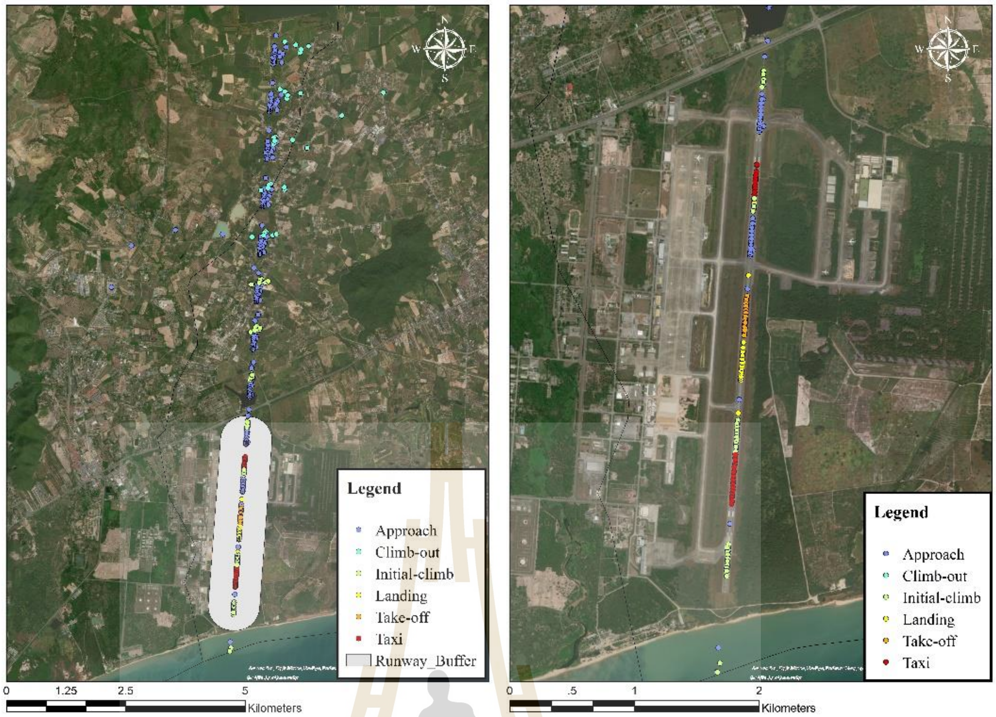


Fig. D.30 The commercial aircraft movement at U-Tapao airport

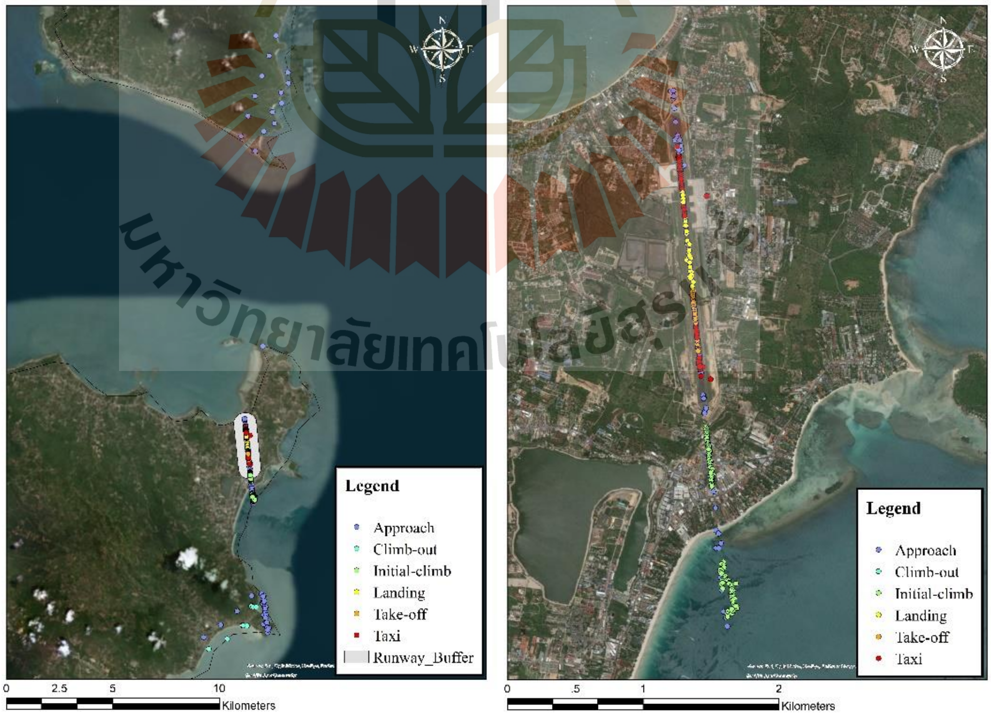


Fig. D.31 The commercial aircraft movement at Samui airport

APPENDIX E

SPATIAL EMISSIONS

The spatial emissions were created based on the annual emission data, route map of the commercial aircraft movement data, and the satellite image through the function in a GIS program. The annual emission data based on the year 2015. The spatial emission map revealed the distribution of CO, NO_x, and HC in various modes of the flying cycle. The spatial emissions were computed based on the cell size of 50 meters for LTO mode in grid resolution 1x1 kilometer, while the cruise mode was interpolated with the cell size of 1 km.

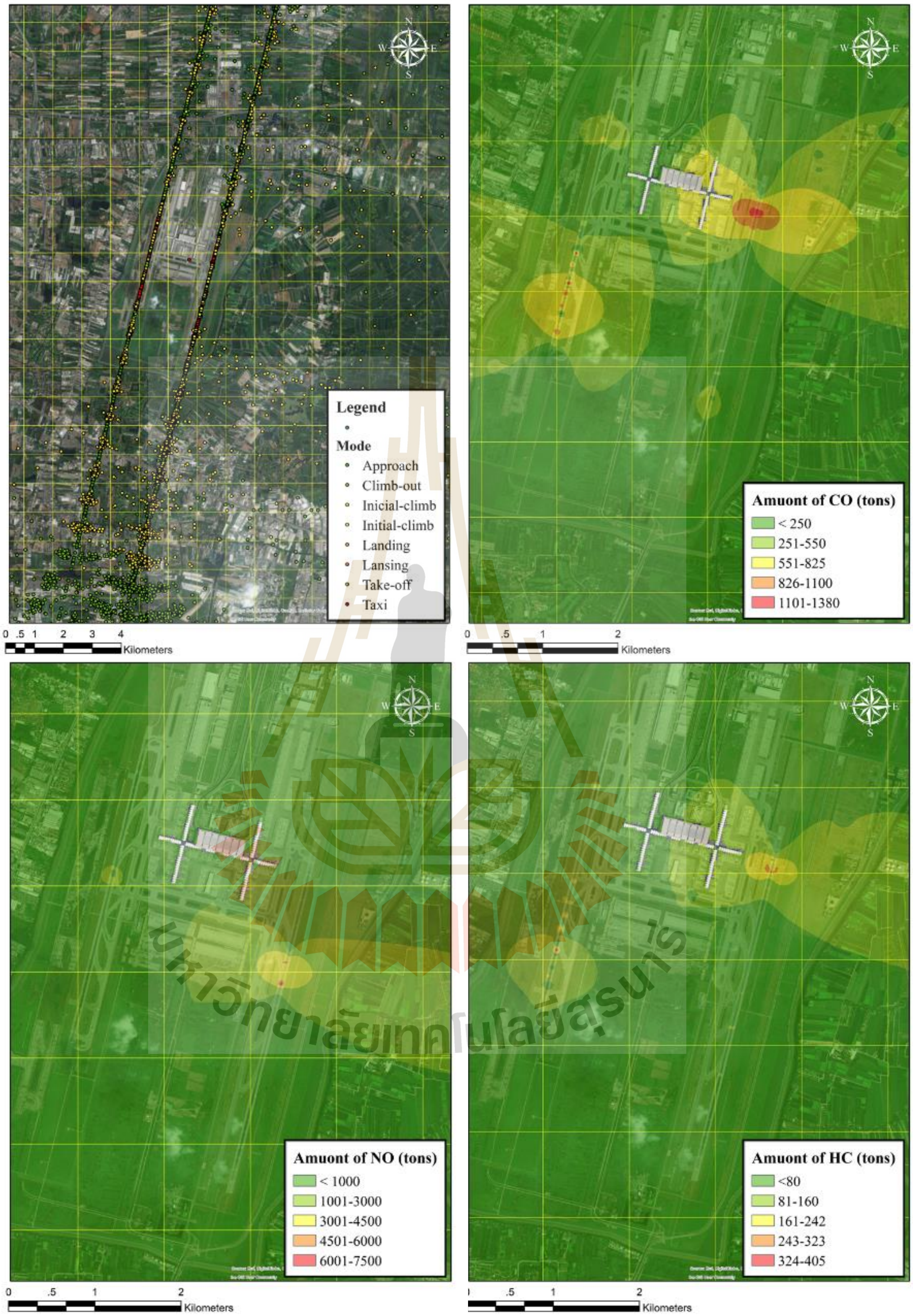


Fig. E.1 The spatial emissions at Suvarnabhumi airport

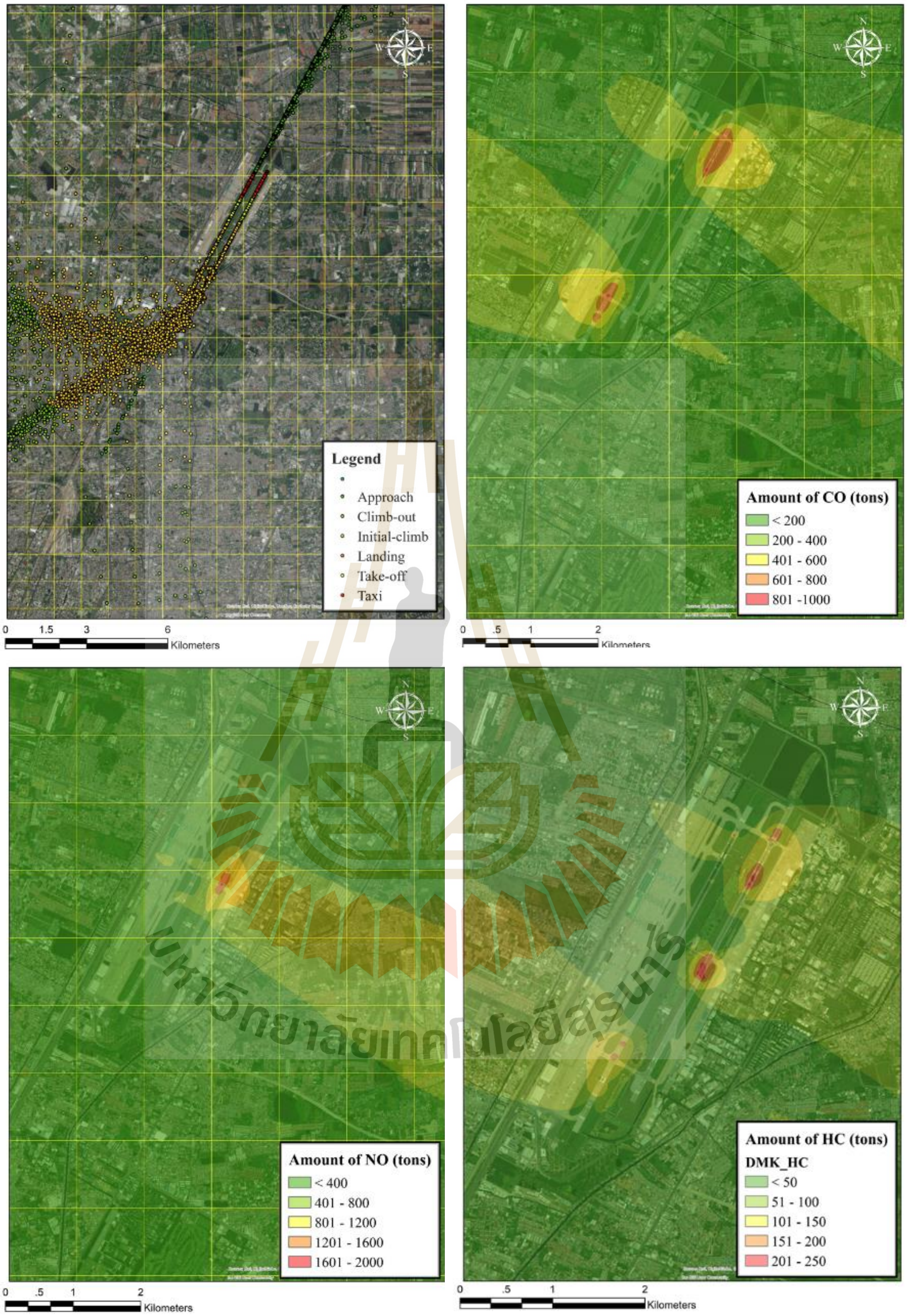


Fig. E.2 The spatial emissions at Don Mueang airport

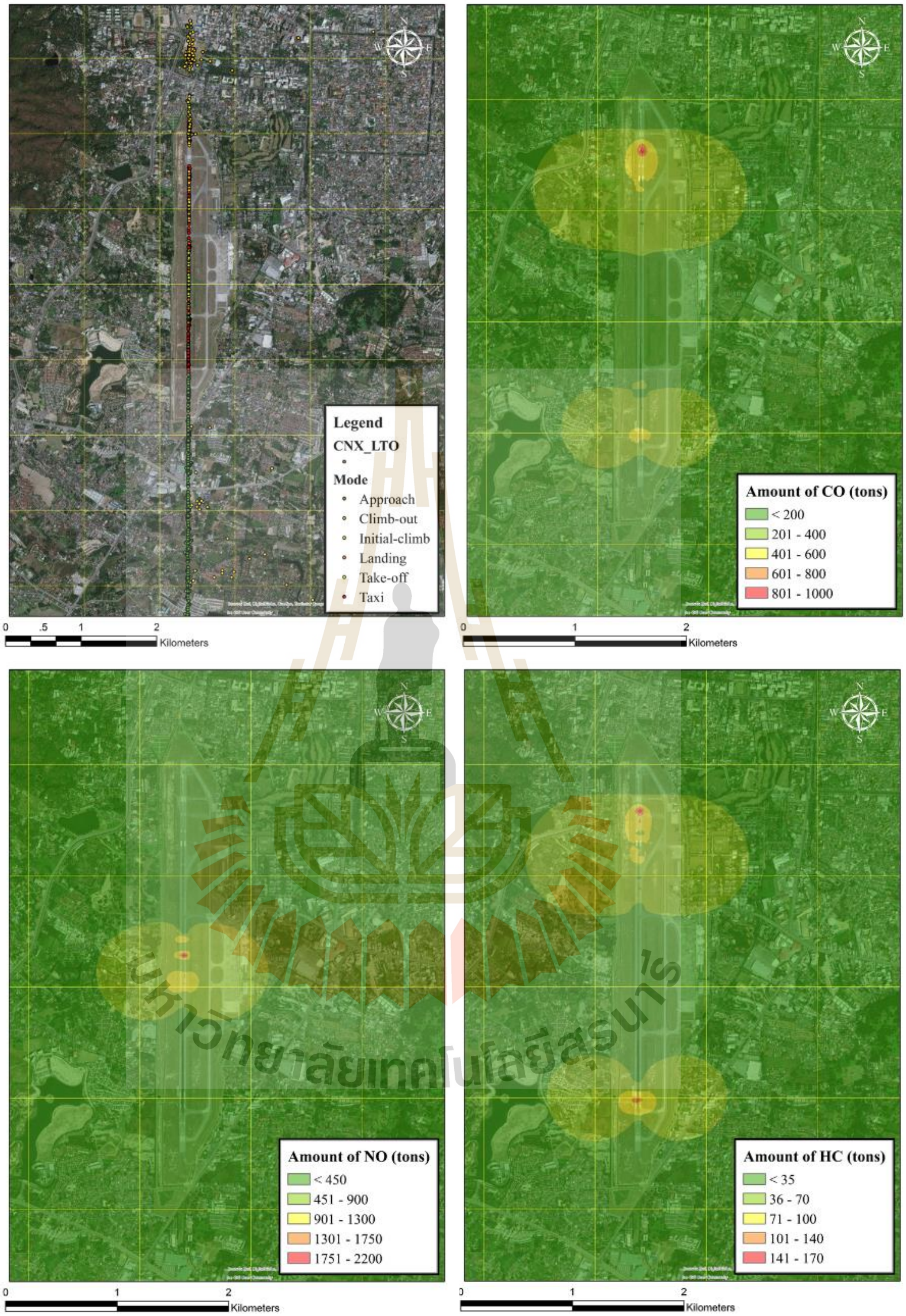


Fig. E.3 The spatial emissions at Chiang Mai airport

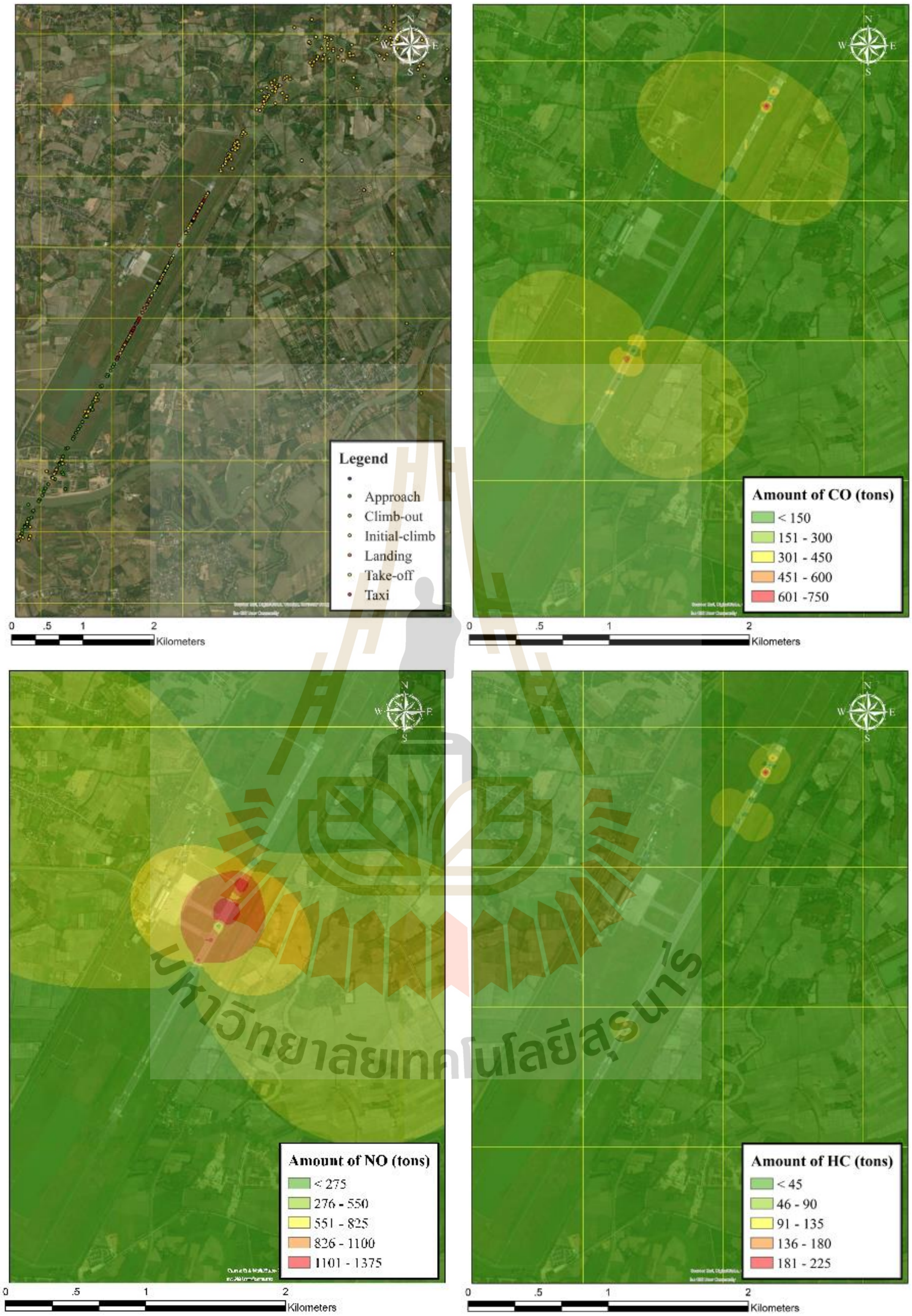


Fig. E.4 The spatial emissions at Mae Fah Luang Chiang Rai airport

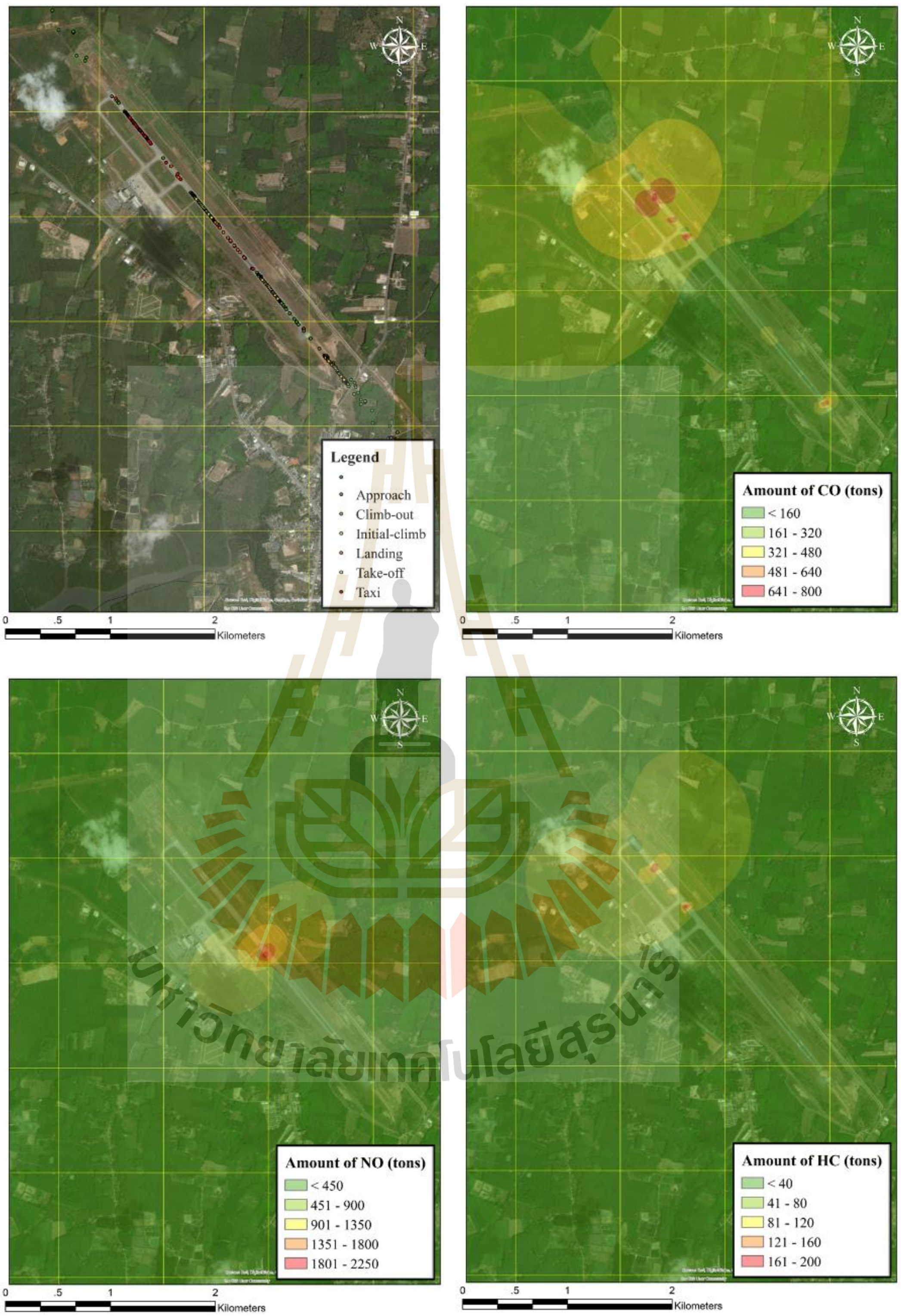


Fig. E.5 The spatial emissions at Krabi airport

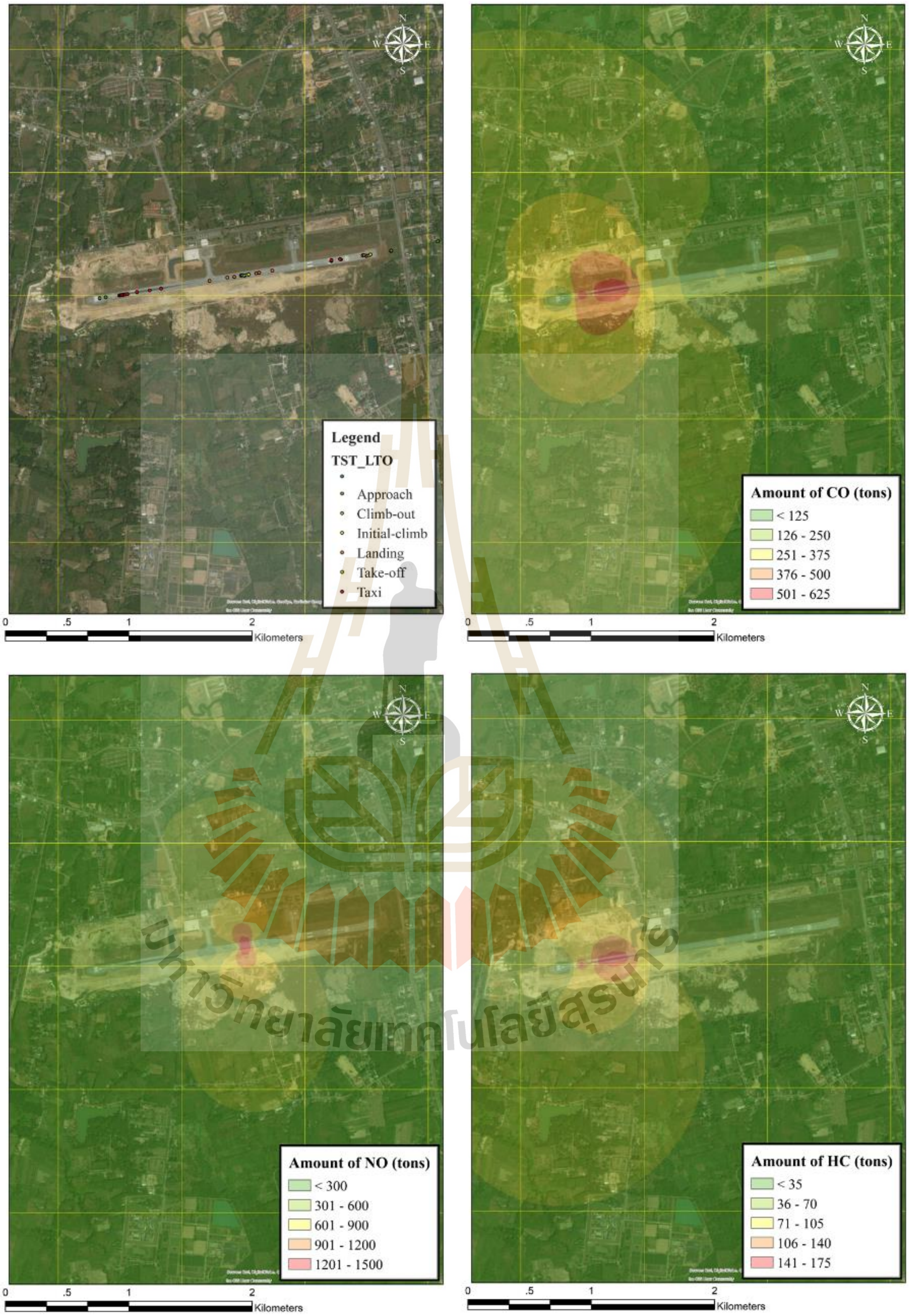


Fig. E.6 The spatial emissions at Trang airport

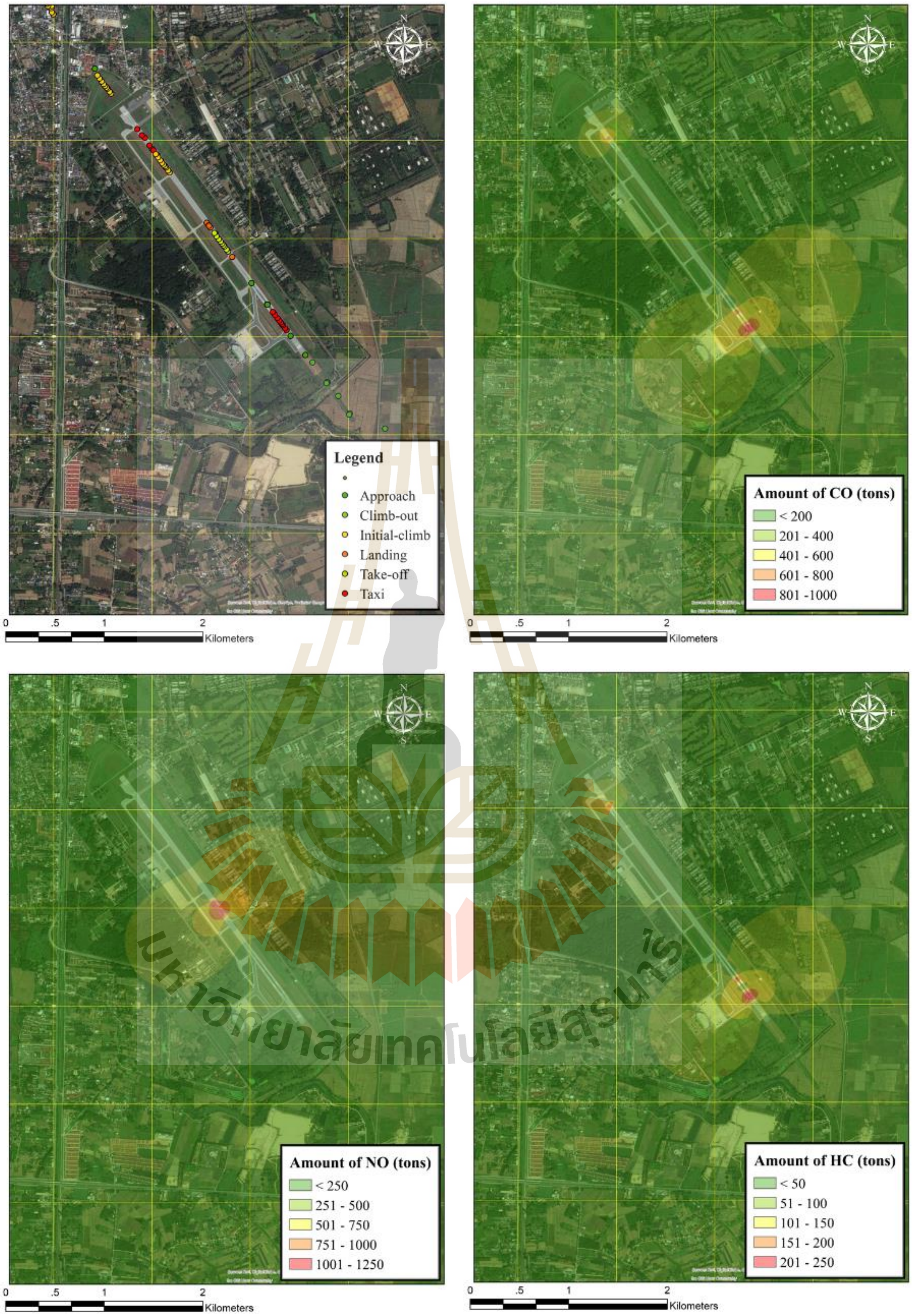


Fig. E.7 The spatial emissions at Phitsanulok airport

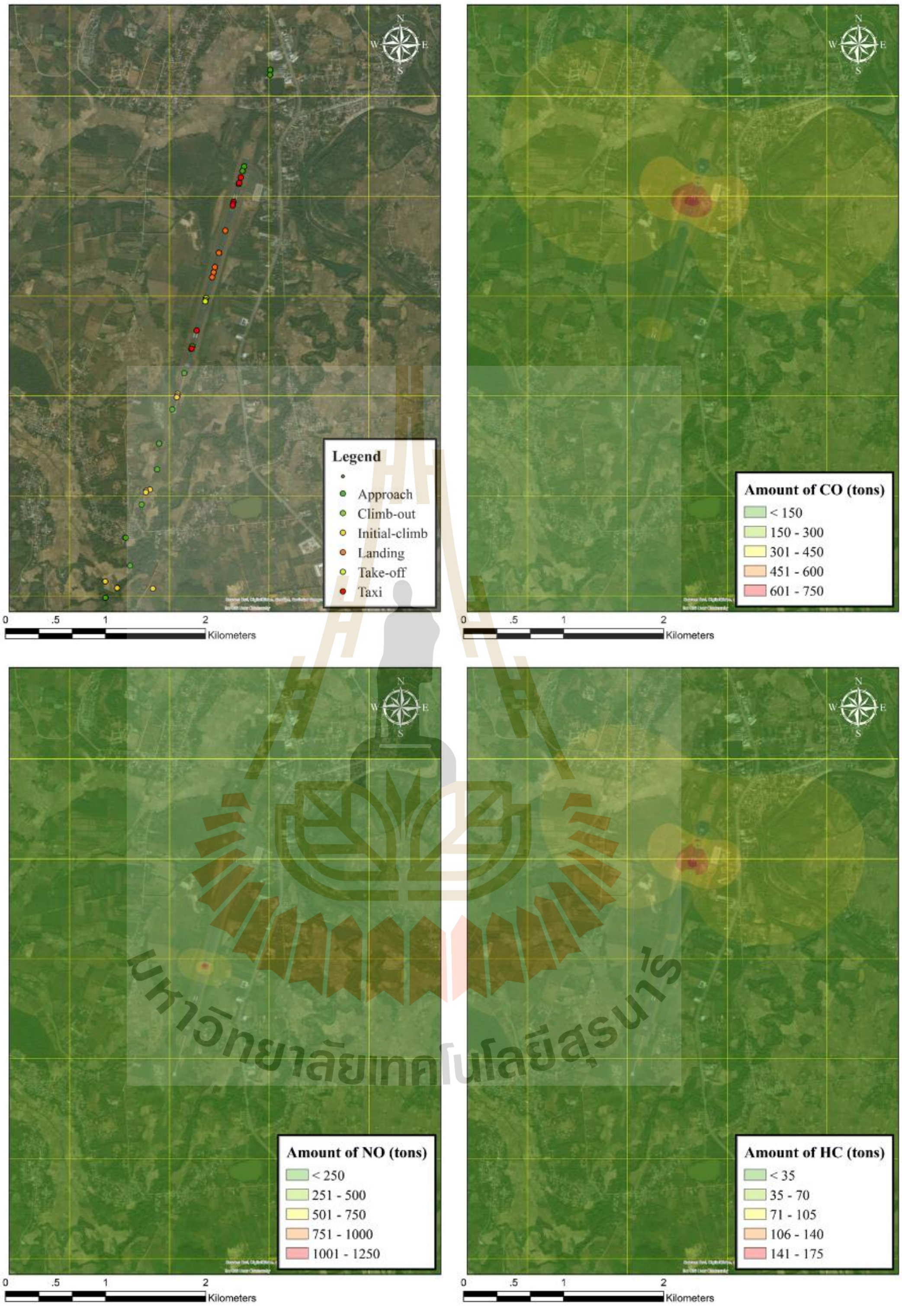


Fig. E.8 The spatial emissions at Loei airport

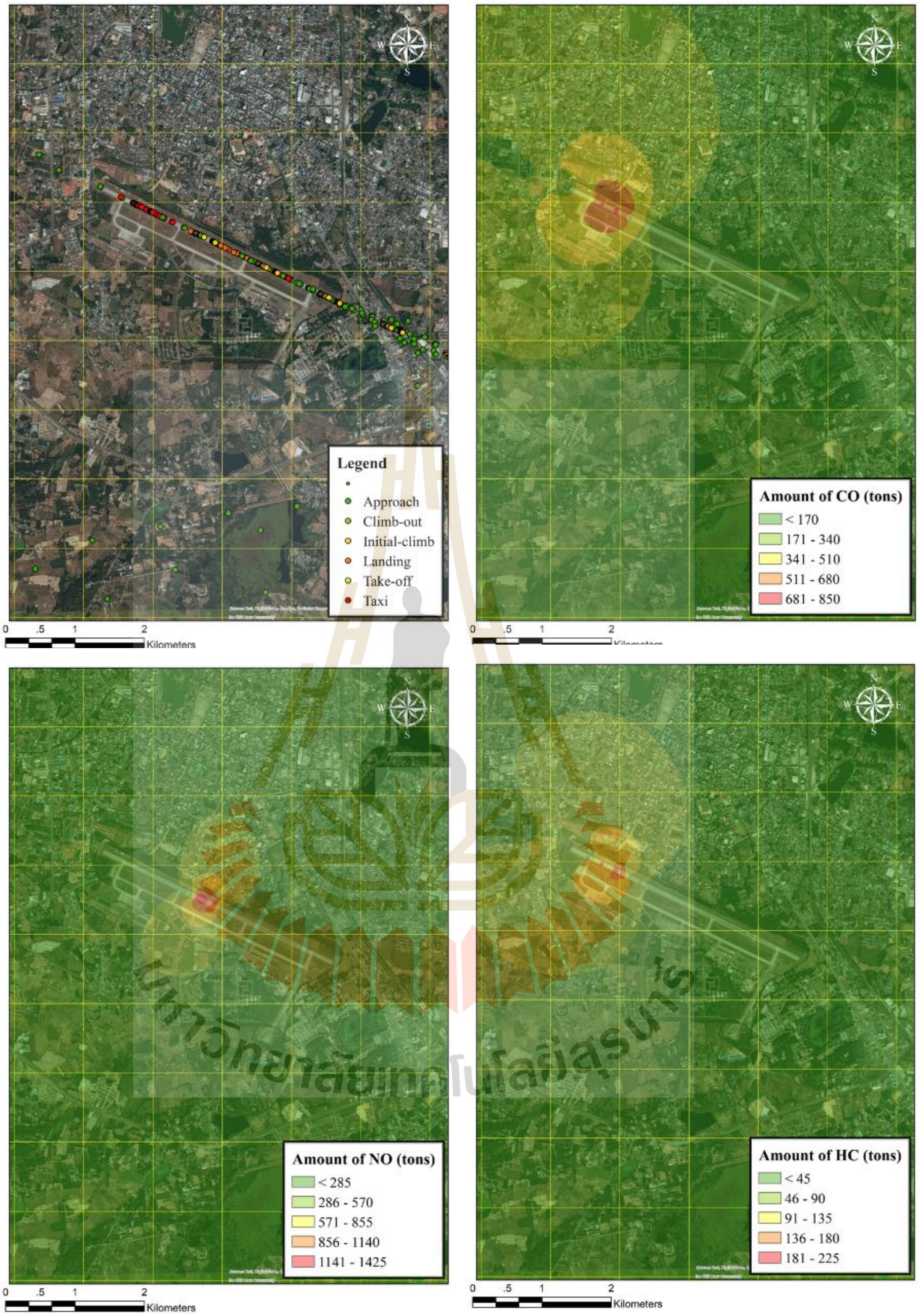


Fig. E.9 The spatial emissions at Udon Thani airport

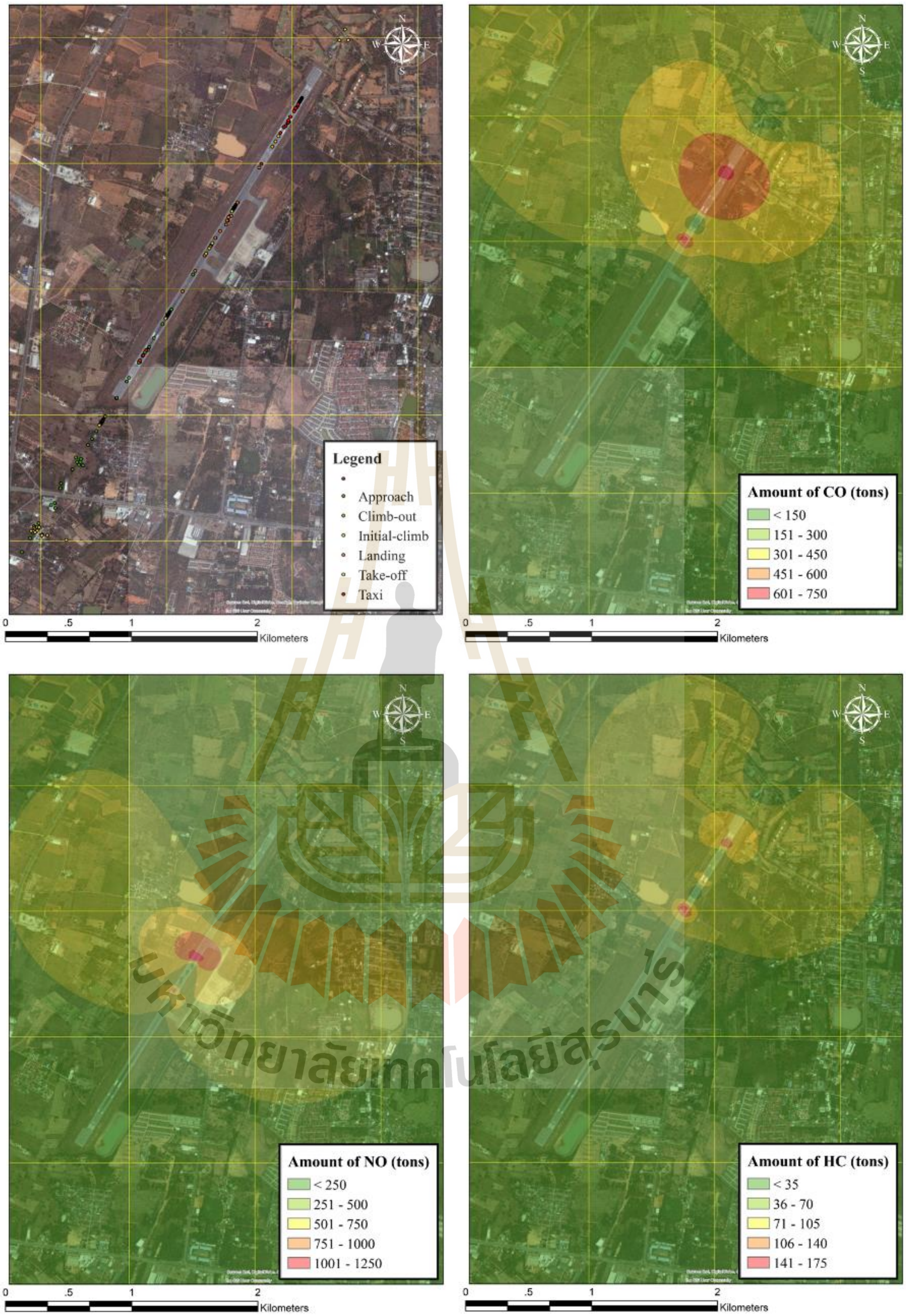


Fig. E.10 The spatial emissions at Khon Kaen airport

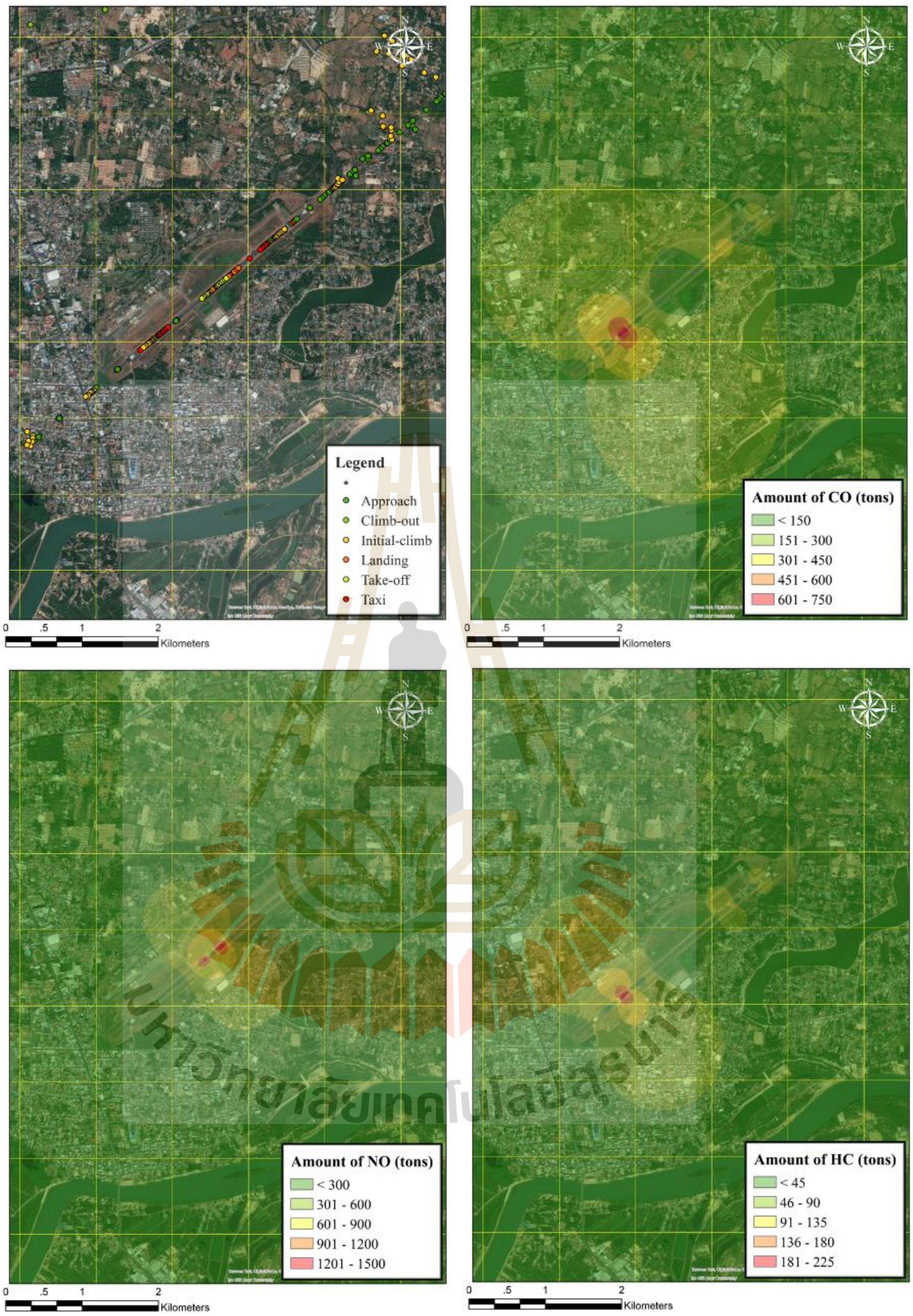


Fig. E.11 The spatial emissions at Ubon Ratchathani airport

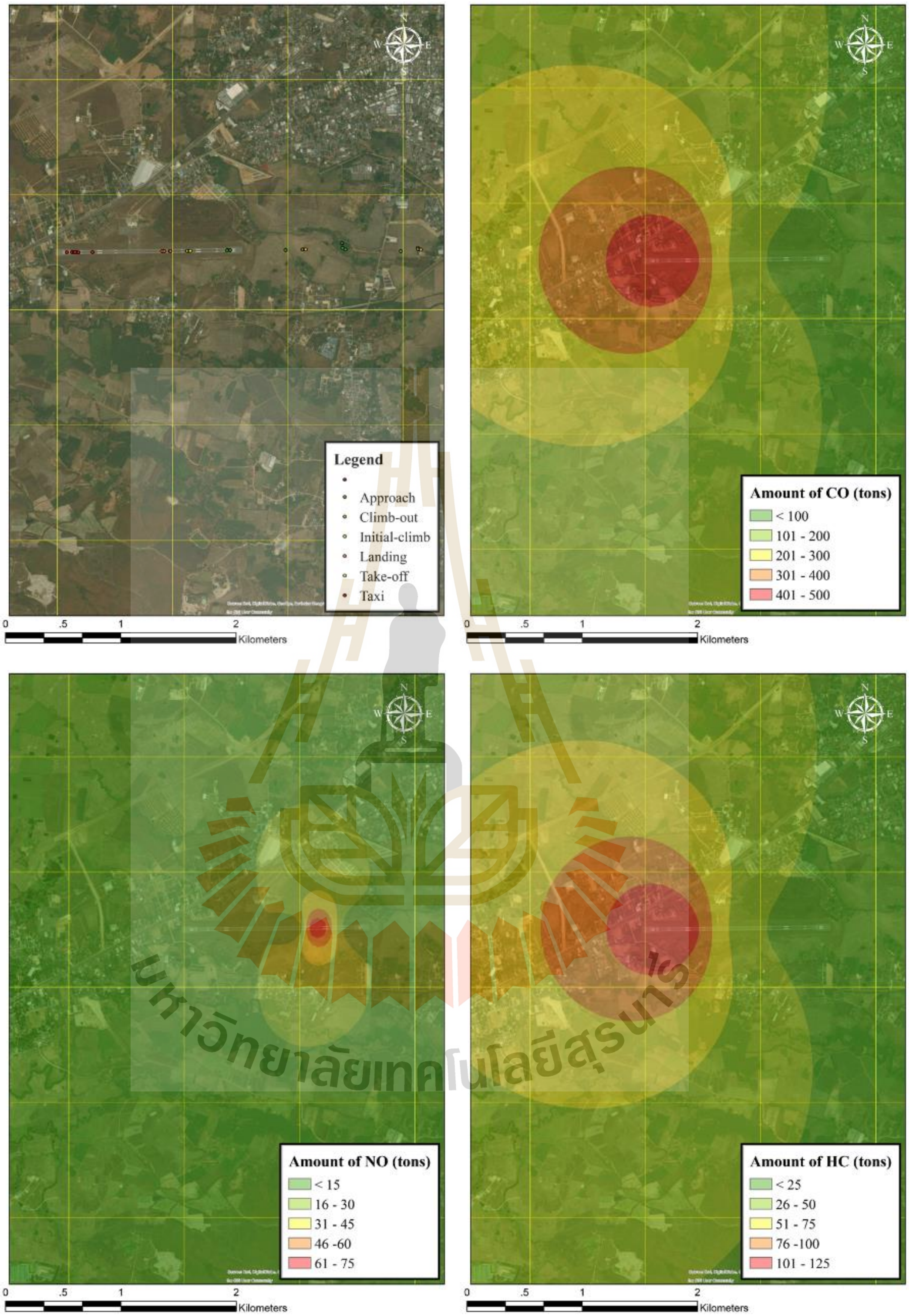


Fig. E.12 The spatial emissions at Mae Sot airport

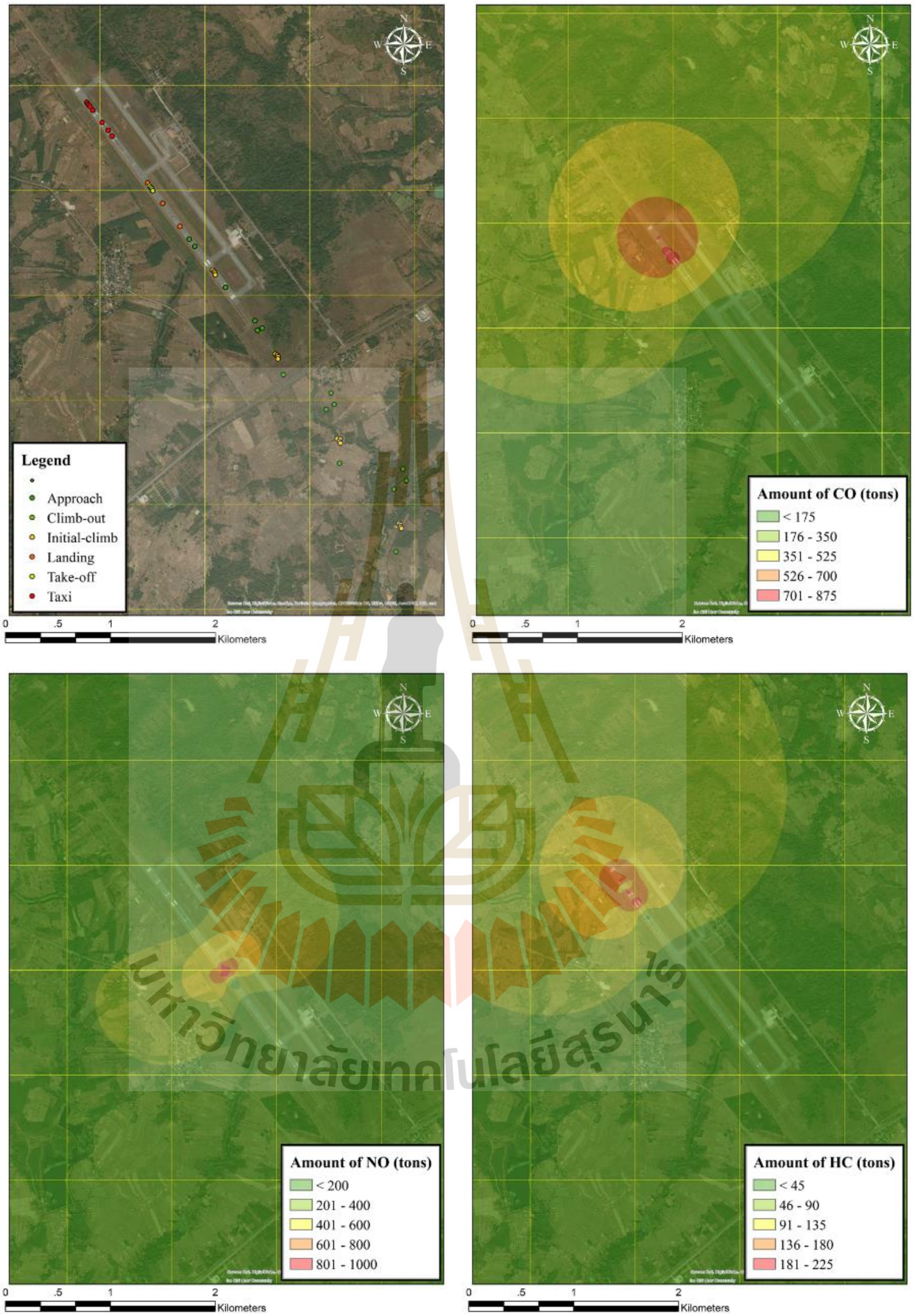


Fig. E.13 The spatial emissions at Nakhon Phanom airport

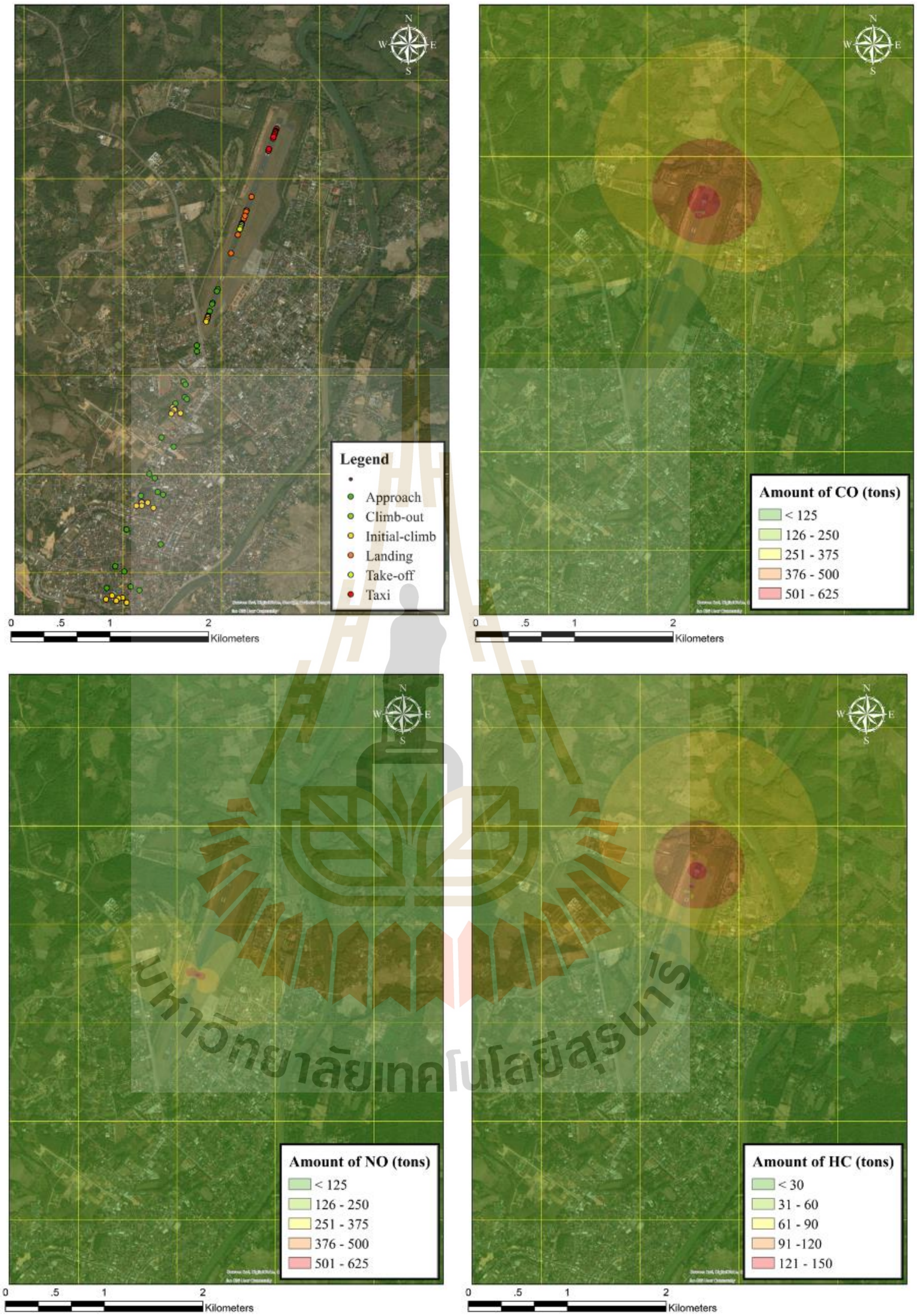


Fig. E.14 The spatial emissions at Nan Nakhon airport

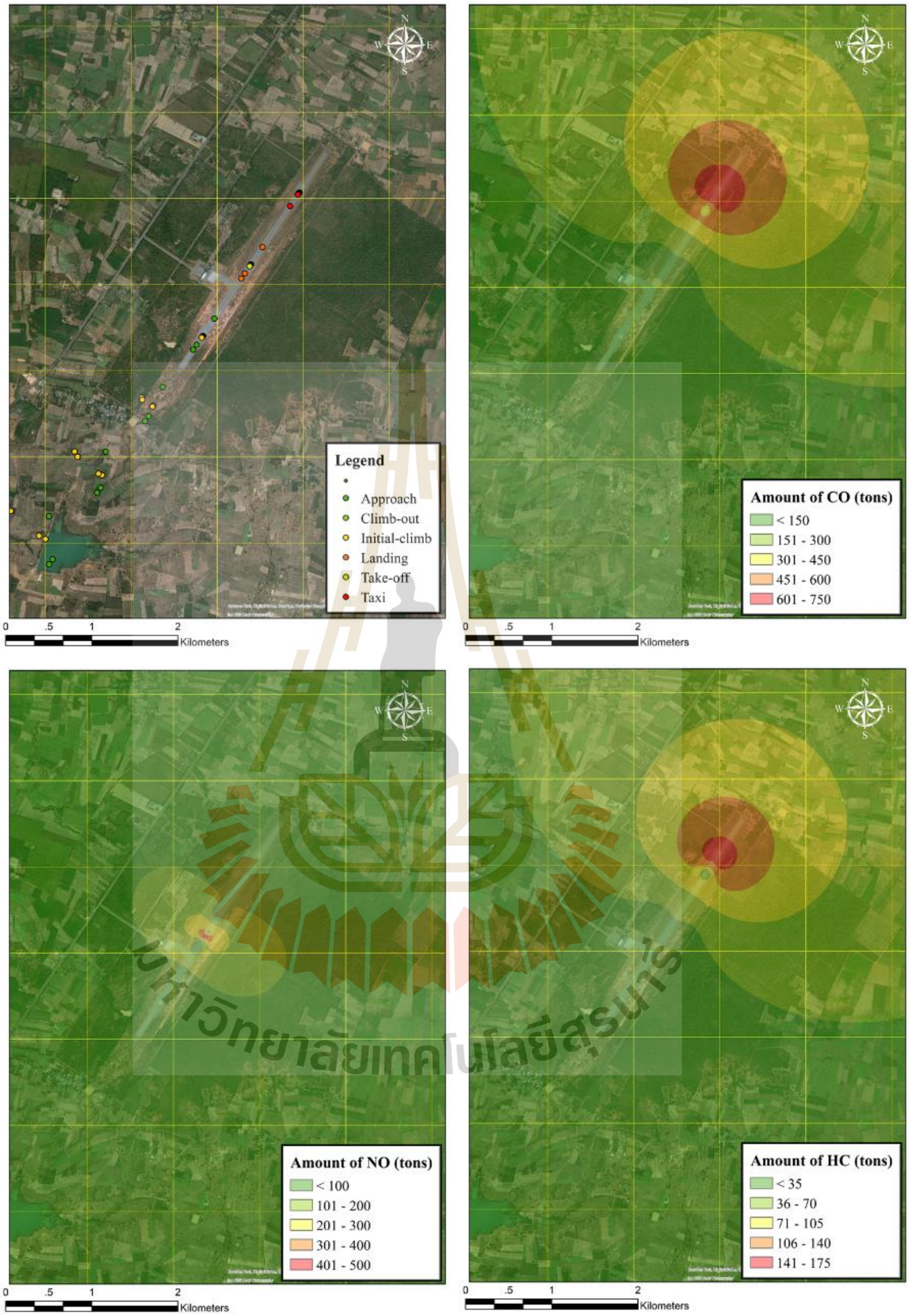


Fig. E.15 The spatial emissions at Buriram airport

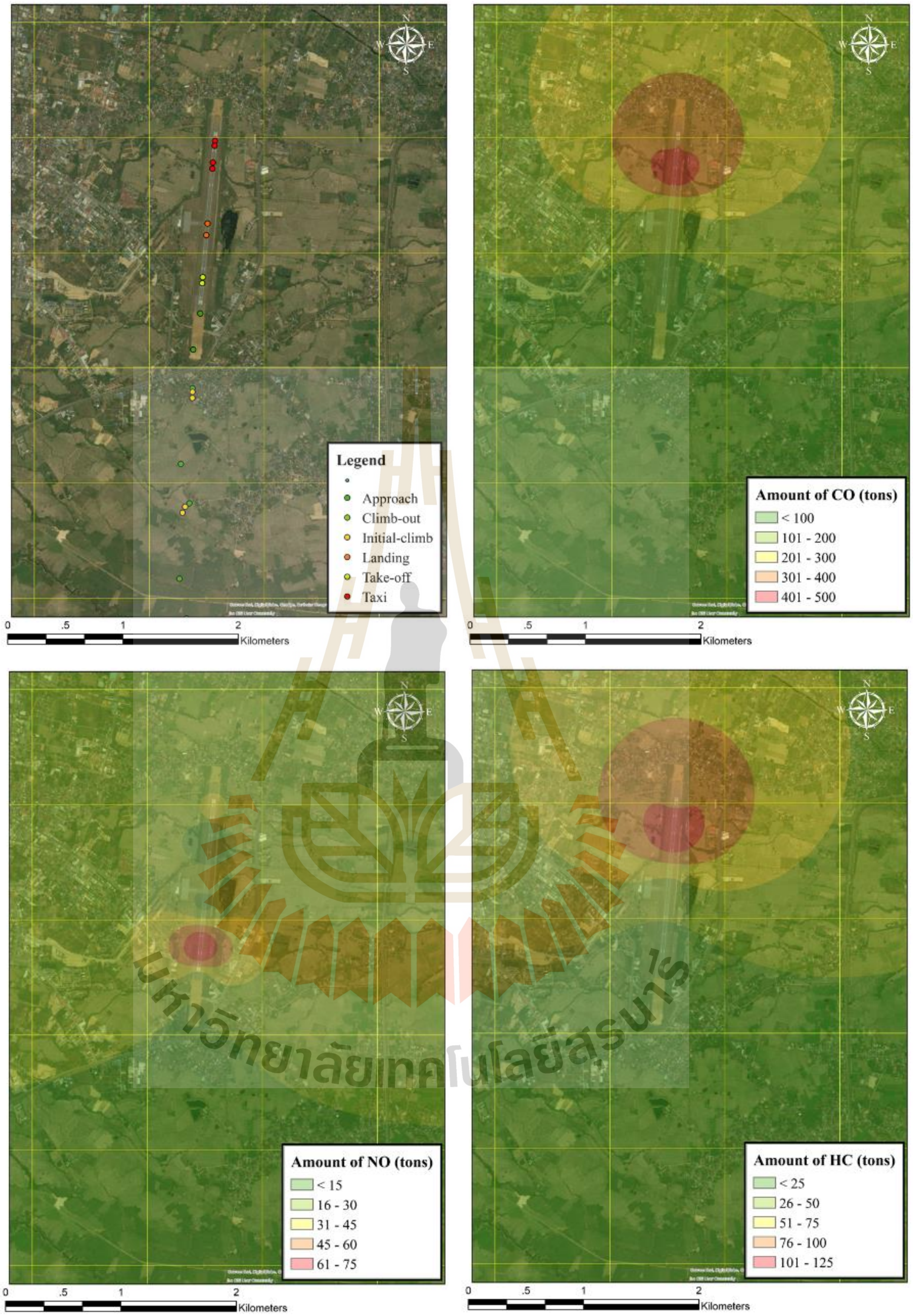


Fig. E.16 The spatial emissions at Phrae airport

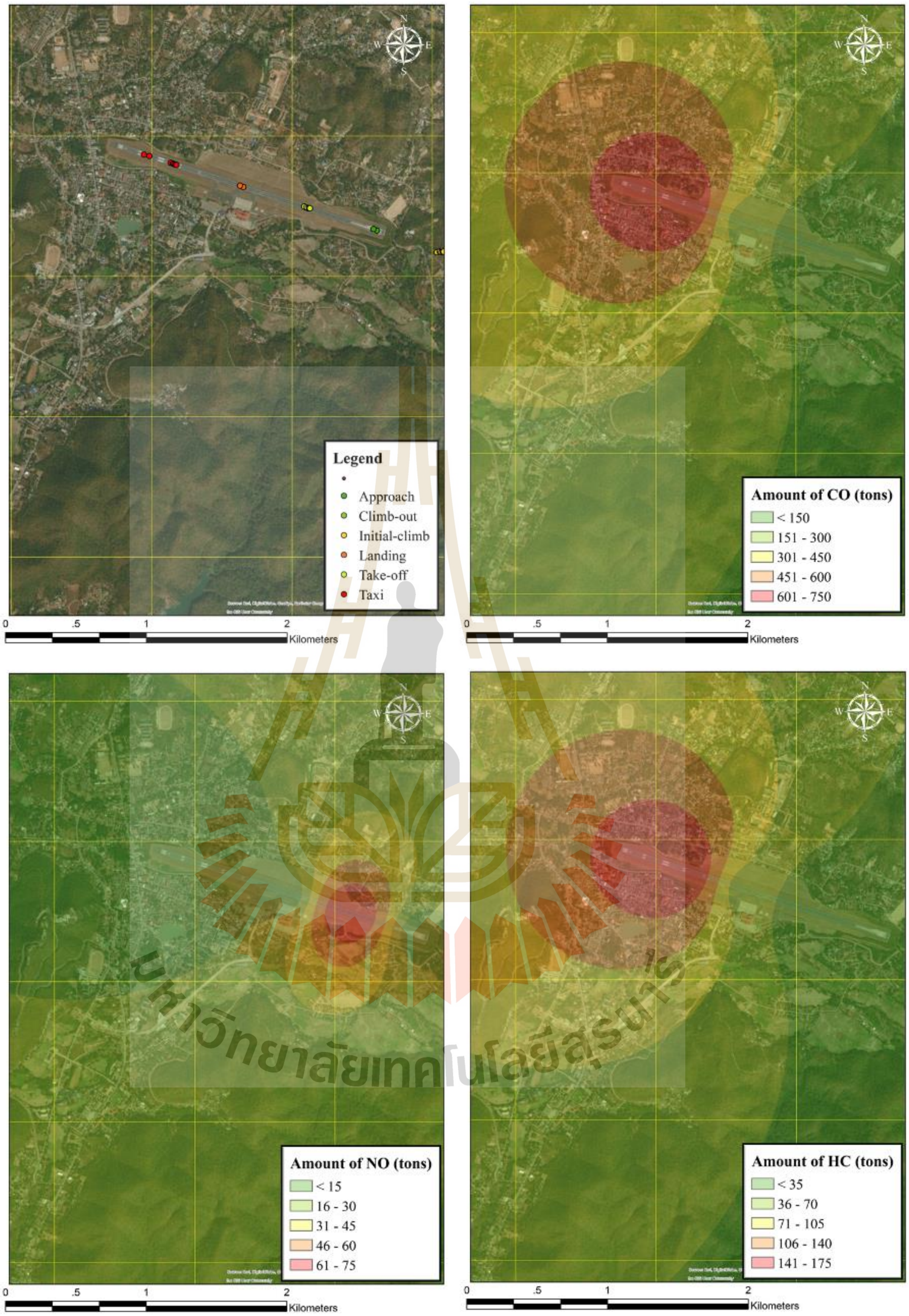


Fig. E.17 The spatial emissions at Mae Hong Son airport

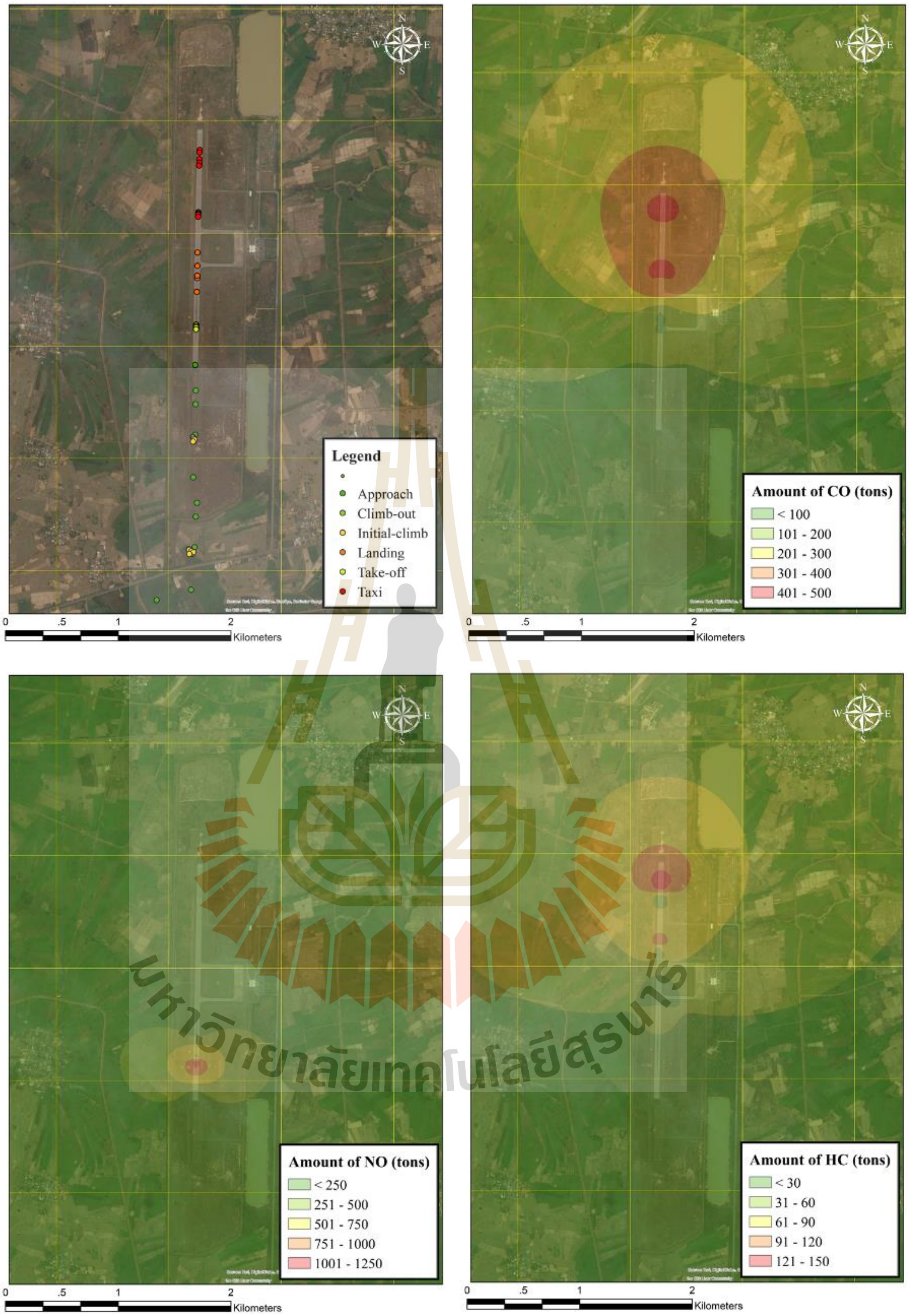


Fig. E.18 The spatial emissions at Roi Et airport

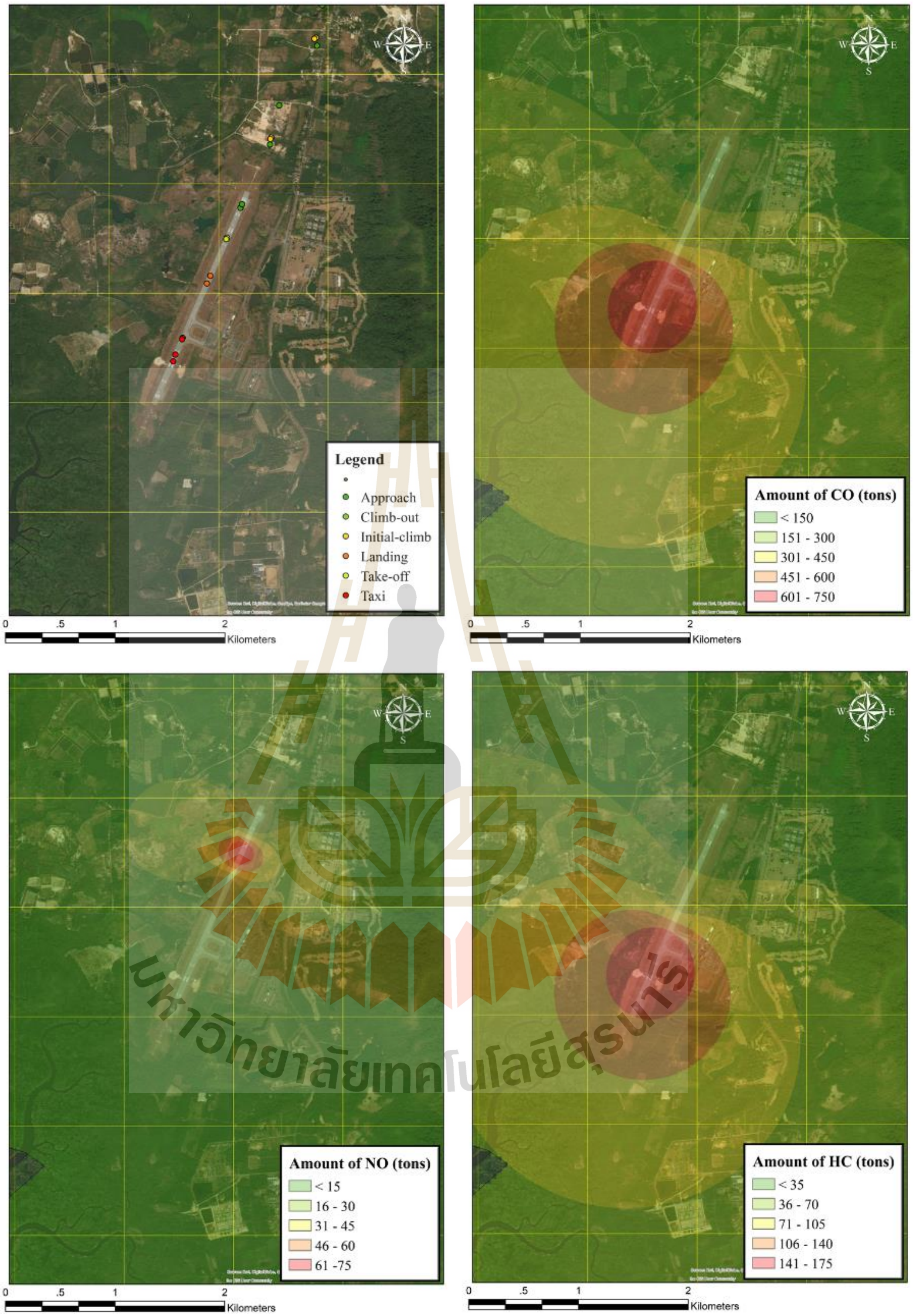


Fig. E.19 The spatial emissions at Ranong airport

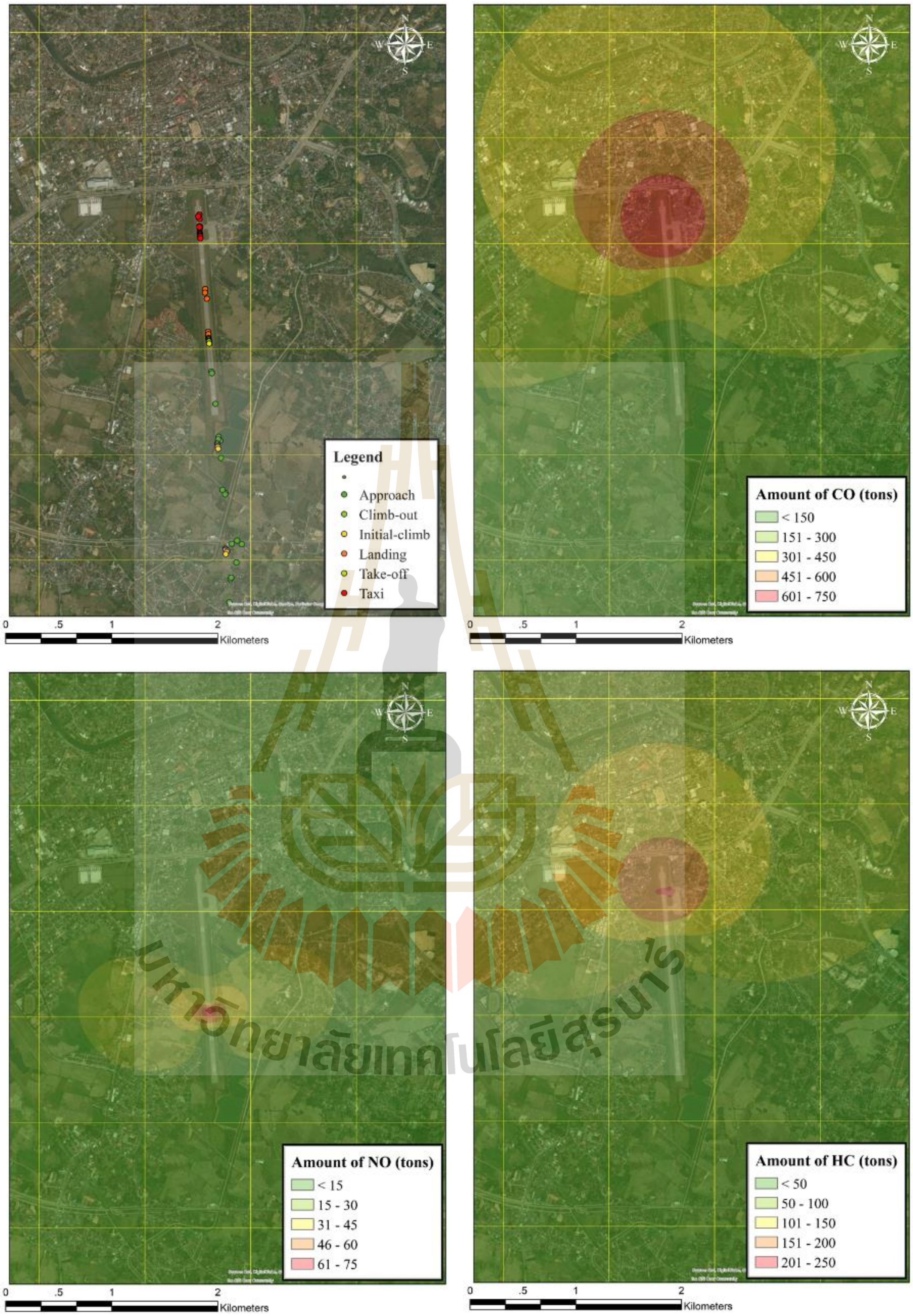


Fig. E.20 The spatial emissions at Lampang airport

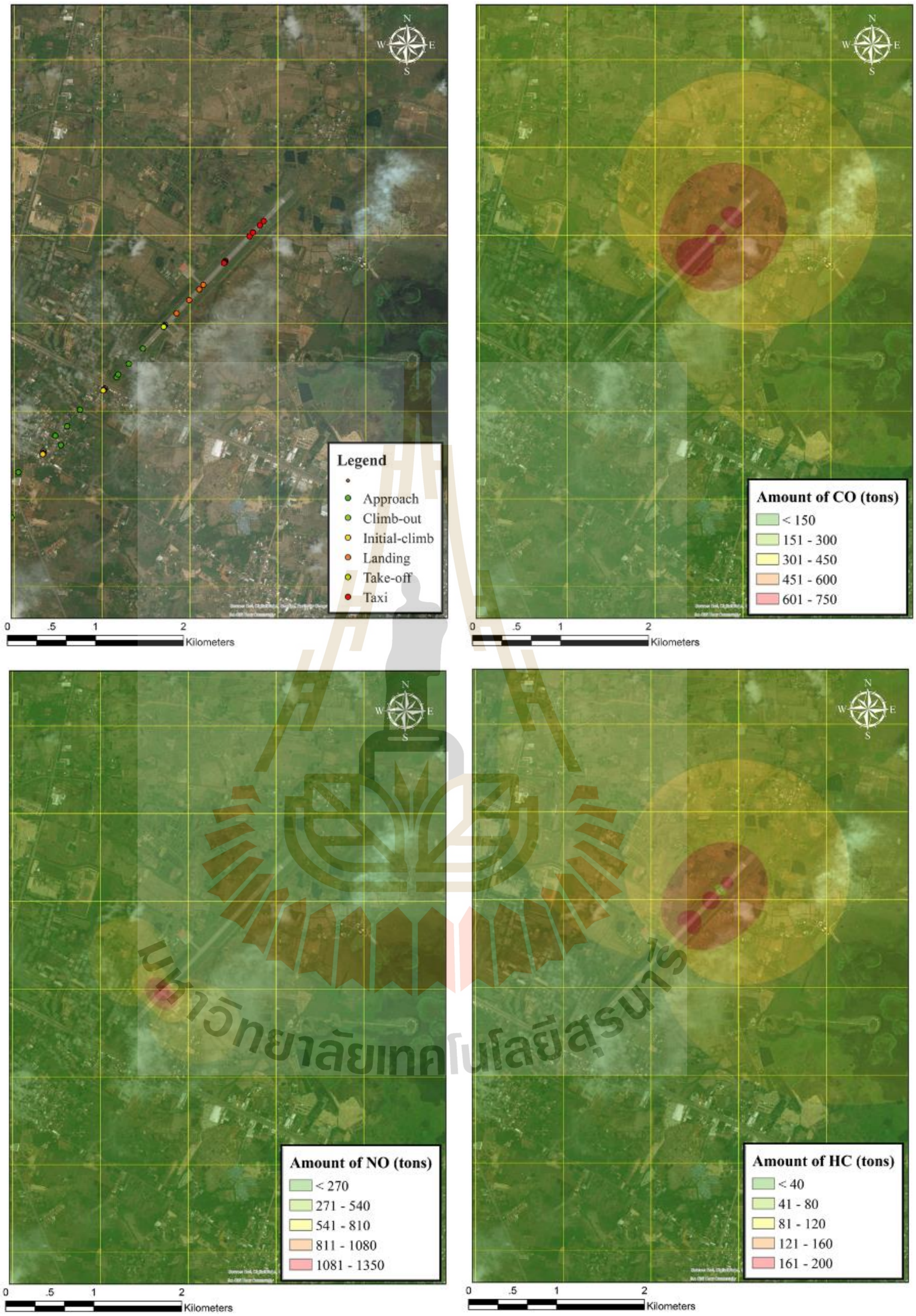


Fig. E.21 The spatial emissions at Sakon Nakhon airport

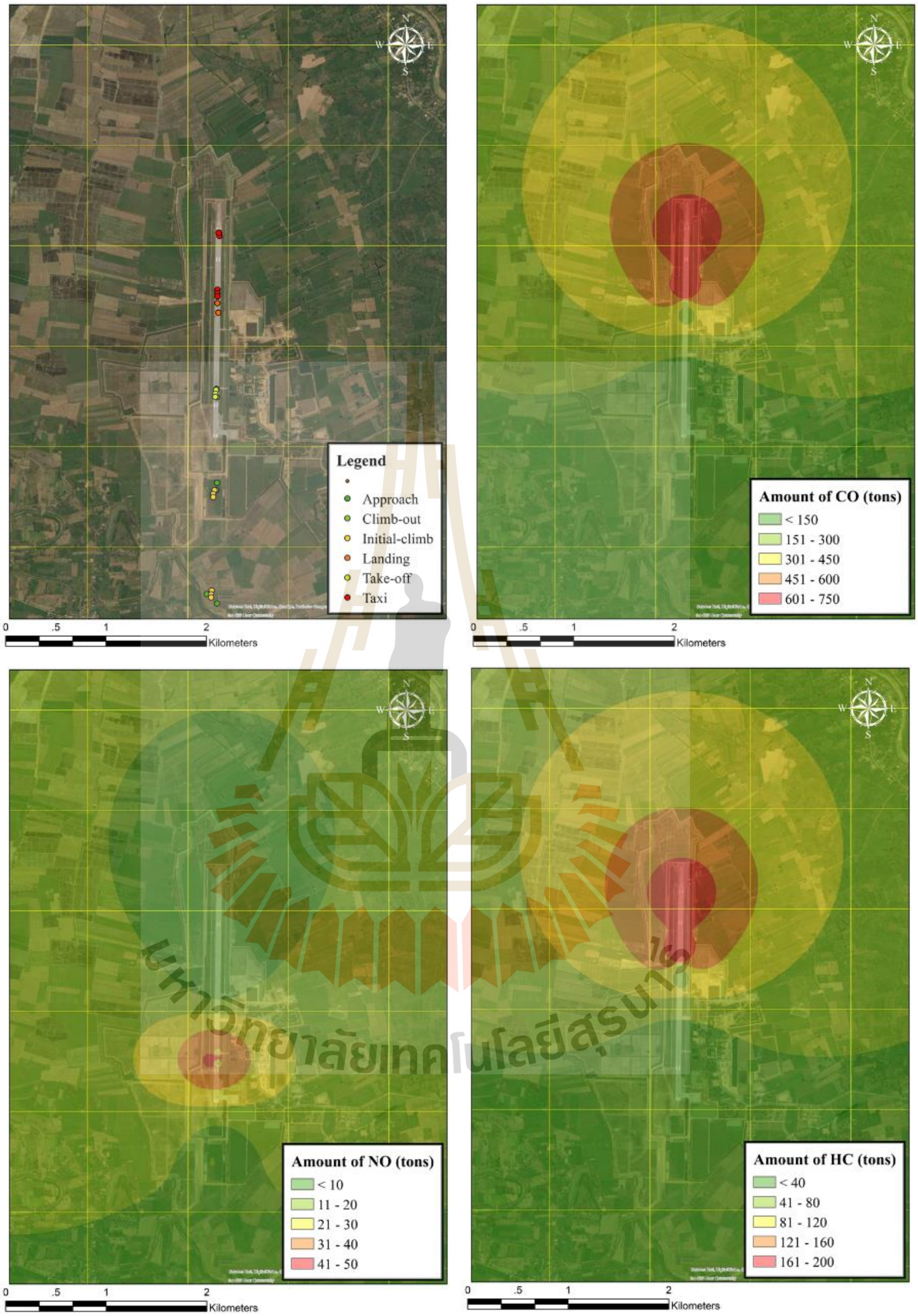


Fig. E.22 The spatial emissions at Sukhothai airport

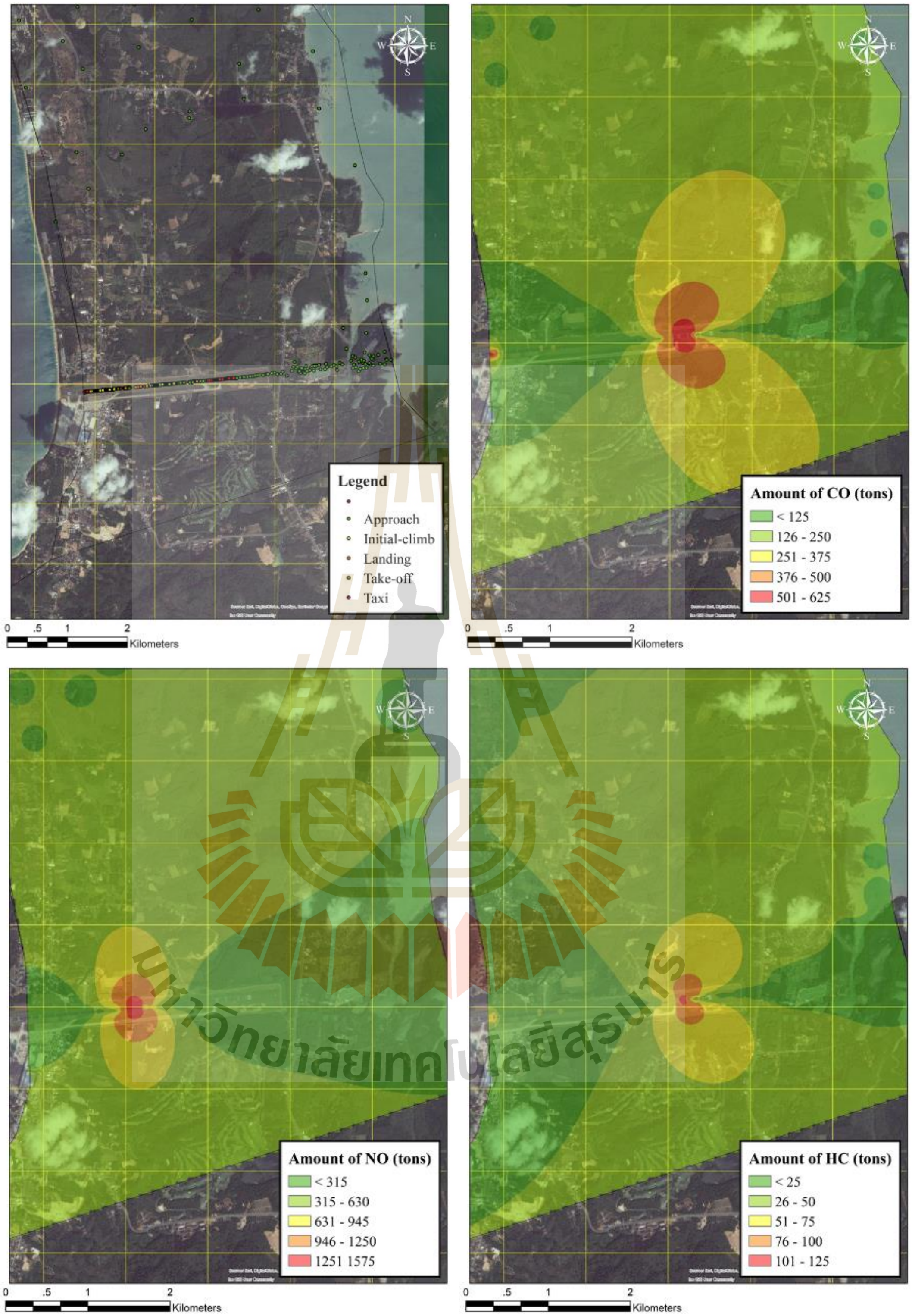


Fig. E.23 The spatial emissions at Phuket airport

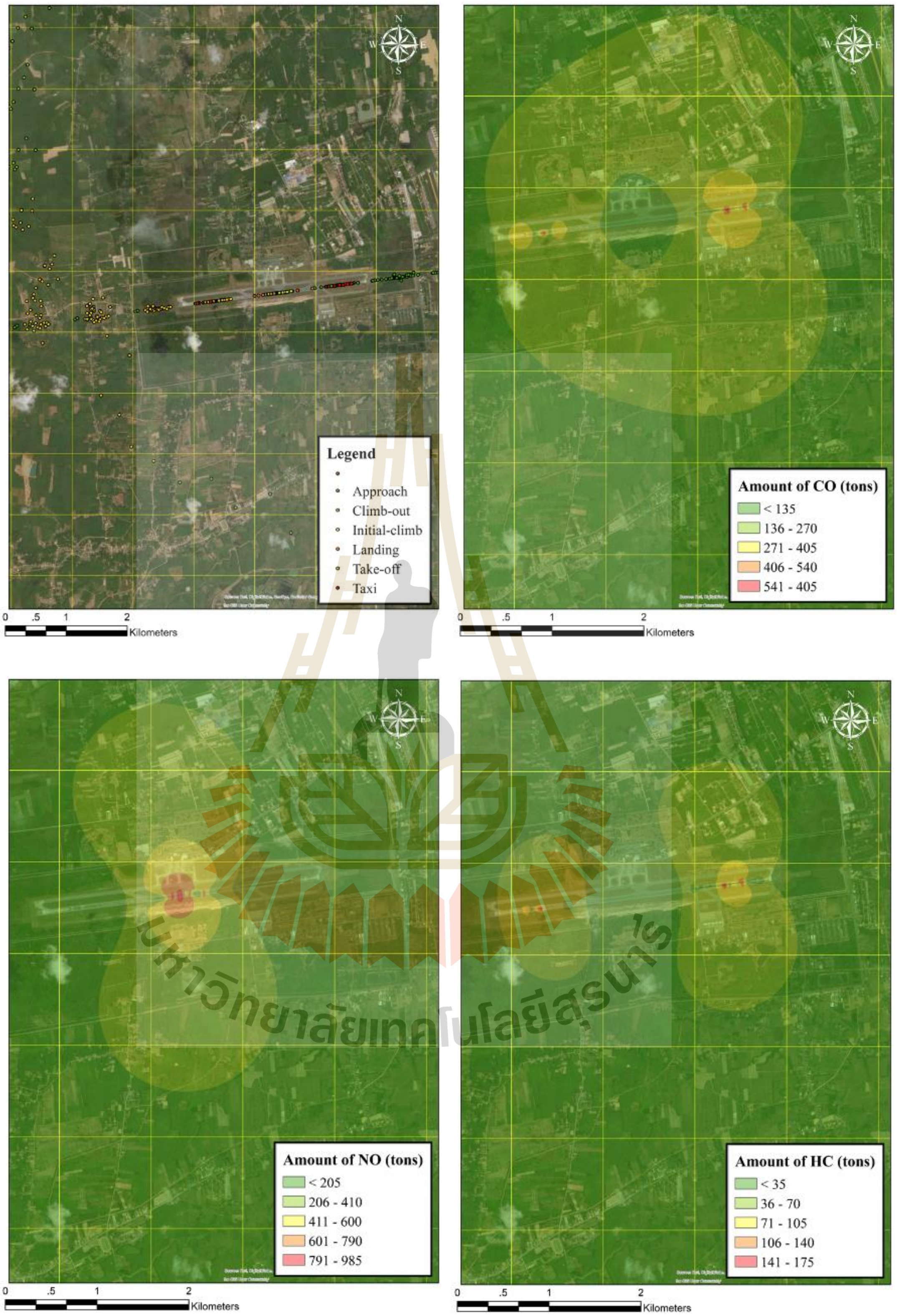


Fig. E.24 The spatial emissions at Hat Yai airport

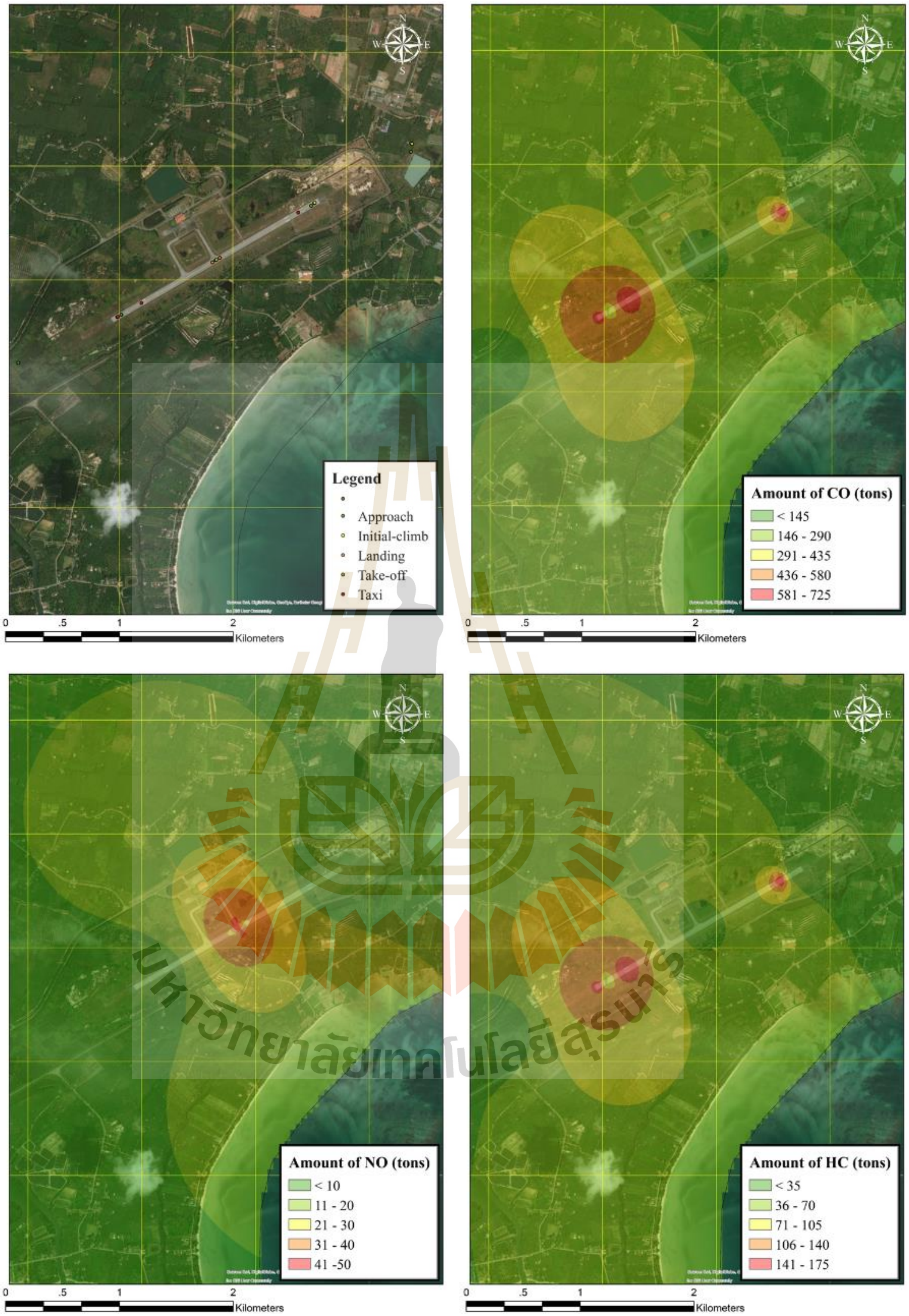


Fig. E.25 The spatial emissions at Chumphon airport

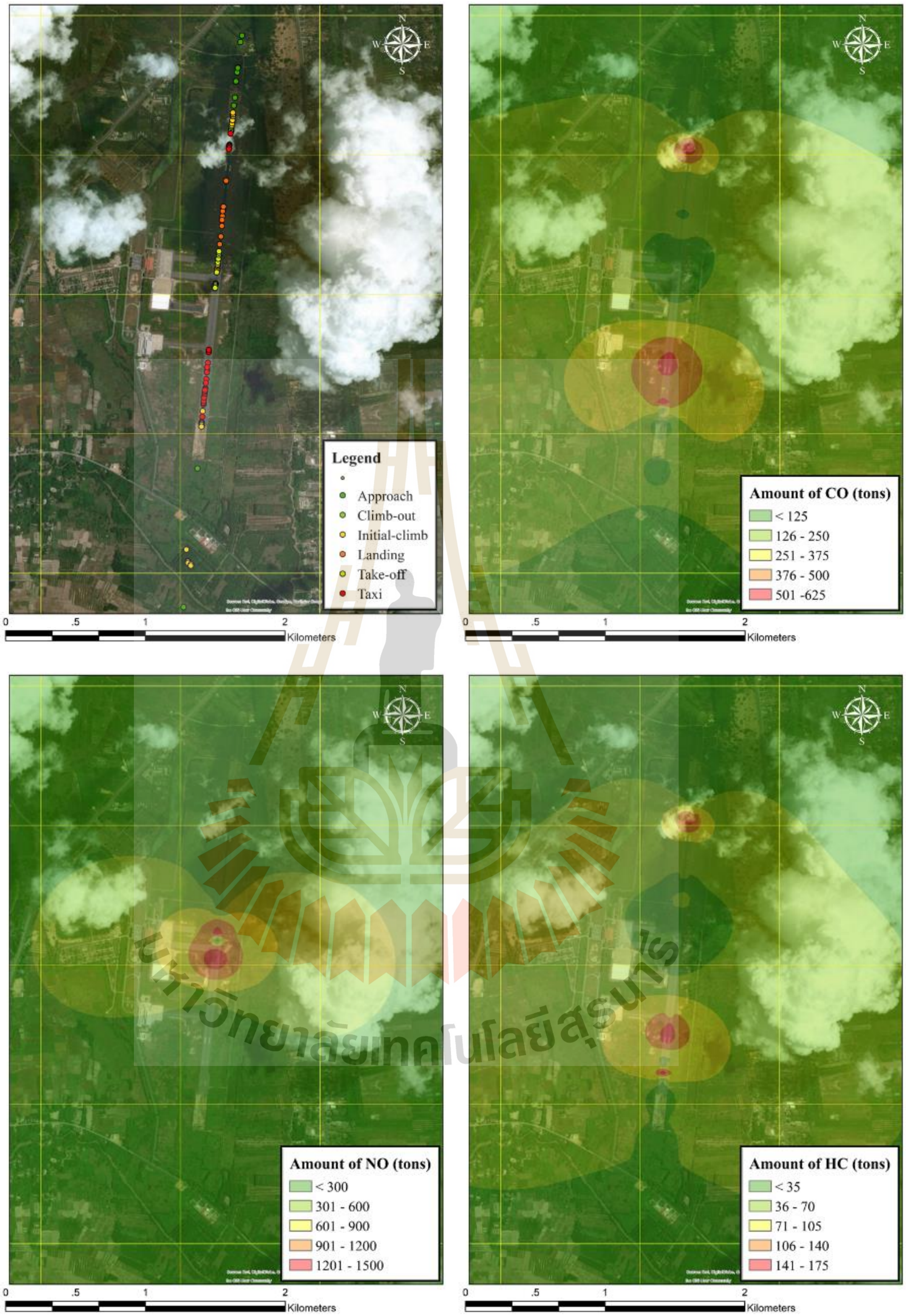


Fig. E.26 The spatial emissions at Nakhon Si Thammarat airport

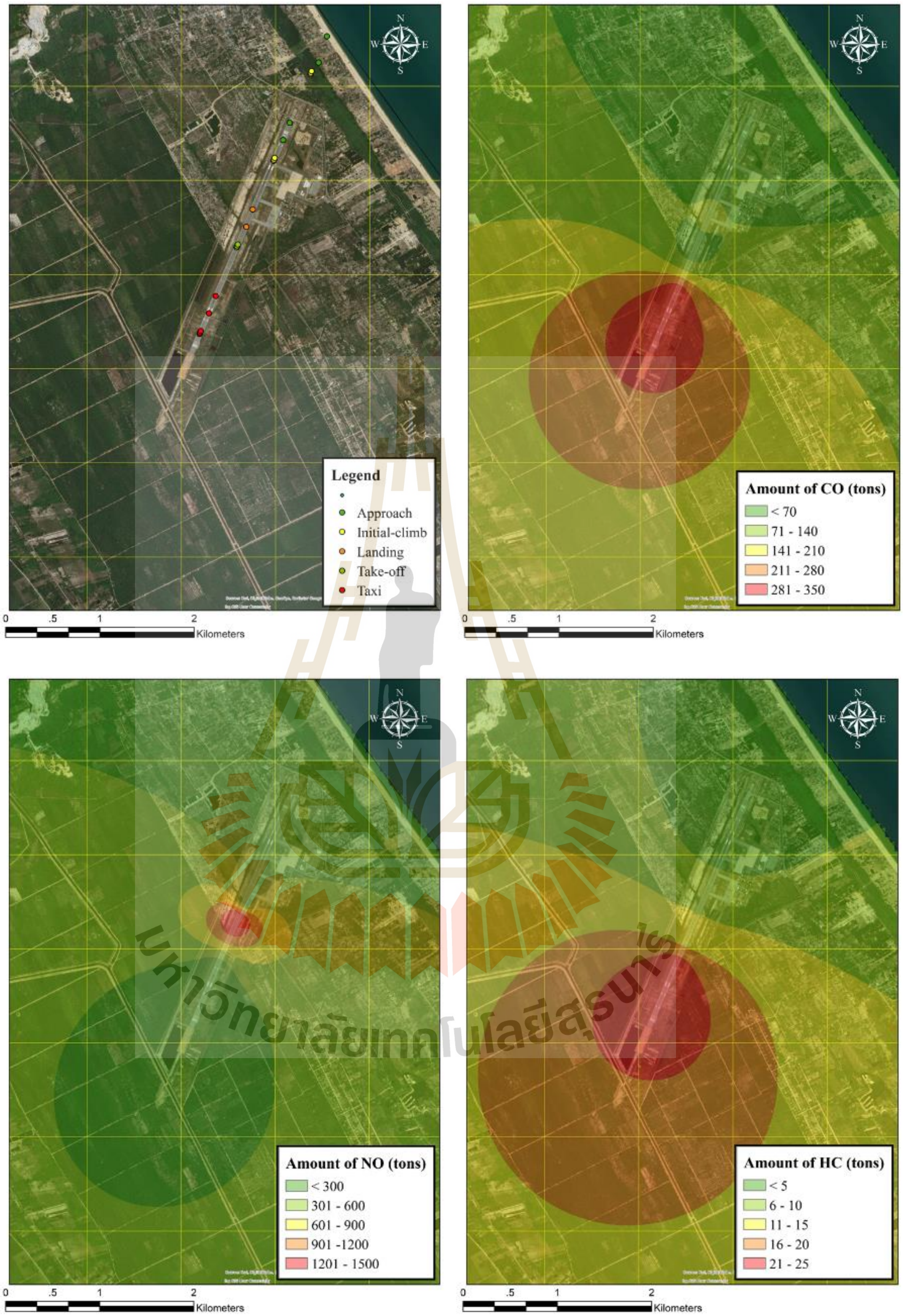


Fig. E.27 The spatial emissions at Narathiwat airport

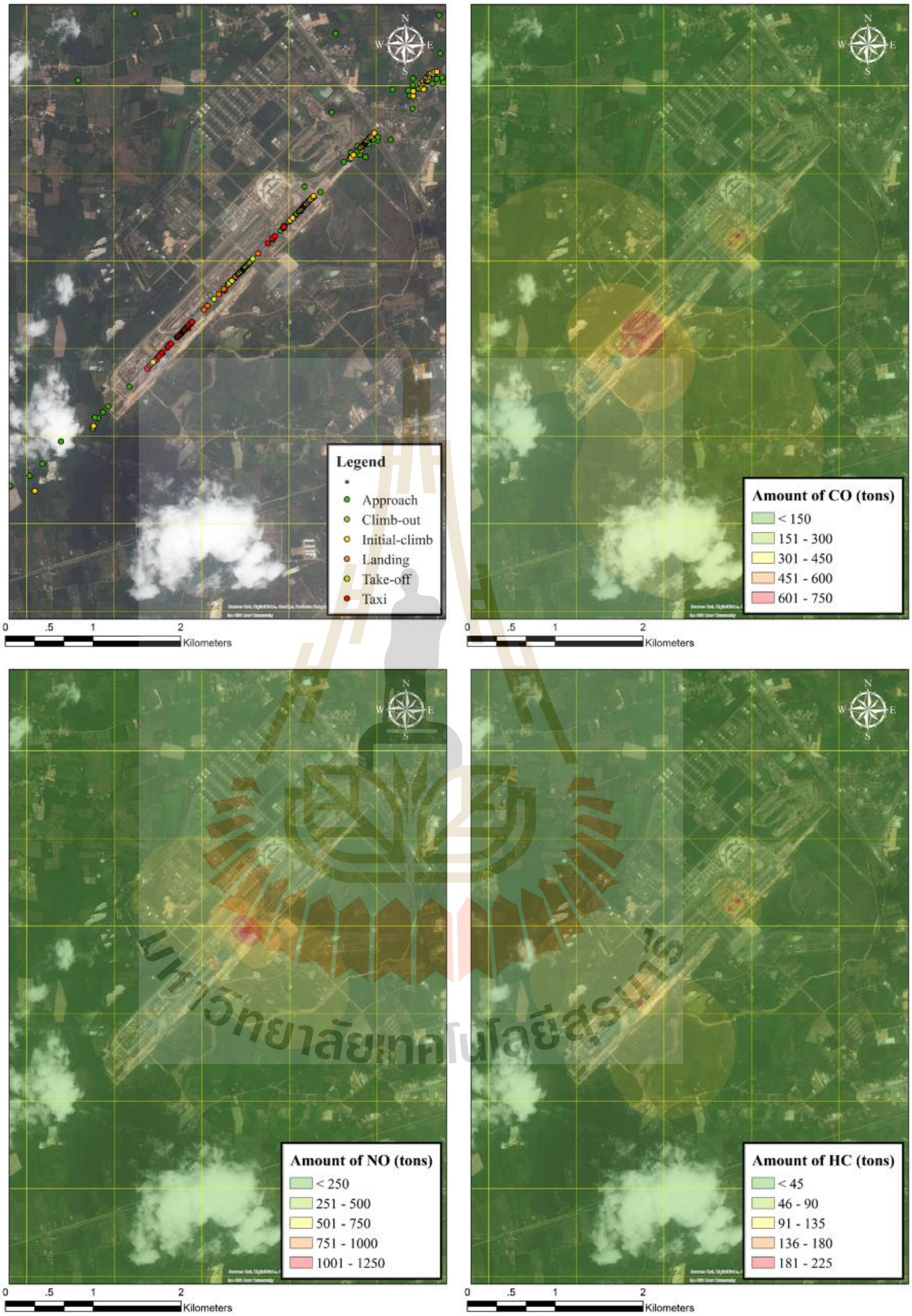
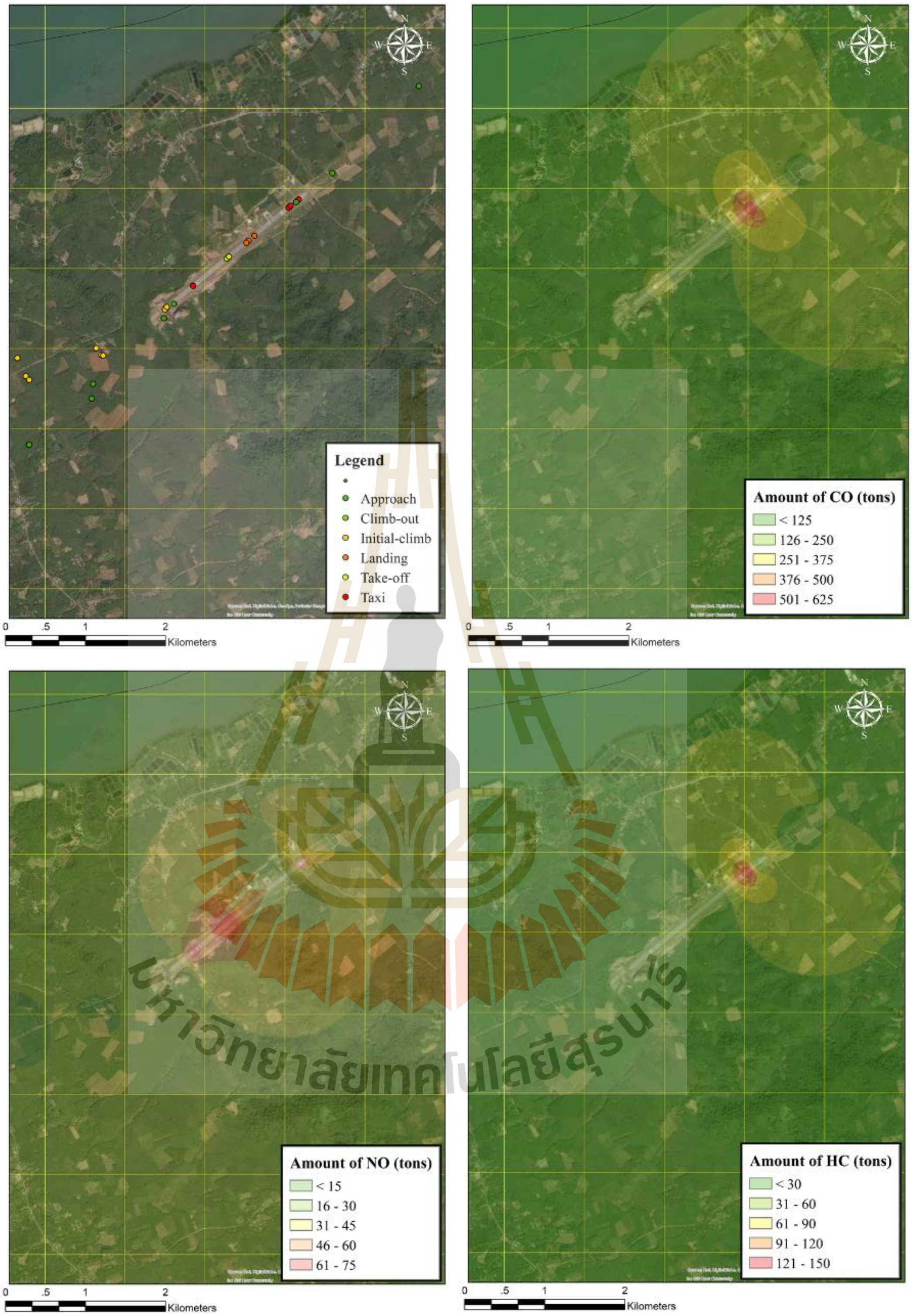


Fig. E.28 The spatial emissions at Surat Thani airport



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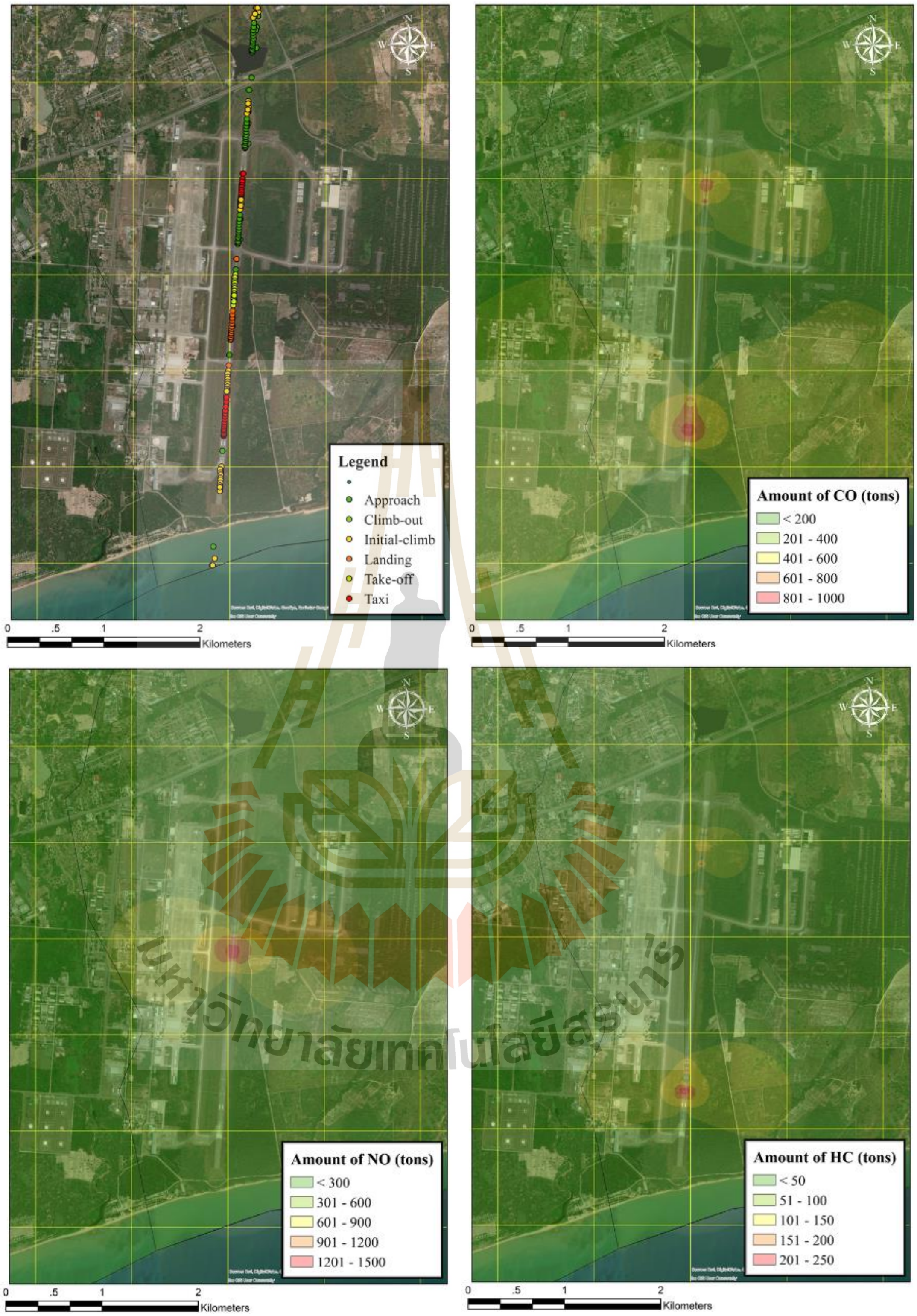

Fig. E.30 The spatial emissions at U-Tapao airport

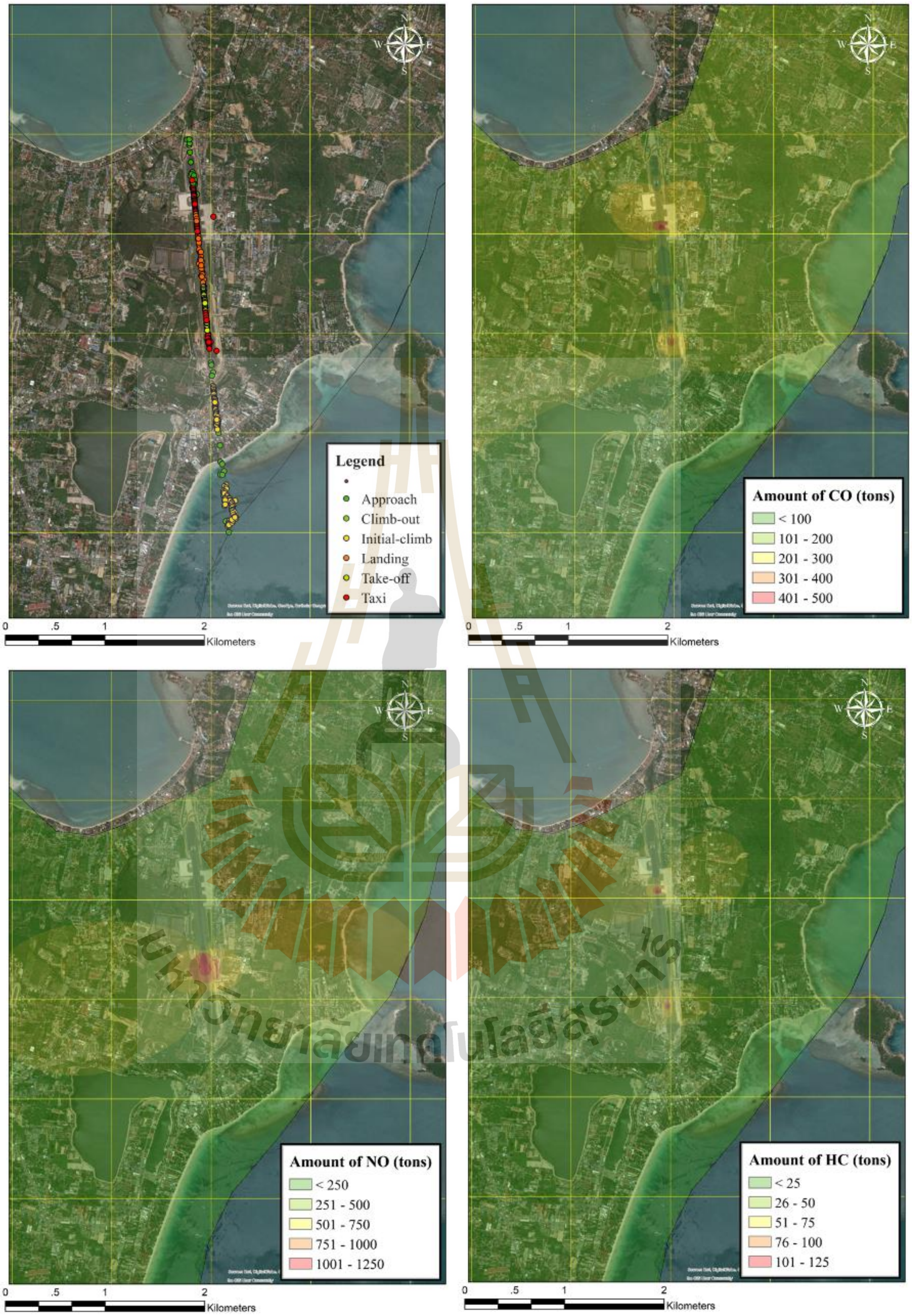

Fig. E.31 The spatial emissions at Samui airport

PUBLICATION

Thanjangreed, W., and Chuersuwan, N. (2018). **Commercial Aircraft Emission Estimates with 1 km x 1 km Resolution: A Case of Departure Flights at Suvarnabhumi Airport**. The 2nd International Conference on Environment, Livelihood, and Services, November, 19-22, 2018, CW Tower, Bangkok, Thailand

Thanjangreed, W., and Chuersuwan, N. (2019). **Emission Estimates during Landing/Take-off Activities from the Commercial Aircrafts at Large International Airports in Thailand**. The 5th EnvironmentAsia International Conference, June, 13-15, 2019, Convention Center, The Empress Hotel, Chiang Mai, Thailand

Thanjangreed, W., and Chuersuwan, N. (2019). **Emission Estimates of Commercial Aircrafts based on LTO Cycle at International Airports in Thailand**. National Conference on Air Quality in Thailand: PM 2.5, December, 12, 2019, Pathumwan Princess Hotel, Bangkok, Thailand

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Oral presentation, "**Emission Estimates during Landing/Take-off Activities from the Commercial Aircrafts at Large International Airports in Thailand**", The 5th EnvironmentAsia International Conference, June 13-15, 2019 at Convention Center, The Empress Hotel, Chiang Mai, Thailand

Oral presentation, "**Emission Estimates of Commercial Aircrafts based on LTO Cycle at International Airports in Thailand**", National Conference on Air Quality in Thailand: PM 2.5, December, 12, 2019, Pathumwan Princess Hotel, Bangkok, Thailand

Grants and Fellowships

The scholarship of outstanding academic performance from Suranaree University of Technology