A GIS-based Analysis for Selecting Ground Infrastructure Locations for Urban Air Mobility

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As the growth of cities and urban region expand, the commuting process on the surface level is likely to increase travel time. Meanwhile, the burgeoning advancement of aviation technologies is now able to create rapid, light, less noisy, and more environmentally-friendly Personal Air Vehicles.

By using shared mobility concepts, on demand mobility (ODM) aviation is getting closer to economic and technological feasibility and thus, realization. This concept might be the future of commuting. Nevertheless, ODM aviation is not as flexible as surface ODM in regard that, passengers not able to easily board and alight into shared vehicles as with ground-based modes. ODM aviation needs dedicated vertical take-off and landing (VTOL) infrastructure, a so called vertiport, as a dedicated place for the passenger to board and alight into Personal Air Vehicles.

Determining the infrastructure requirements to enable ODM aviation operation in an urban environment and factors that influence vertiport availability are two of the crucial challenges during initial development of ODM aviation. ODM aviation definitely requires specially built infrastructure, as, to date, no Personal Air Vehicle has ever been integrated into an urban transport system. Once the infrastructure has been defined, an elaboration of the placement criteria and how such criteria influence vertiport location is required. This thesis comprises of a literature review to analyze those aforementioned challenges and, further, efforts to implement suitable vertiport location analysis on GIS-based software. To apply and test the forthcoming model, a case study of a selected city with adequate required data availability is to be undertaken.

The student will present intermediate results to the mentors (Prof. Dr.-Ing. Rolf Möckel and Raoul Rothfeld (Bauhaus Luftfahrt)) in the fifth, tenth, 15th and 20th week. The student will submit one copy for each mentor plus one copy for the library of the Focus Area Mobility and Transport Systems. Furthermore, the student will provide a PDF file of the master thesis for the website of this research group. In exceptional cases (such as copyright restrictions do not allow publishing the thesis), the library copy will be stored without public access and the PDF will not be uploaded to the website.

The student must hold a 20-minute presentation with a subsequent discussion at the most two months after the submission of the thesis. The presentation will be considered in the final grade in cases where the thesis itself cannot be clearly evaluated.

Prof. Dr.-Ing. Rolf Moeckel Dimas Numan Fadhil

Declaration Concerning the Master's Thesis

I hereby confirm that the presented thesis work has been done independently and using only the sources and resources as are listed. This thesis has not previously been submitted elsewhere for purposes of assessment.

Munich, May 15th, 2018

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Abstract

The burgeoning advancement of aviation and electric vertical take-off and landing (eVTOL) vehicle lead to a novel possibility of traveling in a metropolitan area. Worsening surface-level traffic makes the concept of urban air mobility (UAM) using eVTOL vehicle as a promising alternative. The problem occurs when there are no available take-off and landing places within the boundaries of a metropolitan area. Several previous studies provide methodologies of UAM ground infrastructure placement by means of simple geography analysis. This thesis conducts a different approach in UAM ground infrastructure placement using a geographic infromation system (GIS)-based analysis. A suitability analysis using the weighted linear combination (WLC) method is implemented by this thesis to locate suitable areas for UAM ground infrastructure. Previously, a review of relevant literature has been conducted to draw minimum requirements and influencing factors of UAM ground infrastructure placement. Generating the weights for the WLC analysis, this thesis conducts an analytic hierarchy process (AHP)-Delphi methods. To enhance the result of AHP-Delphi method, two "super-experts" are interviewed to give their personal weight on influencing factors of UAM ground infrastructure. They also give insights about further factors that are not included in the WLC analysis. In total, there are three different weights that create three different scenarios. Los Angeles and Munich are the two cities are taken as a case study for applying the GIS-based UAM ground infrastructure placement. The result of case studies in two metropolitan cities and three different scenarios show that the city center (which has high office rent prices in Munich and Los Angeles), airports and inter city train stations are suitable for the initial operation of UAM. Point of interests can also be an enhancement for these areas, catching niche market of tourism trip.

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Chapter 1

Introduction

1.1 Motivation

The number of inhabitants in cities has been increasing and the settlements are growing dispersedly towards periphery areas in many regions worldwide. The term “rush hour” embodies commuting culture between low-density peripheral areas and high-density city centers. The accessibility from the city center and other important destinations, such as airports, entertainment facilities, and higher education facilities, reduces, therefore adding travel time. As everyone has their own travel budget, in terms of travel cost and travel time, the growing size of cities and their peripheries appears as a problem for its inhabitants.

To cope with an increase in travel time, researchers, engineers, and scientists are putting efforts into establishing new concepts of commuting and travelling. Despite the availability of various travel modes, traffic congestion still increases as a result of urban policies that favor urbanization and agglomeration. Over the past 50 years, traffic congestion has increased significantly within metropolitan areas (Mondschein & Taylor, 2017). Even if the city wants to expand existing networks, they would have to invest an immense amount of taxpayers’ money. The burgeoning advancement of aviation technologies makes aviation manufacturers able to build rapid, less noisy, and more environmentally friendly Personal Air Vehicle (PAV). Major aviation manufacturers as well as slim-structured new start-ups are now competing on this new futuristic urban transport mode (Vascik & Hansman, 2017). Uber, as a major On-Demand Mobility (ODM) provider worldwide, also nurtures the progress of this transport mode as it released its Uber Elevate white paper and held an international summit about the future of Urban Air Mobility (UAM). UAM is a novel notion where Unmanned Aircraft Systems (UAS) and PAV are integrated into current urban mobility concept, flying within Very Low Level (VLL) airspace under supervision from Unmanned Aircraft System Traffic Management (UTM) (Kopardekar, 2017). Both freight and passenger services are operating in this three-dimensional urban mobility concept to fulfill the demand of rapid and seamless mobility. In fact, the initial stage of implementing UAM is seems to be not completely autonomous, the aircraft still requires pilots or certified drivers (PAV is envisaged as user-friendly and easy to be operated aircrafts, by the help of numerous sensors installed). Operating the futuristic PAV in an ODM concept makes the conceptual UAM costs similar to surface-level ODM service for the same travelled kilometers, yet might provide faster travel time (Uber Elevate, 2016). Although it looks promising, UAM is not deliberately developed and designed to reduce traffic congestion and loosen up cramped public transport. It is perceived to provide additional transport supply and high accessibility for periphery settlement inhabitants as well as providing better mobility service for disabled people.

Not only aircraft manufacturers but also startups, technology companies, and car manufacturers are competing in the PAV development. There are two types of PAV, conventional and short take-off and landing (STOL) and extremely short/vertical take-off and landing (VTOL) (Shamiyeh, Bijewitz, & Hornung, 2017). Recently, electric vertical take-off and landing (eVTOL) vehicles are under the spotlight as many start-ups in this category received abundant funding or were acquired by giant companies. As a part of VTOL genus, the development of eVTOL vehicles began when the drone was invented. The accomplishment of drone take-off and landing reflected the potential to develop novel concept of aerial vehicle further. Alike drone, the usage of distributed electric propulsion in eVTOL vehicles bring a lot of advantages, for instance reduced energy cost and reduced maintenance hours (Duffy, Wakayama, & Hupp, 2017). Regarding community acceptance, in which noise annoyance plays an important role, eVTOL, such as CityAirbus (Airbus, 2017), Volocopter (e-volo GmbH, 2017) and Lilium Jet (Lilium, 2017), claimed emitting low acoustic footprint.

1.2 Problem Statement

UAM not only requires aircraft, which can safely accomplish a vertical landing process, but also ground infrastructures to offer seamless access for the passengers and to provide maintenances for the vehicles. The term Vertiport denotes ground infrastructures of eVTOL Vehicle operation. Vascik and Hansman (2017) created several Concepts of Operations (ConOps) that demand Vertiport as a dedicated place for the passenger to board and alight into eVTOL vehicle. He also stated that the availability of ground infrastructures for UAM is the second most important near-term limitation.

In line with this, Uber Elevate (2016) also wrote in its white paper that the biggest operational challenge of implementing UAM in metropolitan vicinity is the deficiency of ground infrastructure. Compared to the initial investment requirement for surface-based urban transportation mode, the construction of UAM ground infrastructure could cost less. The operator has chances to utilize current helipads with some modification according to VTOL vehicle requirements, as well as alter rooftops of high rise parking garages.

Nevertheless, there are only a few studies that have been done assessing the infrastructure requirement of a UAM operation. To date, there are only a few focused studies about eVTOL ground infrastructure requirements (Alexander & Syms, 2017; Seeley, 2017a; Vascik & Hansman, 2017; Antcliff, Moore, & Goodrich, 2016). Moreover, there is no established standard on how an UAM ground infrastructure should be designed (Alexander & Syms, 2017). The first research question in this thesis is aimed to offer new approach in UAM ground infrastructure standard and design.

Research Question 1: What are the minimum requirements of UAM ground infrastructure?

The number of passengers who are willing to use eVTOL vehicle for their commuting or non-commuting purpose is also another problem raised. To establish an economically sustainable UAM operation, the placement of UAM ground infrastructure should cover potential demand. This principle also applies to the surface public transport system, which designs its network to attract as many passengers as possible (Vuchic, 2005). While UAM is envisaged bringing innovation and disruption into the current urban transportation landscape, noise nuisance remains as a major problem for community acceptance. If the eVTOL vehicle is capable of producing less noise, then diffused ground infrastructure for UAM operation could be built throughout urban areas (Parker, 2017). Privacy and flying restriction could also be factors hindering UAM ground infrastructure development. Assuming the helicopter as a proxy for this research, there are many rules and regulations which differ from one another, depending on where the rules and regulations take place (Vascik & Hansman, 2017). Integration between PAV (especially eVTOL) and UAS in a UTM system has a potential to generate additional air traffic, especially in crucial infrastructure such as in the airport vicinity. Among many factors that tend to influence UAM ground infrastructure, the second research question refines what are the factors should be considered in UAM ground infrastructure location.

Research Question 2: What are the factors influencing UAM ground infrastructure placement?

The factors influencing UAM ground infrastructure placement are not spatially translated to find suitable locations for initial construction of ground infrastructure. In many recent studies about UAM, the location of UAM ground infrastructure are selected based on census block (German, Daskilewicz, Hamilton, & Warren, 2018; Syed et al., 2017). This thesis aims to go into more fine-grain resolution level with geographic information system (GIS)-based approach, as the current development of UAM demands more implementable outcome. To that end, the third research question drives this thesis in endeavoring geospatial research in area of future air-borne transport mode.

Research Question 3: How to determine suitable location for UAM ground infrastructure?

1.3 Research Objective

This thesis aims to define and set minimum ground infrastructure requirements for eVTOL operation as the first research objective. To that end, it is necessary to go further and establish a designated standard for UAM ground infrastructure. The influencing factors of ground infrastructure for UAM through a widespread literature review will be the second step and predecessor to following objective. Following this, suitable analysis will be conducted to find potential location for developing initial ground infrastructure for UAM. Geographic Information System (GIS)-based software will also be utilized in two case studies, Los Angeles (LA) and Munich. The importance of having such a case study is to give particular example of the sequence of UAM ground infrastructure site selection process. Providing an assessment result of narrowed-down suitable ground infrastructure location for the initial phase of UAM operation is the final objective of this thesis.

1.4 Scope

Since most of the manufacturers come with their own concepts and ideas of how a PAV will be designed, this thesis will only consider the particular VTOL vehicle type called electric Vertical Take-off and Landing (eVTOL) vehicle. This thesis will only consider manned aerial mobility, thus the UAM ground infrastructure placement in this thesis will be focusing on passengers demand.

1.5 Thesis Overview

The structure of this thesis is as follows: Chapter 2 consists of a review of relevant literature about urban transport infrastructure planning, eVTOL infrastructure and accessibility analysis. Compiling several references and variables from the literature review, Chapter 3 offers three types and their proposed designs of UAM ground infrastructure. Summary of literature review about criteria that influence UAM ground infrastructure selection process builds up chapter 4. Chapter 5 explains about the implementation of analytic hierarchy process (AHP)-Delphi method. Implementation of case study using GIS software comprises Chapter 6. Chapter 7 concludes the result of this research along with recommendations for further research in this field.

Chapter 2

Background and Literature Review

2.1 Urban Air Mobility

There are several studies about air-based transportation that deliver passengers within urban boundaries. Nonetheless, the concepts of this intra-regional aircraft operation have been evolving over the years. On-demand Mobility Aviation (ODM Aviation), Personal Air Transportation System (PATS), Sky Transit, or UAM are examples of different concepts in which air-based transportation is operated within metropolitan and regional areas. European researchers initiated the concept of PATS, which has similar goals as NASA's Small Aircraft Transportation Systems (SATS). Both are aimed to provide harmless, affordable, and environmentally friendly door-to-door air transport using small (4-10 seats) aircraft. Both concepts were planned to use a conventional take-off and landing system, in a maximum 600 m runway (Rohacs, 2002).

Around 15 years later, NASA commenced its new air-based urban transportation concept called On-Demand Air Mobility (Parker, 2017). This appears to be similar to ODM Aviation (Vascik & Hansman, 2017) and On-Demand Urban Air Transportation (Uber Elevate, 2016). These concepts aim at goals similar to their predecessors', yet as on-demand mobility arises around the world, this current concept try to embrace on-demand flight operation. As the technologies became more advanced, aerial urban transportation envisioned using eVTOL vehicles, which is closer to realization of initial concept. By using on-demand mobility concept in operating eVTOL vehicle, the operator, in this case Uber, expected to reduce the fare for each passengers to as low as the price of ground ridesharing UberX today (Uber Elevate, 2016). Another term is Regional Sky Transit, a civil aviation agreement which denotes ubiquitous, accessible, affordable, equipped with electric propulsion, accommodates two person Vertical / Extremely short take-off and landing (V/ESTOL) vehicles operate within metropolitan region (Seeley, 2016). The latest term that also being discussed in the realm of air-based urban transportation is UAM. Alike with aforementioned concepts, UAM supposed to provide safe, affordable, environmentally friendly door-to-door air transport within urban area. Nevertheless, this concept took UAS services into its system, like autonomous cargo delivery systems and ground-piloted operations (SUASnews, 2017; German et al., 2018). Despite different names and slightly difference, those concepts need ground infrastructure where eVTOL vehicles can pick up and deliver its cargo freights, as well as passengers.

2.1.1 eVTOL Vehicles

Vascik and Hansman (2017) wrote that as the time goes by, the research and development progress has favored the development of VTOL aircraft. This is including the advancement of electric propulsion that brings the realization of PAV closer, as it reduces noise and increase safety. PAVs which are powered by fuel or helicopters has become a nuisance since they produce a lot of noise from their rotors and is consequently not suitable for urban area operation. The complexity of mechanical rotor components of a helicopter are not efficient and can be simplified by turning into electric propulsion usage. This simple electric propulsion will be installed redundantly to reduce noise and increase safety, hence one eVTOL vehicle can have six or more electric propulsors (Uber Elevate, 2016).

The maiden flight of a manned eVTOL vehicle has finally been done by EHANG 184 in February 2018 (Heater, 2018). This was a successful effort to show how safe an autonomous eVTOL can be. Another success story comes from Volocopter 2X. Since the end of 2017, electric propulsion for VTOL vehicle has been getting more spotlight, when Royal Transport Authority in Dubai announced authorization of Volocopter as an Autonomous Air Taxi. The unmanned maiden flight the eVTOL vehicle has been done on 25 September 2017 in Dubai, in an autonomous mode, which lasted for 5 minutes and reached 200 meters high before landed (Reuters, 2017).

Besides Volocopter and EHANG, there are other eVTOL vehicle manufacturers that develop and fabricate their own eVTOL vehicles. For instance, Jobby Aviation with their S2 concept, Airbus with Vahana and Citybus, and Lilium with Lilium Jet. These manufacturers are developing an aircraft equipped with electric propulsion and autonomous flying capability as an option for urban mobility. Nevertheless, if those manufacturers could manufacture a safe, less noisy, affordable, and environmentally friendly eVTOL vehicle right now, UAM will not likely happen since there is no available ground infrastructure for eVTOL vehicles to perform take-off, landing, parking, and maintenance operation.

2.1.2 On-Demand Mobility

The fare on a single commuting trip using eVTOL vehicles would be unaffordable for the most targeted demand/commuters, especially if eVTOL vehicles are operated in a sky taxi business model. Only the affluent can afford to pay UAM service. To cope with this problem, Uber has proposed to operate UAM in an ODM-way (Uber Elevate, 2016). Despite the continuous loss and declining performance in recent years, Uber has proved that operating ODM through ride-hailing apps is way more profitable than normal taxi as Uber can reduce the fare up to 30% or more (Sherman, 2017). This principle also could apply to UAM, if the target market is willing to sacrifice their privileges and privacy for a faster and affordable trip using eVTOL vehicles.

There are many types of ODM, mainly differentiated based on vehicle ownership and driver availability. The most famous one is Transportation Network Companies (TNCs) such as Uber and Lyft. Unlike their businesses in surface-level ODM, TNCs will have difficulties in operating UAM because the lack of certified pilots and eVTOL vehicle ownership. For the initial stage of UAM implementation, another ODM business model called Transportation Service Providers (TSP) might be more suitable. TSPs arise as surface-level TNCs prepare for the upcoming autonomous vehicle. TSPs own the vehicle itself and provide pilots to serve the demand. Previously, the business model of TSP have been utilized by Very Light Jet (VLJ) air taxi companies before many went to bankrupt due to the 2008 financial crisis. Recently, Uber is willing to team up with eVTOL vehicles manufacturers to find a sustainable UAM concept. Subsequently, If the demand arises, more eVTOL vehicles will be manufactured and highly likely to reduce the price down to the price of manufacturing a private car (Vascik & Hansman, 2017).

Unlike Taxi, the surface-level ODM does not need specific infrastructure. For example, Uber and Lyft drivers do not need any garages or depots to store and repair their cars. Surface-level ODM also does not need taxi cab standing for queueing and waiting the passengers at important places like airports, major shopping centers, tourist destinations, train stations, and hotels. The same principal applies to UAM. Despite of using a TNC-like business model, UAM still need places for the eVTOL vehicles parking and waiting for the passengers.

2.2 Minimum Requirement for UAM Ground Infrastructure

During the Uber Elevate summit session, Alexander and Syms (2017) mentioned that there are only a few research studies and reports about ground infrastructure for UAM operation despite the importance of designing a scientifically analyzed vertiport. Alexander and Syms (2017) also brought up the fact that 90% of accidents in helipad happened because of no compliance made with the regulations during the planning, designing, and operation phase. Heli Expert, a heliport consulting expert co-founded by the speakers, published a working paper about design proposals of UAM ground infrastructures, namely Vertiport. The working paper comprises conceptual designs for ground UAM infrastructure in a residential area, highway plaza, floating barge over water, parking garage and high-rise building.

Uber Elevate (2016) in its white paper proposed two supporting terms in UAM ground infrastructure, vertiport and vertistop. Vertiport is not only a place for boarding and alighting the passengers, but also equipped with parking space for a maximum of twelve eVTOL vehicles and supporting facilities like charging point, personnel, and maintenance. Vertiport also should be able to operate simultaneous VTOL take-off and landing, hence optimize its throughput capacity. Another term coined by Uber Elevate white paper is vertistop. Vertistop only consist of touch down and lift off (TLOF) area, without any supporting facilities available, where an eVTOL vehicle can perform the boarding and alighting process. Based on the same Federal Aviation Administration (FAA) Advisory Circular with HeliExperts, Uber Elevate offered three design proposals: the first two designs are atop high-rise building and floating barge over water functioning as vertiport. Another one is inside a major roadway cloverleaf as a vertistop example.

To provide UAM ground infrastructure, Vascik and Hansman (2017) defined six approaches in developing new UAM ground infrastructure. On rooftops, on a barge over the water, inside highway clover, overtop highway/road/rails, and atop of a parking lots/high rise building are the potential approaches developed by the author, which are similar to the aforementioned research. However, the authors proposed an approach to co-located UAM ground infrastructure with gas stations/superstores/geographically well-distributed business. By doing so, the authors believe that UAM coverage will increase efficiently. Under a single contract, UAM operator can use available locations owned by its partner and expand the UAM coverage. A geographical analysis has been undergone to observe the impact if such approaches are applied. If every identified gas station within analysis scope provides a TOLA for eVTOL vehicles to drop off and pick up passengers, then the first/last mile of UAM passengers may possibly be reduced to a maximum of 1.7 miles (2.7 km). The first/last mile distance can be reduced to just 1200 ft. (365 m), if every 50 ft. by 50 ft. (15 x 15 m) vacant land (i.e. green spaces and parking lots) converted into a TOLA and enable eVTOL vehicles to board and alight its passengers.

Another UAM ground infrastructure concept is pocket airpark. This concept was coined and examined by Seeley (2016, 2017b) to complete the main requirement of regional sky transit system. The author investigated the operable size of pocket airpark should be designed based on eight parameters: noise footprint, aircraft speed & accelerations, footprint of the aircraft, terrain nearby, adverse weather, elevation, noise surrounding airpark, and future rules and regulations. Considering those parameters and requirements from Sky Taxi, a VTOL aircraft design concept, the size of the smallest pocket airpark is 162.2 m by 75 m. In a minute, pocket airpark can handle six Sky Taxis take-off and six Sky Taxis landing simultaneously. 13 docking stations are able to provide maintenance and battery changing. This size is bigger than a standard FAA helipad with 15 m diameter of TLOF area and 35 m diameter of final approach and take off (FATO) area. The author mentioned that the relatively small size of standard FAA helipad is deceiving because it is against the famous height-velocity diagram or "dead-man curve". FAA has coped with this problem by mentioning specific requirement for approach and departure pathways for VTOL aircraft with single rotor (i.e. Helicopter) (FAA, 2012).

Another cause of why the smallest feasible pocket airpark is bigger than a standard FAA helipad is that the author was considering the conceptual Sky Taxi as the main aircraft operating in pocket airpark. The clarity of Sky Taxi concept in this analysis is also questioned because there were five design concepts of Sky Taxi, from A to E, as explained in the previous paper about Regional Sky Transit. If the pocket airpark is analyzed using Sky Taxi type D (quadcopter) or E (tilt-rotor), like the vast majority of current eVTOL vehicles development, then the problem about height-velocity diagram would have not occurred because they were assumed to be immune to this problem (Seeley, 2017a).

The minimum requirement of an UAM ground infrastructure could be established by taking the assumption of helicopter as the closest vehicle type to eVTOL vehicle. Both helicopter and eVTOL vehicle are approaching and departing vertically. Table 2.1 contains a summary from both heliport and proposed eVTOL ground infrastructure design, that was gathered from different academic papers, working papers, and best-practice standards. However, to simplify the analysis process, this thesis assumes that the heaviest eVTOL vehicle in the future will be similar to an SUV car (around 2,000 Kg) (Uber Elevate, 2016).

Concept	**TLOF**	**FATO**	**Safety Area (SA)**
Seeley (2017b)			162.16 x 75 m
Uber Elevate (2016)	15.24 x 15.24 m	35 x 35 m	60.96 m
Alexander and Syms (2017)	13.72 x 13.72 m	21.34 x 21.34 m	30.48 m
FAA (2012)	RD (Rotor Diameter)	1.5 D (overall Dimension)	
Vascik and Hansman (2017)	15.24 x 15.24 m		
ICAO (2009)	0.83 D	D	0.25 D
Syed et al. (2017)	13 x 13 m	19.81 x 19.81 m	
Antcliff, Moore, and Goodrich (2016)	15.24 x 15.24 m	30.48 x 30.48 m	60.96 m
Transport Canada (2017)		1.5 D	3 m

Table 2.1: Minimum Ground Infrastructure from Previous Studies

In general, there are three fundamental areas of heliport, namely TLOF, FATO, and Safety Area (SA). TLOF is a circle in the center of heliport, functioning as a pad for a helicopter to be landed on. It is often co-located FATO, which provides buffer area while helicopter approaching or leaving heliport in a certain glideslope. SA is the circle located in the most outer part of these three fundamental areas of heliport. Its function is to give an additional buffer. Both TLOF and FATO are located inside SA. Nevertheless, a TLOF may not be located within a FATO and can have similar size to a FATO (Transport Canada, 2017). Seeley (2017b) arranged the so-called pocket airpark, which equipped with two heated TLOF areas, one for take-off and another for landing respectively. Pocket airpark provides 13 docking stations for parking, charging and performing maintenance. This concept intendedly serves specific aircraft, called VTOL Sky taxis.

Applying the heliport standard as an approach, Uber Elevate (2016) designed a UAM ground infrastructure with the minimum diameter of 15 m for TLOF area, 35 m for FATO area, and 61 m for Safety Area. FAA's Advisory Circular underlies this UAM ground infrastructure design by Uber Elevate, similar with the concept from Vascik and Hansman. Vascik and Hansman (2017) took FAA Advisory Circular AC 150/5390-2C: Heliport Design (FAA, 2012) as a guidance in defining minimum space required for UAM ground infrastructure. Although FATO is not explicitly written, he imagined that 15 m times 15 m pad (TLOF) is decent for a eVTOL to safely land.

Likewise, Alexander and Syms (2017) adopted FAA guidance by having a hexagonal 45-foot (13.72 m) diameter TLOF, a 70-foot diamater FATO (21.34 m), and a 100-foot diameter (30.48 m) Safety Area. These are the result of applying biggest possible aircraft in UAM into FAA guidance. On the other hand, Syed et al. (2017) took Joby's S4 eVTOL vehicle diameter as a consideration. With 43 feet span, minimum square shaped TLOF size is 43 feet (13 m), minimum FATO size is 65 feet (19.81 m) and minimum safety area is 95 feet (28.96 m). Following the same recommendation from FAA, Antcliff et al. (2016) used 50 feet (15.24 m), 100 feet (30.48 m), and 200 feet (60.96 m) diameter respectively for the TLOF, FATO, and safety area.

FAA (2012) itself, through its Advisory Circular, have never explicitly stated certain distance as the minimum size for a heliport. FAA just set a standard, referred to the highest organization in civil aviation sector, ICAO. Although ICAO has the responsible to develop and regulate airborne transport world wide, that does not necessarily mean all the inferior will follow automatically. For example Canada Airport Regulation (CAR) and FAA did not follow exactly ICAO recommendation. FAA recommends RD (rotor diameter), 1.5 D (overall dimension), and 0.33 D (1.83 D in total) respectively for the TLOF, FATO, and safety area (FAA, 2012), whereas CAR recommends 1.5 D for the minimum size of a FATO and 3 meter for the minimum size of safety area, without any precise limitation on TLOF size (Transport Canada, 2017). ICAO itself recommends 0.83 D for the minimum size of TLOF, 1 D for the minimum FATO and at least 0.25 D for the safety area (ICAO, 2009).

From all the aforementioned standards, table 2.1 only summarizes size standards for usual heliport type and not capture all the exceptional or specific situation like atop of building or in the river embankment. Reference for UAM ground infrastructure located in a water body embankment lies on ICAO (1995), which recommends a water heliport should pay attention towards other water users during the approach and departure glide. Nevertheless, the minimum size of TLOF, FATO and safety area remains the same. The placement of UAM ground infrastructure in a water body embankment intendedly only to abate noise in the city center neighbourhood (Alexander & Syms, 2017). Another specific example that may be taken into consideration is elevated UAM ground infrastructure. In an elevated heliport, as a reference, ICAO (2009) allowed to build TLOF and FATO coincidentally, if there is not enough space to build proper TLOF and FATO at for example, rooftop parking.

eVTOL Vehicle	Span (m)	eVTOL Vehicle	Span (m)
Airbus Vahana	7.3	Ehang 184	5
Aurora eVTOL	8	Passenger Drone	4.2
Carter Copter	10.4	Volocopter VC200	9.15
Flyt2	7.9	Volocopter 2X	9.15
Lilium Jet	10	Vimana	10
Joby S4	13.1	Bartini Flying Car	5.2
Trifan 600	11.5		

Table 2.2: Various size of eVTOL vehicle (Datta et al., 2018; Lilium, 2017; Syed et al., 2017)

According to table 2.2, the biggest upcoming eVTOL vehicle size is 13 m. Be this number on the safe size to anticipate the unknown future, then rounded up to 15 m. This thesis follows ICAO standard of the TLOF, which is 0.83 time of the largest eVTOL vehicle's span. Assuming 15 m is the safe span of eVTOL in the future, 13 m is the rounded up value for TLOF diameter. Surrounding the TLOF, the FATO size is referring to ICAO standard, which is 1 D. Consequently, 15 m is the minimum FATO size in this study. 19 m is the safety area size, rounded up from 18.75 m as the result from ICAO standard of one quarter of the vehicle diameter. Likewise safety area, safety net is also another important buffer area in the TLOF vicinity, which is recommended by ICAO; Transport Canada for elevated or raised heliport. The water embankment UAM can also install safety net for preventing the falling of human or vehicle into water case. The parking stand, since eVTOL vehicle will be directed to the parking stand, either using remote-controlled tug or a guide rail (could be similar to the conveyor belt or the catapult in the carrier vessel), do not necessarily needed safety area for turning radius. Therefore, the size of parking stand is adjusted to the maximum size of eVTOL vehicle span (15 m). Due to its bigger coverage, circular pad will be used as the pad shape, rather than hexagonal shape for the same radius.

Marking and lighting will just simply referring to the existing standard, in this thesis is EASA helideck. Helideck is a heliport mostly located in the offshore oil rig or atop of buildings. The underlying concept of marking and lighting at helideck is designed for terrible weather, meaning applicable all year round for UAM operation. For the supporting facilities, this minimum requirements for UAM ground infrastructure is referring to Vascik and Hansman. They put the importance of having supporting facilities, for instance public access, parking area, security area and check-in area for creating safe and secure UAM.

Prior to its construction, UAM ground infrastructure should make sure that electricity grid is ready to support fast charger system. Baxter (2017) proposed a modular and scalable platform of fast charger, that could fly eVTOL vehicle hundreds of miles of range under 15 minutes charging. This fast charger supplies up to 400 kW per port for 5 minutes at 2C rates (2A/30 minutes).

Factors	Minimum Requirements
Operational Safety	TLOF: 13 x 13 m (round up from 12.45 m) FATO: 15 m Safety Area: 19 m (round up from 18.75 m) Parking Stand: 1 D = 15 m Circular Pad
	Marking and Lighting: adequate perimeter lighting, adequate floodlighting, status lights (for night and day operations e.g. signalling lamp), dominant obstacle paint schemes and lighting, helideck markings, and general installation lighting levels
	Public access and egress route, vehicle parking or drop-off point, passenger staging area, facility security, flight security check area, check-in and customer identification area
	Safety net
Charging Station	400 kW charge for 5 mins at 2C rates (2A/30 Minutes)
Noise	Night curfew
Weather	Adequate gap helideck
	Well-designed approach/departure paths permit pilots to avoid downwind conditions and minimize crosswind operations.
	Illuminated Windcone
	Heated pavement of helipad and passenger access
Fire Hazard	No fuel & fluids mean reduced risk of fire and potential to reduce requirement
Communication Infrastructure	ADS-B ground station broadcast / FLARM receiver
Parking	Depo/Garage for idle eVTOL vehicle, well distributed and adequate to store all of the eVTOL
	Remote-controlled Tug or Guide rail

Table 2.3: Minimum Requirement for UAM Ground Infrastructure

Although DEP is foreseen as the solution to reduce noise nuisance, noise abatement in UAM ground infrastructure will make a better public opinion. For this reason, night curfew shall be implemented and limited UAM operation in the night. Despite aircraft noise is louder the envisaged UAM's noise, this thesis encourages night curfew for a most likely better public opinion. Taking Tegel airport in Berlin as an example, the authorities ban night flight between 11 pm to 6 am, with some exceptions (Senatsverwaltung für Gesundheit Umwelt und Verbraucherschutz, 2008).

As weather plays an important role in UAM operation, UAM ground infrastructure should be, at least, equipped and designed to protect the operation itself Dziubinski (2016). wrote that providing an adequate gap is necessary to avoid sudden gusts for elevated helipad, if the helipad is build in an additional structure above the existing building structure. Wind and gusts are important factors influencing UAM operation, as FAA (2012) recommends providing well-designed approach and departure paths to prevent downwind and crosswind hindrance. Not only that, but FAA (2012) also recommends to assess the impact of turbulence in a given location. Furthermore, for UAM ground infrastructure Alexander and Syms (2017) suggested to use illuminated wind cone, as an aid for the pilot during the night. In sub tropic climate, icing is also another issue. To avoid that and prevent the heliport and UAM ground infrastructure from slippery surface due to thick ice, Lily Helipad has manufactured a heated pavement helipad, as well as the passenger access (Lily Helipad, 2018)

The advantage of operating eVTOL is less hazardous liquid involved in the daily operation. Alexander and Syms (2017) stated that the fire hazard of UAM ground infrastructure tend to be lesser than a heliport. Therefore, no extra spaces needed for plentiful fire extinguishers or complex piping arrangement. It also means that no space needed for fuel tank in UAM ground infrastructure

The evolving communication infrastructure might also require some space in the UAM ground infrastructure. Although currently there is no conventional communication system between ground traffic controller and eVTOL vechicles, eventually UAM ground infrastructure should accommodate the need of communication among UAM components. DLR (2017) conceptualized U-Space, where autonomous eVTOL vehicles are able to communicate among them, as well as with the ground infrastructure and air traffic management. This notion requires space for FLARM receiver and ADS-B receiver at UAM ground infrastructure. For further detail about the proposed notion of UAM communication, please refer to work done by DLR (2017).

The last requirement for UAM ground infrastructure, parking stand, is important if the UAM operator wants to establish an efficient operation. To that end, parking stand of eVTOL vehicle should be counted thoroughly and simulated, if necessary, resulting the exact demand and location of parking stand. Spatially thinking, the growth of technology allows UAM ground infrastructure to compress the space requirement for parking stand. For instance, Tiger Tugs manufactures a towing robot, which able to carry and move an eVTOL (Tiger Tugs, 2017). Additionally, any form of guiding rail can provide similar function.

2.3 UAM Ground Infrastructure Placement

2.3.1 Site Selection for UAM Ground Infrastructure

Among limited research about UAM ground infrastructure, Uber Elevate (2016) performed a simulation of UAM, using a model that was created based on long distance Uber ground trip data in London and Los Angeles. The ground infrastructure itself were selected from passenger demand, from each different trip-ends and trip-origins. The conclusion from this model is the placement of the first 25 vertiports covered 60% all long-distance trips in Los Angeles and 35% in London, which infers that UAM has an opportunity to enhance existing surface-level transport mode. This model also shows high demand of trip's beginning and ending in the central business districts (CBDs) and major transport hubs (i.e. Airport and Central train station).

Demand is a preferred criterion to be taken into account when trying to simulate UAM operation and UAM ground infrastructure planning. German et al. (2018) conducted research about UAM operation for logistics purpose and attempted to select UAM ground infrastructure location using a proxy of potential customer. The authors then created potential customer proxy from the number of inhabitant's data and income data, situated in a fine resolution level of census tracts. After the proxy was reclassified, high-value census tracts are supposedly to build one ground infrastructure, ideally at the centroid of each census tracts. In other words, this ground infrastructure will be able to serve a certain number of potential customers within a particular census tract.

Syed et al. (2017) also undertook a research about the estimation of UAM demand. To that end, the authors performed landing site location analysis as a foundation for flight-origins and flight destinations. Similar with the work from German et al., Syed et al. (2017) exploited the open source American Community Survey (ACS)-estimated census data and the origin destination employment statistics (LODES). From this database, Syed et al. (2017) interpolated the high income commuters and potential origin-destination pairs with an income level of at least $ 100,000 to choose potential UAM ground infrastructure location, from which centroids are taken to the following sequence. Furthermore, the authors performed k-means clustering analysis to select the first 200, 300, and 400 locations of UAM ground infrastructure.

Another approach for selecting ground infrastructure location based on existing infrastructure supply has been undergone by Vascik and Hansman (2017). They tried to list any available take-off and landing area (TOLA) in Los Angeles, regardless the function (airport or helipad) and the owners (private or public). TOLA can support initial UAM development in providing existing ground infrastructure within a wide range of geographic coverage. There are 310 TOLA available in Los Angeles area, yet 70% of them are emergency helicopter landing facilities (EHLF), which are not certified by the FAA and can only be used in an emergency state. Over 80 helipad are converged in the CBD districts within a 3.2-kilometer radius, while the rest are scattered in the regions. This leads to approaches in increasing the number of available TOLAs in many underserved areas. To give an illustration of the proposed approach, Vascik and Hansman mentioned to use UAM ground infrastructure or TOLA adjacent to gas stations, supermarkets, or other business that were dispersedly located. Vascik and Hansman also proposed to employ 50 ft by 50 ft-size vacant land, rooftops (as well as atop a parking lot), and barge (or identical infrastructure) over water. These approaches can only be achieved if eVTOL vehicles meet certain requirements, for example reduced noise nuisance, reduced downwash effects, and increased maneuvering capability in tight curves or areas.

Antcliff et al. (2016) divided UAM ground infrastructure location according to legal status of the place where it will be placed. They proposed to site UAM ground infrastructure in the following categories based on infrastructure siting requirements, which have been analyzed previously. These categories are namely public infrastructure (urban), public infrastructure (metropolitan), and private infrastructure. Antcliff et al. came up with the idea of using highway cloverleaf interchange as UAM ground infrastructure location, which suitable for public infrastructure located in urban area. This idea depicts a location with a high existing noise level, uncomplicated legal compliance, and are well-distributed, not to mention its seamless intermodality with private cars. Other category, public infrastructure located in densely metropolitan area comprises an idea that utilizes water body, for example coastline and river embankment. Historically, big cities were formed along rivers or large bodies of water, thus UAM operation potentially uses body of water in the proximity of demand area. Last category is private infrastructure. Aligned to the increasing number of interested parties to UAM, this category maximizes stakeholders' asset to build UAM ground infrastructure. The authors took Silicon Valley as an example, where many hi-tech companies are located and are willing to contribute in the development of UAM. This category resembles to aforementioned approaches from Vascik and Hansman.

2.3.2 GIS-based Suitability Analysis

There are many examples of the usage of suitability analysis, for example in mobility hub placement (Anderson, Blanchard, Cheah, Koling, & Levitt, 2015), air quality monitoring stations placement (Alsahli & Al-Harbi, 2017), photo voltaic siting (Charabi & Gastli, 2011), and transit-oriented development (TOD) location (Banai, 1998). Researchers proposed different approaches in suitability analysis. Alsahli and Al-Harbi (2017) combined suitability analysis in GIS with the WLC method, while Banai (1998) and Anderson et al. (2015) combined suitability in GIS with WLC as well as the AHP method. Research by Charabi and Gastli (2011) underwent a different approach. They joined suitability analysis in GIS with AHP and ordered weighted averaging (OWA) methods.

Although these papers are using different combinations of methodology, there are some similarities among them. For example, these papers have the usage of GIS-based software, especially for overlay tool, regardless of the data format, raster or vector. The coefficient for each consequential factors, which are generated from particular analysis, such as AHP, OWA, or else, can also be easily found in those papers. Reclassification process tends to appear among these papers, yet in many different methods and applications.

Anderson et al. (2015) endeavored a research about mobility hub location selection. Using a multicriteria evaluation, the authors aimed to determine suitable locations for mobility hub in the city of Oakland, California and modal distribution. Anderson et al. firstly collected and processed all data of interest. Secondly, the authors constructed an index, consisting of several factors that embodies mobility hub site selection goals, which are equitable and resilient transportation. These indices were then subjectively weighted based on references and expert interviews. Census block, as the smallest resolution of published census data in the U.S., acted as the spatial display for all of primary factors, before furthermore were interpolated to create every single index. The reclassification process took place in this index-making step, where each attributes were given particular coefficient when calculating indices. The final step was developing scenarios related to the stakeholders target and locating the suitable mobility hub accordingly.

Another research about the implementation of GIS-based multicriteria analysis in transport-related issue was performed by Banai (1998) to determine suitable location for TOD. Likewise Anderson et al., Banai collected data at the initial phase of their research. He used a vector-based shapefile data to represent suitability factors for TOD. Then, all the factors were brought into pairwise comparison or AHP, as the coefficient can be drawn afterwards. Some data from the initial phase were reclassified as per their type or their value. For instance, the road network category is reclassified into three classes, grid, hybrid, and curvilinear. The incremental rating of high, moderate and low, were applied to road network classification in the same order as mentioned. On the other hand, density category is reclassified into the same amount of classes like road network, yet based on its value. A density of 40-65 du/acre is labeled as high rating, density of 7-18 du/acre is labeled as low, and density of 18-40 du/acre is labeled as moderate. The final step was to superimpose all the factor's shapefile and create the final layer of suitable TOD location.

GIS-based multicriteria analysis is not only used in transportation or land use related fields, but also in various disciplines, for example in renewable energy. Charabi and Gastli (2011) underwent a GIS-based multicriteria evaluation for determining suitable location of photo voltaic farm. Beginning with converting and collecting all the required data from relevant factors, this research has a similar flow with the transport-related GIS-based multi criteria analysis. From Digital Elevation Model (DEM), solar radiation, to land accessibility, data were gathered and processed to proceed into the next research step. In order to gain coefficient, pairwise comparison have been performed. These coefficients were prerequisite input for the fuzzy logic OWA. Charabi and Gastli (2011) then overlay the raster images from all factors to create the final suitability map of photo voltaic locations.

Another field that uses GIS-based suitability analysis is environmental science. A research about finding a suitable site for air quality monitoring station was conducted by Alsahli and Al-Harbi (2017). The authors began with defining the prerequisite criteria, as well as collecting all the data needed. Furthermore, the criteria was combined with a shapefile of the state of Kuwait. Afterwards, the reclassification process took place and diversified all the criteria into seven classes. Alsahli and Al-Harbi (2017) did not use pairwise comparison to produce the coefficient or weight, rather obtained the weight from layer/criteria order.

An additional GIS-based suitability analysis in a totally different way from the aforementioned research was carried out by Hatzichristos and Giaoutzi (2006). In lieu of AHP, the authors employed the Delphi technique to obtain relevant factors and their classes' definition. The Delphi process was held in nine rounds and varied from open question to simple question. The experts filled the open question and then were asked again to define the limitation of the factors' classes. They also reconsidered their answer during the iteration round. In the end, the experts set twenty rules applied to the final overlay process. Hatzichristos and Giaoutzi (2006) took all the fuzzy or continuous value of all factors into calculation, and thus proceed with the overlay of raster images process.

2.4 Multicriteria Decision Analysis

Multicriteria decision analysis (MCDA) is a tool for decision making process with several criteria involved, aiming at certain goals or creation of several combination of scenarios. MCDA was initially utilized in the Operations Research (OR) field (Triantaphyllou & Shu, 1998). The MCDA method consists of four fundamental elements: criteria, decision makers, decision alternatives and decision matrix. At the most basic principle, MCDA methods analyze several alternatives, which are evaluated based on criteria from the decision makers' preferences (Malczewski & Rinner, 2015). Among many developed MCDA methods, this thesis utilized AHP to partially find the answer of research questions.

2.4.1 Analytic Hierarchy Process

AHP is a decision-making method to generate coefficient or weight from a set of criteria, factors or alternatives according to their importance (Baseer, Rehman, Meyer, & Alam, 2017; Charabi & Gastli, 2011). Saaty (1987) wrote that AHP has three principles: decomposition, comparative judgments, and synthesis of priorities. Decomposition means organizing the problem in many levels, for example top level, second level and sub criteria. The second principle, comparative judgments, is composed of pairwise comparison matrix from several criteria. Lastly, synthesizing the priorities means creating solutions following the arranged levels.

Mu and Pereyra-Rojas (2017) created a simple explanation on how the AHP method works. They composed 7 steps:

1. Develop a model for the decision: The initial part of AHP is developing what are the goals, what are the criteria, and what are the options (alternatives), based on the final goal.

2. Derive weights: After developing the criteria, the next step is creating pairwise comparison between all of the criteria involved. Likert's scale (1-5) or Saaty's (1-9) pairwise comparison

scale can be used in this pairwise comparison. One rule should be applied, if criterion A valued, for example 7, over criterion B then the opposite position (criterion B over criterion A) should be 1/7. This is a naturally simple approach because the respondent will only have to choose two things, regardless how many criteria or factors a questionnaire has. Consequently, the result will be converted into decimal value and will be normalized. After normalizing the matrix, the row average is determined, which represents the importance of each criteria.

3. Consistency: However, every questionnaire should meet a certain limit of Consistency Ratio (CR). This issue is fundamental because each respondent has their own preferences and to avoid inconsistency among many criteria. Saaty (1987) set the CR limit to 0.1, while Goepel (2013) wrote that 0.1 is too strict and therefore compared CR out of 80 respondents. The median of 80 respondents was 0.16 and the 80^{th}-percentile was at 0.36. The result of having CR at 0.16 found out to be practicable (does not necessarily need to be revised) and still relevant according to the respondents. Mu and Pereyra-Rojas (2017) also gave a simple example on how to find CR. Begin with the previously calculated pairwise matrix and then multiply with the priority/criteria weights. Sum all the rows to figure out the weighted sum. Once the weighted sum is calculated, $\lambda_{\max}$ can be generated by adding all the average of weighted sum divided by priority values. This $\lambda_{\max}$ is the important factor to calculate consistency index. The formula is as follows:

$$CI = (\lambda_{\max} - n/(n-1) \tag{2.1}$$

where CI is consistency index, n is the number of paired criteria, and $\lambda_{\max}$ is the average of weighted sum divided by priority values. After the consistency index has been figured out, the CR could be calculated. Yet, random index is should be generated to compare with consistency index. The formula is as follows:

$$CR = CI/RI \tag{2.2}$$

where RI is random index and CI is consistency index.

4. Derive local priorities: The next step is to derive priorities of the alternatives based on each criterion. Firstly, undergo the pairwise comparison between all the alternatives for each single criterion. Then sum all the rows (alternatives) and divide the pairwise comparison value with the sum of all the alternatives. This is the local priority value. For example, if there are three criteria (A, B, and C) and two alternatives/solutions (1 and 2), then during this step three priorities will be derived according to each criteria. According to the pairwise comparison of two alternatives in each single criterion, criterion A favours to alternative 1, while criterion B and C favour to alternative 2.

5. Model Synthesis: If in the previous step a single priority is generated according to each criterion, in this model synthesis step, overall priorities will be generated. Taking the value calculated by the previous step, multiply those value with each criteria weights. Then, sum all the result from previous multiplication to calculate overall priority.

6. Perform Sensitivity analysis: This sensitivity analysis performs a what-if scenario by changing the criterion weight. For example, what alternative will be favoured by the AHP method if all the criteria have the same percentage or if one criterion overweight double another criterion. This step provides several scenarios, which help decision makers or stakeholders to adjust the result according to the real life condition.

7. Making a final decision: When aforementioned steps have been undertaken, the decision maker or the stakeholders are ready to make decision with consideration of all important criteria.

2.4.2 Group Decision Making

Another function from the AHP method is generating consensus between multiple involved parties. The AHP method is often considered as a mathematical method, which is seen as an objective method to find a consensus between decision makers or stakeholders on a particular matter. This assumption makes the result of AHP method easily accepted by the involved parties (Goepel, 2013). The AHP method is also popular for decision making process for large public projects, where a lot of parties with different interests involved, because of its simplicity to aggregate different opinions and its easiness to understand. Due to these traits, conflict resolution processes are also employing the AHP method (Forman & Peniwati, 1998). The consensus of group decision making process will be explained later in AHP-Delphi analysis section (see page 23).

2.5 Delphi Analysis

The utilization of the Delphi method in military area during world war II led to other areas in the following decades, such as health, nursing, and medical research (Keeney, McKenna, & Hasson, 2011). Unlike other methods that might involve common people, this method employs experts to give their opinion about particular topics or areas, which are unimplemented and uncertain, as well as lacking any necessary appropriate data. The technology foresight is another topic that often using Delphi (Bogner, Littig, & Menz, 2009). There is a common premise that group opinion is more valid than single opinion. This premise is the main foundation of the Delphi method, by employing a group of experts to generate a consensus (Keeney et al., 2011). Rowe, Wright, and Bolger (1991) distinguished four characteristics of the Delphi method:

1. Anonymity: The Delphi method deliberately sets the freedom of expression into a high level, without the concern of social pressure from other experts. This can be achieved by distributing the questionnaire individually, without any obligation to fill in the name column.

2. Iteration: This character allows experts to reconsider or to adjust their answer after several inputs, mostly interquartile range or row geometric mean method from all expert's responses. This characteristic also divides the Delphi method into several rounds (usually 2 or 3 rounds).

3. Controlled Feedback: As mentioned in the previous characteristic, the Delphi method has to provide all of the experts with data aggregation, usually in form of simple statistical value such as mean, median, inter quartile range or row geometric mean method. This data will be presented between rounds, so the experts will be able to reconsider their answer in the following round. The benefit of using Delphi is no lead vocalists who control the process of finding consensus. Each experts has equal rights and weights when it comes to the process of finding consensus.

4. Statistical group response: At the end of Delphi method, the final judgment appears in a form of statistical value. This value reflects the strength of the consensus between experts, whether the opinions from the experts are scattered or converged at a roughly single point along the continuum.

The Delphi method has been significantly developed after its first appearance. Keeney et al. (2011) defined types of Delphi and its main characteristics as shown in table 2.4. They also wrote that Delphi is usually composed of several rounds. Time allocation is an important factor on determining how many rounds the Delphi method will endure. Usually a classical Delphi method has one open ended question round and two structured questionnaire rounds. The first round is intended to gain insights and ideas from experts about the given topics by providing them open ended questions. Nevertheless, this freedom of giving opinions can generate 25 pages of the following second round questionnaire.

The second round, as well as the third and the fourth round (depending on the number of rounds the Delphi method will have), consist of structured questionnaires. Between rounds, a feedback will be presented to each experts giving further information, especially statistical value like mean, median, interquartile range and row geometric mean method. The iteration process is intended to reach a consensus between all experts. The consensus value itself is translated into various standard and statistical values. Keeney et al. (2011) took 70% as consensus value for their study. However, classical Delphi often faces low response rate, when the experts do not resend their adjusted or reconsidered answer according to the statistical value.

Types of Delphi	Main Characteristics
Classical Delphi	Uses an open first round to facilitate idea generation to elicit opinion and gain consensus
Modified Delphi	Modification usually takes the form of replacing the first postal round with face-to-face interviews or focus group discussion
	May use fewer than three postal/email rounds
Decision Delphi	Same process usually adopted as a classical Delphi. Focuses on making decisions rather than coming to consensus
Policy Delphi	Uses the opinions of experts to come to consensus and agree future policy on a given topic
Real Time Delphi	Similar process with classical Delphi except that experts may be in the same room
	Consensus reached in real time rather than by post
	Sometimes referred to as a consensus conference
e-Delphi	Similar process to the classical Delphi but administered by email or online web survey
Technological Delphi	Similar to the real time Delphi but using technology, such as hand held keypads allowing experts to respond to questions immediately while the technology works out the mean/median and allows instant feedback allowing experts the chance to re-vote moving towards consensus in the light of group opinion
Online Delphi	Same process at classical Delphi but questionnaires are completed and submitted online
Argument Delphi	Focused on the production of relevant factual arguments
	Derivative of the Policy Delphi & Non-consensus Delphi
Disaggregative Delphi	Goal of consensus not adopted
	Conducts various scenarios of the future for discussion
	Uses cluster analysis

Table 2.4: Types of the Delphi method and main characteristics (Keeney, 2012)

The definition of an expert is still on debate, therefore no fixed explanation. Bogner et al. (2009) wrote in their book that everyone can be an expert of their own life. Then they explained that an expert should be reviewed by his/her expertise in a particular area or a specific competence, rather than common-sense knowledge or everyday knowledge. Keeney et al. (2011) seconded the idea that an expert should be knowledgeable in a particular area, which is similar to the research topic. They also mentioned that it is more common nowadays to make a clear delineation criteria, like number of publication, years of experience, and specific qualification in a particular area.

There is also no common agreement on the number of experts one should incorporate for a research. The number of experts depends on the purpose of the project, design selection, and time window (Keeney et al., 2011). Bogner et al. (2009) also emphasized that to get a broader point of view, it is recommended to involve experts coming from different background. 10 experts might be sufficient to perform Delphi, but to avoid a high-rate of drop out (discontinued participants), a higher number of experts should be considered. To make the drop-out rate lower, it is recommended to simplify the Delphi questionnaire for the experts. Every statement in the questionnaire should not exceed 20 words, is easily understood, and limited to 25 questions (Parentè & Parentè, 1987).

Like other methodologies, The Delphi method is not perfect and free from critics. Its validity and accurateness are common reasons that many researchers attack (Rowe et al., 1991). In the light of Delphi method, Dalkey, Brown, and Cochran (1970) suggested to undergo two options that enhances the accuracy of the results: iterating the responses and selecting the more expert subgroup. After conducting the experiment, the author implied the lesser participants, the better accuracy of the feedback or iteration process. Correspondingly, Rowe et al. (1991) concluded that despite many critics, the characteristics of Delphi give the impression of a rational and realistic method. The iteration process seems prominent to make a better final judgment and the generated feedback tends to expand knowledge and ignite fresh ideas.

The Development of technology took Delphi to another novel level. The utilization of computer, internet, and server- or cloud-based questionnaires are things that influence the Delphi method. Table 2.4 mentions three types that belong to this novel Delphi method, namely e-Delphi, Technological Delphi, and Online Delphi. The notion from three aforementioned Delphi methods are similar and rely heavily on technological devices. For example, e-Delphi makes the best use of email to exchange the prepared questionnaire and the feedback or a website to fill in and display the feedback. Bogner et al. (2009) described another term for this technological-dependence Delphi method, namely Real-time Delphi, which is slightly different with the definition from previous table 2.4. The authors formulated that a real-time Delphi method should be accessible online practically in real time, providing real-time response (in this case a mean, a median, or other statistical values) and bestow synchronization with other experts. Linstone and Turoff (2002) seconded the latter definition of real time Delphi, which requires the help of computer usage. This definition of real time Delphi is closer to the definition of technological Delphi and online Delphi from table 2.4.

2.6 AHP-Delphi Analysis

Tavana, Kennedy, and Rappaport (1993) attempted to integrate AHP into Delphi structure, aiming to provide robust insights in group decision making process. The principal characteristics from AHP and Delphi are combined together. Tavana et al. (1993) took a pairwise comparison from AHP and iterative process and anonymity from Delphi, as the main characteristics that compose this AHP-Delphi method.

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Figure 2.1: Flowchart of classical Delphi and AHP-Delphi (Tavana, Kennedy, & Rappaport, 1993)

Tavana et al. (1993) tried this method in a case study about choosing an employee for accounting department. The process was using AHP pairwise comparison in the initial round and followed by the iteration round with given feedbacks or statistical value, which are the characteristics of the Delphi method. The iterative process was repeated until the experts reached a certain level of consensus. The difference between classical Delphi and the AHP-Delphi method is shown on the figure 2.1

The integration between AHP and Delphi is possible because AHP has final result of group decision making. As explained before, not only AHP provides a weight for various criteria, but also a statistical value which gives aggregation of judgments in a group decision making process (Mu & Pereyra-Rojas, 2017). This statistical value is practicable for having a benchmark of a consensus from all experts involved in the iteration process. Mu and Pereyra-Rojas (2017) make use of geometric mean as the aggregated decision makers (ADM) value, with number of experts n and input value from expert number 1 x_1, ADM can be given as:

$$ADM = \left(\prod_{i=1}^{n} x_i\right)^{\frac{1}{n}} = \sqrt[n]{x_1 x_2 x_3 \ldots x_n} \tag{2.3}$$

Nevertheless, aggregated decision makers value do not act as a consensus value. It is just a mean value from all different experts valuation or opinion in pairwise comparison process. As a prerequisite value in AHP-Delphi method, Goepel (2013) introduced another new consensus concept using Shannon alpha and beta entropy, namely AHP Consensus Indicator ($S*$) with formula as follows:

$$S^* = \frac{\frac{M - \exp(H_{\alpha \min})}{\exp(H_{\gamma \max})}}{\frac{(1 - \exp H_{\alpha \min})}{\exp H_{\gamma \max})}} \tag{2.4}$$

with M :

$$M = \frac{1}{\exp(H_{\beta})} \tag{2.5}$$

where H_{α} is Shannon alpha entropy, H_{γ} is Shannon gamma entropy, and H_{β} is Shannon beta entropy. For more information on this equation please refer to the comprehensive work by Goepel (2013).

Shannon entropy is a concept that supplies mathematical structure for diversity. Goepel (2013) took Row Geometric Mean Method (RGMM) value from all inputs to create AHP consensus value among the experts. RGMM value is the geometric mean for all cells in a row of converted pairwise comparison matrix. In this research, as the AHP-Delphi method is proposed, Shannon entropy acts as the single statistical value whether the experts has reached a consensus or not. Furthermore, the usage of Shannon entropy as consensus value provides an important step to fulfill the requirements of the Delphi method. (Rowe et al., 1991) mentioned iteration process, statistical group value, and controlled feedback as three out of four Delphi characteristics, which are fulfilled by the usage of Shannon entropy as consensus value. The AHP-Delphi method is theoretically allowed to proceed. It is important to remember that although consensus is successfully achieved, it does not mean the correct answer for forecasting and futuristic issue.

2.7 GIS Multicriteria Decision Analysis

Integration MCDA to GIS brings opportunities to move further as a decision support tool. Both are originated from different research fields, yet completing each other. With GIS MCDA, decision makers are able to combine, to analyze and to present geographic data in many different criteria to produce supporting maps for them (Malczewski & Rinner, 2015).

Malczewski and Rinner (2015) also categorized GIS MCDA into two groups, multiattribute decision analysis (MADA) and multiobjective decision analysis (MODA). Cova and Church (2000) wrote descriptions explaining about the difference, as well as providing examples between MADA and MODA. The authors split the methods based on decision problems. MADA is employed to find good areas for site, while MODA is employed to find out the exact location. Suitability analysis and land screening is used to search good areas for site, whereas site search modeling is used to find out the exact location. Hence, suitability analysis belongs to MADA. As mentioned in chapter 2.3, there are many GIS MCDA applications in various fields.

2.7.1 Suitability Analysis

Under the general term of GIS MCDA, there is one analysis that concerns about land allocation to fit certain goal. J. Eastman (1999) mentioned that suitability analysis is mostly based on quantitative criteria in form of continuous variables, rather than Boolean variables. Factor is the term he gave to a criterion with continuous value, whereas constraint is a term for Boolean value. J. Eastman wrote that instead of being treated as a constraint and posses 0 or 1 value, buffer radius from road is translated as a continuous value and a factor. Nevertheless, wildlife reserves, as an example of valid restriction, is considered as Boolean value. R. Eastman, Jin, Kyem, and Toledano (1991) translated the term suitability analysis into mathematical language in the equation 2.6. He also defined that equation 2.6 consists of two parts, continuous factor and Boolean constraint. Given w_i as the weight assigned to factor i, X_i as criterion score of factor i, and C_j as constraint j, the formula of suitability analysis can be defined as follows (J. Eastman, 1999):

$$Suitability = \sum w_i X_i * \prod C_j \tag{2.6}$$

The continuous factor part from equation 2.6 is made by using Weighted Linear Combination (WLC). Malczewski and Rinner (2015) mentioned that WLC is the most frequently used MADA procedure, due to its simplicity to use and consequently luring decision makers. Despite many developments from traditional WLC, for instance proximity-adjusted-preferences (PAP) WLC, local WLC, and OWA WLC (Malczewski & Rinner, 2015), this research will endure traditional (global) WLC. As no research has ever been working on suitability analysis of UAM ground infrastructure selection, the first attempt should be undertaking the commonly used method, which can lead into a combination with other research methodology. This research is more focusing on how predicting what are the criteria influencing the future of UAM and where ground infrastructure of UAM take place. To that end, this thesis collaborate WLC and other methodologies. WLC is often combined with another methodology to extract criterion weights and to evaluate the criterion. The most common one is the pairwise comparison method or AHP. The main advantage of employing the AHP method in extracting criterion weights is that AHP provides an instrument for the decision maker to engage all important criteria of a decision situation (Malczewski & Rinner, 2015)

To perform the suitable analysis in such a big area, raster image is more favourable than vector due to faster processing time. Therefore, this thesis converts vector layer to raster image data. After converting process has been done, the suitable analysis required standardization of the value against its highest and lowest cell value in the certain layer (R. Eastman et al., 1991). Given R is the raw value (non-standardized) and m is a random multiplier (this thesis sets 10 as the random multiplier), the standardization equation is described as follows:

$$StandardizedValue = (R_i - R_{min})/(R_{max} - R_{min}) * m \tag{2.7}$$

Besides standardized process, several researchers were also providing another method to incorporate all the factors with different standard and measurement called reclassification. Esri (2012) wrote that WLC or weighted overlay analysis should only take discrete value into the superimpose process. Every criteria should be reclassified into a certain range of ordinal or nominal value (could be 1-5, 1-9, depending on the research itself), to form the same classes for each criteria and to unify different measurement units. The result of the reclassification process is then able to be the input for raster calculator (superimpose/overlay process) to create the final raster (Malczewski & Rinner, 2015).

Baseer et al. (2017) in their research about suitable location for wind farm development in Saudi Arabia reclassified their criteria into six classes of suitability level. This reclassification level are mostly according to previous evaluation research. To give an illustration, wind speed at less than 5 m/s is not suitable then each area with wind speed lower than 5m/s is valued as 0. Not every criterion or factor has support from previous literature or studies like Baseer et al. For instance, German et al. (2018) and Anderson et al. (2015) use quantile-based reclassification. German et al. (2018) scaled income data for each Census Tract from 1 to 20. This is also known as standardization. Anderson et al. (2015) reclassified Cal-Fire fire vulnerability area from a 0 to 3 scale, from no risk to high risk to support their self-created criterion called resiliency index. This study, due to its novelty and certainly no previous research about UAM, use quantile-based reclassification for several criteria.

2.8 Spatial Interpolation

Spatial interpolation allows researchers to maximize time saving, while minimizing efforts at the same time. It estimates value within known values, although the accuracy is still being questioned (Simpson & Wu, 2014). There are various spatial interpolation methods and algorithms in the academics realm. The usage of a particular method depends on the research goal and data availability. Three interpolation methods helps this study in estimating missing data in case study area, namely Inverse Distance Weigthing (IDW), Thin Plane Spline (TPS), and Nearest Neighbour (NN). The urge of finishing this thesis on schedule forces to select interpolation method that has quick and simple process, as well as small computing load (Li & Heap, 2008). For comparing estimated value from interpolation method with existing non-interpolated raster, Root Mean Square Error (RMSE) is the common formula that have been utilized by many academicians. For example, Wise (2011) conducts a research about DEM which formed from five different interpolation methods. Xie et al. (2011) perform a research about the accuracy of heavy metal contaminants in the soil. To that end, the author compare 3 interpolation methods.

2.8.1 Inverse Distance Weighting

IDW is a non-geostatistical interpolation, which estimation is build according to linear combination of available data or sample points (Xie et al., 2011). This values from sample points are being weighted by an inverse function to estimate unknown value in its surrounding. Sample points that are located closer to each other are having similar traits and value than those which located far away (Li & Heap, 2008). Xie et al. (2011) described IDW in the equation 2.8. Given IDW as the estimation value at non-sample location, Z_i as the value from sample location, n as total of sample points, W_i as the given weight at sample location i, IDW formula is depicted as follows:

$$IDW = \sum_{i=1}^{n} W_i Z_i \Bigg/ \sum_{i=1}^{n} W_i \tag{2.8}$$

$$W_i = d_i^{-u} \tag{2.9}$$

Furthermore, the weight formula is defined as equation 2.9, with W_i is the assigned weight at sample point i, d_i is the distance between sample point i and the estimated point and u is the determinant, controlling how the weight decreases as the distance increase.

2.8.2 Thin Plate Spline

Li and Heap (2008) explained TPS in their review of interpolation methods as a scientifically strong method because of the minimization of cross validation function (CGV). Xie et al. (2011) wrote that TPS is a derivative methods from radial basis functions (RBFs). In general, RBF based on a equation with dependency to the estimated location and value of sample location. It is conceptualized as a sum of two parts, the trend function and radial basis functions. The derivative methods are distinguished by the radial basis functions. For TPS, the radial basis function is described in equation 2.10. Given $\psi(d)$ as radial basis function, c as a smoothing factor, d as the distance from sample point to estimation point, the authors depict TPS in mathematical equation as follows:

$$\psi(d) = c^2 d^2 \ln(cd) \tag{2.10}$$

2.8.3 Nearest Neighbour

Different from the aforementioned methods, NN forms Thiessen polygons to estimate value in a non-sample location. Thiessen polygons contains one sample point, which value acts as the single value valid for any point in the entire polygon. Therefore the estimated value at certain location is predicted based on the value of the closest sample point (Li & Heap, 2008).

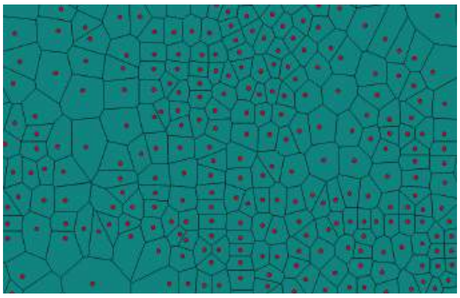


Figure 2.2: Thiessen (Voronoi) Polygon

2.8.4 Root Mean Square Error

Szypuła (2017) wrote that the common method for measuring the result of interpolation model is RMSE. It is an important parameter of the accuracy of the spatial analysis, as it compares the result of interpolation and the actual values. Wise (2011) compares five different interpolation methods of DEM by means of RMSE. RMSE is also used by Xie et al. (2011) to differentiate four interpolation methods in their paper about the escalation of soil heavy pollution. RMSE is calculated as:

$$RMSE = \sqrt{\frac{\sum(z_p - z_o)^2}{n}} \tag{2.11}$$

where z_p is the estimated value in non-sampled points, z_o is the actual value in sample points and n is the total number of points.

Chapter 3

UAM Ground Infrastructure Categorization and Designs

This thesis categorizes UAM ground infrastructure into 3 types: vertihub, vertiport, and vertistop. It is important categorizing UAM ground infrastructure, hoping in the long run as the demand growth and traffic increase, UAM operation could manage the flow efficiently. As those types categorized based on space availability and demand estimation, each type serves different function in UAM operation. To examine the minimum requirement and proper design, this thesis follows working flow in the figure 3.1. Figure 3.2, figure 3.3, and figure 3.4 are the variance of UAM ground infrastructure designs, which are proposed by author.

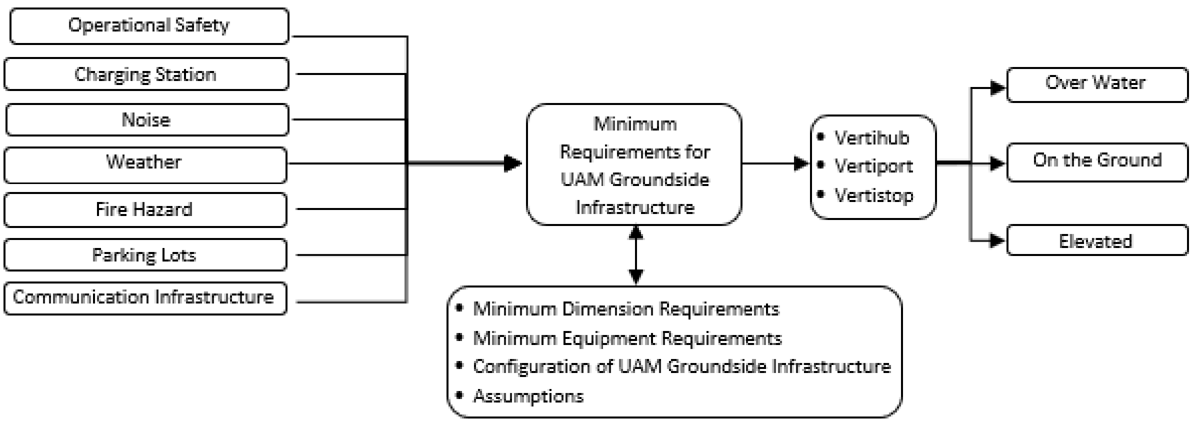


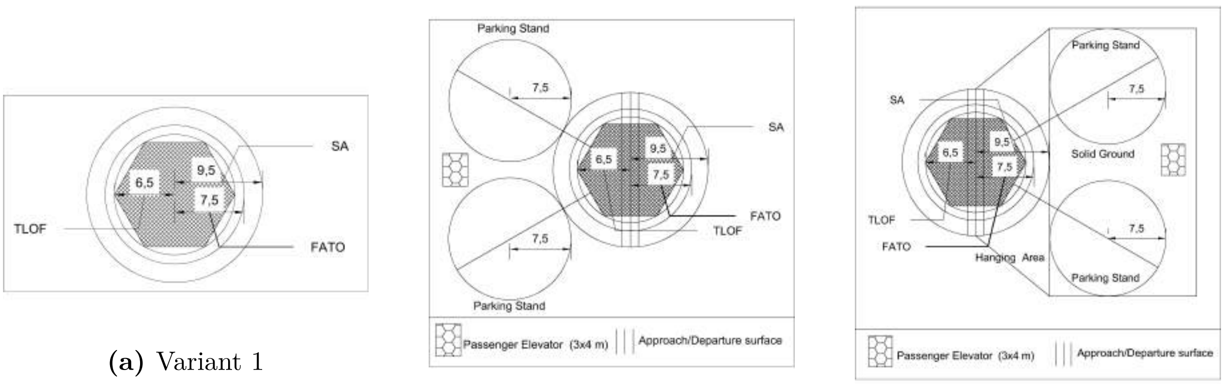
Figure 3.1: Minimum Requirement Flowchart

Referring to table 2.3, each proposed variant has the TLOF diameter of 13 m, the FATO diameter of 15 m, and safety area of 19 m. To maximize safety and avoid collision, parking stand diameter is set to 1 D or 15 m, if using the premise 15 m span of an eVTOL vehicle. Safety is also significant consideration when designing the approach/departure surface. Most of the proposed variants use 180 degrees separation, although FAA (2012) recommends to use at least 135 degrees separation between approach and departure surface. Assuming the eVTOL vehicle takes steeper glideslope than rotor VTOL aircraft (i.e. Helicopter), 120 degrees separation for approach/departure path is still considered as a safe separation, as stated by Alexander and Syms (2017).

3.1 Vertistop

The smallest type of UAM ground infrastructure are vertistops. Since it consists only a pad and maximum two landing pads, it is predicted to be build everywhere. Low density residential area in the periphery, high rise commercial and office buildings, and many locations are fit to build this compact vertistop. Figure 3.2 displays three variants of vertistop. Variant 1 (figure 3.2a) is just a single landing pad for the passengers to egress and ingress from eVTOL vehicle. With total area 361 m^2, this variant fits into any kind of space available. The variant 2 (figure 3.2b), with 1,094 m^2 area, has two parking stands and one pad. This is a versatile vertistop which can be placed in the rooftop of high rise building, on the ground, or along water body embankment.

Although both have two parking stands and a pad, the difference between variant 3 and variant 2 is in the pad. Unlike variant 2, variant 3 (figure 3.2c) is using hanging pad, similar to the proposal of Volocopter (Hawkins, 2018). Hanging pad means the pad for eVTOL vehicle performing take-off and landing is installed as an additional feature of a building and attached to the existing structure. Already consuming area of 520 m^2, this variant is beneficial from hanging pad because it is adding the space in the limited rooftop building. The hanging pad itself provides additional 398 m^2 area for the main activity at UAM ground infrastructure. Furthermore, this variant can only be installed in a rooftop or a high rise building.



(a) Variant 1

(b) Variant 2

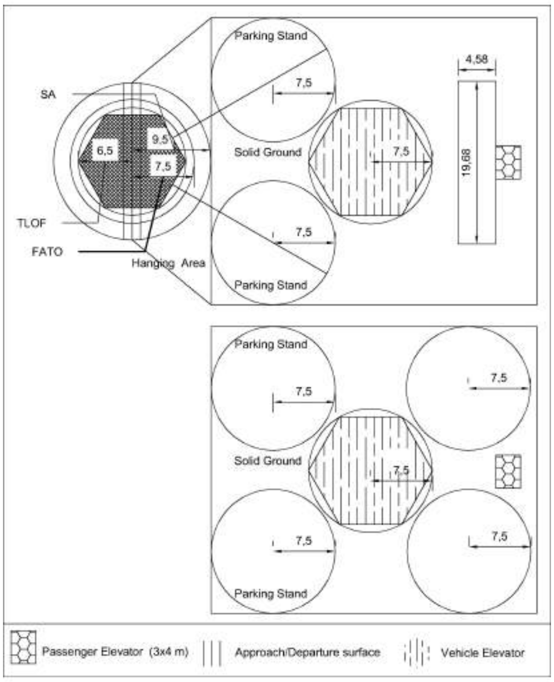
(c) Variant 3

Figure 3.2: Design of Vertistop

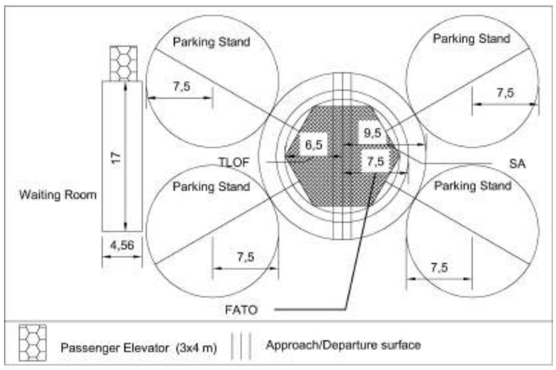
3.2 Vertiport

The intermediary type in UAM ground infrastructure categorization are vertiports. It is seen to be constructed in the city center, because of its ability to hold at least 4 eVTOL vehicles at the parking stands and less space requirement than vertihub. It serves major areas, like business center, shopping center, and dense residential area, where demands are concentrated. Small maintenance and repair operations are carried out here. Variant 5 (figure 3.3b) is an example for a vertiport. It has four parking stand and one pad, as well as one waiting room and maintenance equipment storage. With total area around 1,583 m^2, this variant can be placed along water embankment, on the ground or elevated in a high rise buildings.

Variant 4 (figure 3.3a) is another option for vertiport, which has two-level arrangement. The upper level, which consumes building footprint has the pad, two parking stands and the waiting room for total area of 1,366 m^2, while the same size lower level has four parking stands, as well as maintenance equipment storage. The exceptional feature of this variant is the vehicle elevator to bring down and up eVTOL from one level to another. Likewise variant 3, UAM ground infrastructure is beneficial from hanging pad feature because it adds more space for the operation. This variant is only possible to be installed in high rise buildings, due to its hanging pad and two-level arrangement feature.



(a) Variant 4



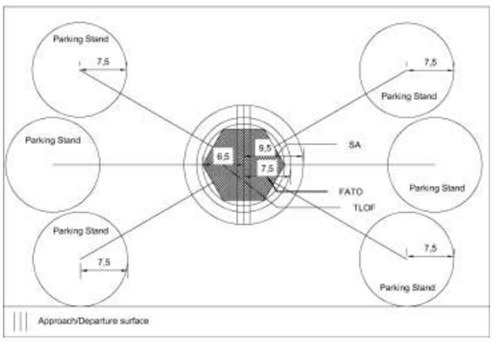
(b) Variant 5

Figure 3.3: Design of Vertiport

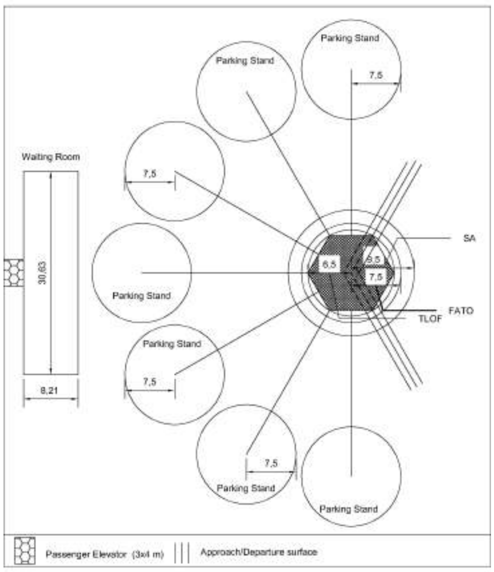
3.3 Vertihub

Vertihubs define the biggest UAM ground infrastructure type. It is forecasted to be a major hub, as well as depo, depending on the location. Vertihub could be placed either in the city center or periphery area. The land acquisition cost is the significant factor in placing vertihub. Maintenance, repair and overhaul operations of eVTOL fleets are performed in vertihub. Variant 6 in the figure 3.4a is one out of two proposed design for vertihub. This vertihub has six parking stands and one pad, sizing in total 3,426 m^2. Due to lesser land acquisition cost, this variant is mostly proper to be located in the ground area, in the less dense periphery area, as well as along river/water embankment. The difference between those two surface types is only the tool for pushing eVTOL vehicle to the parking stand. On the ground variant 6 could use either towing device or guiding rail, whereas the water embankment variant 6 should hovering slowly to the parking stand.

With total area of 4,710 m^2, variant 7 (figure 3.4b) is also proper for a vertihub usage. It has 7 parking stands and one pad. Furthermore, this proposed variant could be extended by duplicating this variant in a mirror way, so then both pad will be positioned in the outer part of the extended variant. Similar to variant 6, variant 7 is proper to be located in any type of surface, ground, water embankment or elevated, depending on the budget. The water embankment variant 7 should hovering to the parking stand, whereas the elevated variant 7 should be equipped with elevator. UAM operation is envisaged to have one vertihub in the city center, as many trip are began and ended there.



(a) Variant 6



(b) Variant 7

Figure 3.4: Design of Vertihub

Chapter 4

Factors Influencing UAM Ground Infrastructure Placement

Aided the realization of the UAM implementation, this thesis defines what are the influencing factors for UAM ground infrastructure placement. UAM ground infrastructure is one of the critical issues affecting the implementation of UAM (Vascik & Hansman, 2017; Uber Elevate, 2016). Nevertheless, only a few research studies are focused on this landing equipment of UAM. Thus, the following factors are concluded from these few research studies, as elaborated in chapter 2.3. To enhance factors selection, the AHP-Delphi and Expert interview methods are conducted afterwards, resulting a ranking of factors and their weights. For detailed explanation go to chapter 5. The factors are divided into two categories, demand side and supply side. The demand side consists of factors that potentially generate trip in a particular area, while the supply side is formed from existing factors that support establishment of UAM ground infrastructure.

4.1 Demand Side

The novelty of UAM concept should be balanced with demand or in other words, passengers that are willing to fly with eVTOL vehicles to their destination. To figure out where mostly potential passengers of eVTOL vehicles begin and end, this section presents results from literature review.

4.1.1 Population Density

Population density is the number of inhabitants living in a particular area. The aim of transportation infrastructure is to draw maximum number of passengers, as well as provide maximum area coverage (Vuchic, 2005). German et al. (2018) took number of inhabitants as an estimation for potential customers in UAM ground infrastructure site selection process. The authors perform a simulation of the cargo delivery operation using eVTOL vehicles. German et al. assumption is similar to the previous argument, in which population density becomes a proxy for potential demand.

From the assumption used by two aforementioned literature, this thesis concluded that by having dense population living in a particular area, the possibility of UAM ground infrastructure to reach potential passengers is becoming better. The bigger number of inhabitants in UAM ground infrastructure catchment area has, the higher probability of UAM operation capture potential passenger. Consequently, this thesis takes population density as one of the factors that determines UAM ground infrastructure location.

4.1.2 Median Income

Median income is the median value of total population income in a particular area. . However, several different format of income level were used in studies for determining UAM ground infrastructure location, for example Syed et al. (2017), Vascik and Hansman (2017), German et al. (2018). The number of individuals with income earning more than $ 100,000 and the number of households with income earning more than $ 200,000 are income formats that utilized by Syed et al., while total income per area (census tract in this case) is income format utilized by German et al. Another form for income level factor in UAM ground infrastructure site selection process is by estimating home value heat map (Vascik & Hansman, 2017). Vascik and Hansman assumed that high property valuation extrapolates demand for wealthy commuters.

In the initial operation of UAM, it is predicted that the fare of flying using UAM vehicle will be expensive, even in ODM mode. The UAM fare is estimated to be more expensive than a ride with uberX service (Uber Elevate, 2016). That is why three previously mentioned studies used income level of a population in a particular area as a demand indicator. This thesis selects median income as one of the demand factors because higher median income means more potential passengers for initial UAM operation. High median income in a particular area means more inhabitants who could afford initial UAM fare. Median income is particularly chosen as it represents the population better by trimming down the outliers (Rost, 2018).

4.1.3 Office Rent Price

For business trip purpose, which often constrained by time limitation, flying to the another destination where located in inhospitable landscape or surrounded by traffic jam hot-spots produces a vital niche helicopter market (Nexa Advisors, 2009). Although business trip is a niche market for helicopter operators, UAM operation with eVTOL vehicle is envisaged as a turning point for business trip due to its lower noise level (Uber Elevate, 2016). This premise makes eVTOL vehicle possible to land on any elevated ground infrastructure where many offices are located within ground infrastructure proximity and eventually more corporate demand are generated.

Office rent price factor is a proxy for estimating business trip budget of a company. The higher office rent price a company should pay supposedly represents higher budget for business trips done by its employees. As a result, more potential UAM demand in the location where office rent prices are high. This premise also makes this thesis incorporates office rent price factor as one of the factors that influence UAM ground infrastructure placement.

4.1.4 Points of Interest

Points of interest (POI) factor comprises of the most visited places by tourist, both international tourists and local residences. Tourism symbolizes an evidence of demand for urban transportation mode (Albalate & Bel, 2010). Therefore, it is important that catchment area of any transportation node covers tourist attraction place. The way tourists arriving at the tourist attraction place should be convenient for them (Gronau & Kagermeier, 2007). Vuchic (2005) also seconded the influence from point of interests over transportation demand and emphasized that transport node should be planned to serve major activity points.

The overview of current VTOL vehicle services display prospective demand in tourism trip. Current chartered helicopter companies in Los Angeles region serve many tourist attractions, for example Dodger Stadium, Angel Stadium/Honda Center, Orange County, Santa Monica and downtown Los Angeles (Vascik & Hansman, 2017). The number of tourist travel by VTOL vehicles could capture 5 - 20% of the total travel demand generated by tourism (Amoroso, Migliore, Catalano, & Castelluccio, 2012). The prospective demand of tourism trip makes this thesis chooses POI factor as one of the factors influencing UAM ground infrastructure placement.

4.1.5 Major Transport Node

Major airports and major intercity train stations are making up this factor. There is a potential demand of UAM from and to major transport hubs, as shown by the current helicopter charter services routes in Los Angeles (Vascik & Hansman, 2017) and current Uber long-distance trip data in Los Angeles and London (Uber Elevate, 2016). Major transport nodes are also important when it comes to intermodality. Taking railway station as a proxy for UAM ground infrastructure, the planning process of railway station takes intermodality between train and another mode of transport into account (Vuchic, 2005). Three previously mentioned demand consideration are the reason why major transport node factor is selected as one of the influencing factors.

Providing UAM ground infrastructure in major transport nodes can improve traveling convenience, as the long distance passengers could change mode of transport almost seamlessly from one mode of transport to another. eVTOL vehicles could serve the first and last mile in a long distance trip, in which airplane or high speed intercity train acts as the main leg carrier. Reflecting from chartered helicopter characteristics, it is foreseeable that major transport nodes generate potential passengers in the initial operation of UAM.

4.1.6 Annual Transport Cost

Annual transport cost is the average of total household expenses in transportation category within an area in a calendar year. The cost of public transport tickets is included in this factor, among with vehicle ownership cost and vehicle miles traveled cost (The Center for Neighborhood Technology, 2017). This thesis assumes if the household has an excessive amount of annual transport cost, the mode-shifting process from their daily transport mode to UAM will be easier, even though only for non-commuting trip. Based on that premise, this thesis selects annual transport cost as one of the influencing factors for UAM ground infrastructure placement.

4.1.7 Job Density

Job density means the number of jobs available in particular area. In the planning phase, a transportation infrastructure should be designed to create a supporting relationship with land use patterns (Vuchic, 2005). In the implementation, The taxi stands in New York city are predominantly located adjacent to office building (Giuliani, Rose, & Weinshall, 2001). Therefore having UAM ground infrastructure to support and serve business district or an area where a lot of offices located is economically potential.

The transport demand generated by job density could be a daily routine (commuting) trip or irregular business trip. This factor complements aforementioned office rent price factor ideally. The combination of those two factors makes demand estimation more powerful. If there is a lot of office in one area and it has high office rent, then almost certainly this area is suitable for UAM ground infrastructure. Although there is no previous study about UAM ground infrastructure using taking this assumptions, a high value in job density tends to indicate high demand in UAM. Consequently, this thesis perceive job density is one of the influencing factors for UAM ground infrastructure placement.

4.1.8 Extreme Commuting

eVTOL vehicles are expected to carry passengers that are willing to pay more for getting an advantage in travel time. Often, those are person who travel through traffic jam hot spots or long distance trip (Vascik & Hansman, 2017). Extreme commuters are person who endure long distance trip, translated into 90 minutes, one way to get into their office (Rapino & Fields, 2012).

Extreme commuting also acts as a proxy for long distance trips data, which have been utilized by Uber Elevate to estimate where to locate UAM ground infrastructure (Uber Elevate, 2016). Since there is no available data, it is hard to follow Uber Elevate analysis and create UAM ground infrastructure constructed based on Origin-Destination point for long distance ride-sharing. A high number of extreme commuters is seen by this thesis as a proxy for UAM demand. Hence, this factor counts as one of the influencing factors in UAM ground infrastructure placement.

4.2 Supply Side

As the cost of building completely new from the scratch UAM ground infrastructure is expected to be costly, the placement of ground side infrastructure of UAM should exploit existing infrastructure and other less costly possibilities. Therefore, supply side provides a general term for existing factors that are offered by the city to welcome UAM operation.

4.2.1 Existing Helipads and Potential Spots

A cost-saver solution came from Vascik and Hansman to utilize existing helipads and petrol stations. This factor could reduce initial cost of UAM operation because no construction and land acquisition are necessarily needed. Compare to the construction costs of intercity highway or a new subway line that can costs hundreds of millions of dollars, UAM operation only requires ground infrastructure, as well as the charging stations (Porsche Consulting, 2018).

In this thesis, the existing helipads location and the availability roof of petrol station are taken into account as they reduce the initial capital needed for setting up UAM operation. Section 2.2 explains that UAM ground infrastructure has similarity to heliport. The potential spots are subject to be changed, depending what assumption is taken into account, such as the availability of parking lot in a supermarket chain or the availability of park area. Although the proposed concept of UAM ground infrastructure defines that the initial cost or the ownership can belong to private sector, but the usage of UAM ground infrastructure should be accessible to all UAM operators, as the traffic flow within internet infrastructure (Porsche Consulting, 2018)

4.2.2 Existing Noise

Existing noise is the current level of noise, generated by the traffic, both surface-level and at the airport traffic. Noise is one of the biggest hindrances in implementing UAM within urban area

(Vascik & Hansman, 2017; Uber Elevate, 2016; Alexander & Syms, 2017; Porsche Consulting, 2018).

Consequently, overlaying existing noise with noise generated from electric propulsion of eVTOL vehicles may offering a convenient benefit for the public. This idea is similar with the proposal to utilize cloverleaf interchanges along the highway (Antcliff et al., 2016). Dissolving noise generated from eVTOL vehicles with existing noise from traffic, which already accepted by public, might lead to a higher public acceptance. A high noise level is seen as a potential for a location to build UAM ground infrastructure and that is a reason to select existing noise as a factor in locating UAM ground infrastructure.

4.3 Binary Considerations

Binary consideration is the opposite of continuous value that have been defined earlier in chapter 4.1 and chapter 4.2. Binary consideration factor has a Boolean (discrete) value, either 0 or 1 and there is no value in between. Factors that belongs to this category can directly determine whether an area is suitable or not for an UAM ground infrastructure.

Binary consideration consists mainly of flying and landing restriction. This factor creates areas that are not allowed legally for UAM ground infrastructure site. Flying and landing restriction varies in different countries, states or any legal domain. Nonetheless, the message is indistinguishable. Not a single aircraft is allowed to fly or to land through or in this area. This restriction is the outcome of certain restricted areas, for example military base, education facilities, health facilities, national parks, and so on.

If there is no available landing restriction then this thesis takes flying restriction only into account and produces the following valid premise. If there is a flying restriction over particular area then it is obviously impossible for a civil aircraft or upcoming eVTOL vehicles to take-off and landing there.

Airspace classes and UAM operations in the airport vicinity are also another important consideration. Nevertheless, this factor has nothing to do with spatial analysis. An area under particular airspace class is only required to communicate with authorized air traffic control (ATC) tower or air traffic management (ATM) in order to avoid a collision with other conventional aircraft, eVTOL vehicles, and airport ground infrastructure. Communication devices development makes a breakthrough proposal which is able to find a solution to this traffic issue. Hence, there is no further problem with building an UAM ground infrastructure in the airport vicinity as long as it is registered to the authorized tower or ATM and complying with the given regulation (DLR, 2017).

Chapter 5

AHP-Delphi Analysis

As presented in chapter 2.6, equation 2.6 shows the suitability analysis formula. It consists of two parts, WLC and Boolean constraint. As the WLC analysis requires weight or coefficient for each variables/factors, this thesis conducts the AHP-Delphi analysis to fill in the requirement. In other suitability research, normally the weights are generated from the AHP analysis (Banai, 1998; Charabi & Gastli, 2011; Baseer et al., 2017). This thesis, since UAM is an avant-grade topic, involves Delphi analysis altogether with AHP analysis to generate the weights for GIS-based suitability analysis. The Delphi analysis forecasts futuristic research topic with the help from experts. To that end, a group of experts is expected to reach a consensus. If the database in particular case study location were could not found or not publicly available, then the weights from the AHP-Delphi analysis should be normalized.

5.1 Real-time AHP-Delphi Analysis

With the help of Microsoft Excel template created by Goepel (2013), this analysis is conducted simultaneously in a meeting room, where all the invited experts sat together and brought along their laptop. Each laptop has an access to the server where corresponding files stored. For the purpose of this thesis, the excel template acted as a master file, while different files were created for the participants/experts. The experts' file and the master file were stored in the same server, where every experts (as well as the author) had access to it. In total there were 13 experts coming from various background. They altogether gathered in a conference room and were given the introduction and the explanation of factors, as well as on how to complete the survey at the beginning. Afterwards, the experts proceeded to fill in the given excel sheet. Once everyone has finished answering the pairwise comparison, the master file concurrently calculate the RGMM value, weights value, ADM value, consensus value and CI from all the experts. Table 5.1 shows the result from the initial round AHP-Delphi analysis. More detailed result can be seen in appendix A

Factor	Weight
Major Transport Node	18.2%
Point of Interest	12.7%
Jobs Density	9.5%
Number of Extreme Commuters	9.1%
Average Total Transport Cost	9.1%
Existing Noise	9%
Office Rent Price	8.9%
Median Income	8.8%
Potential Supply	7.7%
Population Density	7.2%

Table 5.1: Result of AHP-Delphi Analysis Initial Round

Factor	Weight
Major Transport Node	18%
Point of Interest	12.6%
Jobs Density	10%
Average Total Transport Cost	9.3%
Office Rent Price	9.1%
Number of Extreme Commuters	9%
Median Income	9%
Existing Noise	8.4%
Potential Supply	7.8%
Population Density	6.8%

Table 5.2: Result of AHP-Delphi Analysis First Iteration Round

Factor	Weight
Major Transport Node	19.4%
Point of Interest	12.3%
Jobs Density	9.9%
Number of Extreme Commuters	9.5%
Office Rent Price	9.5%
Median Income	9%
Average Total Transport Cost	9%
Existing Noise	7.6%
Potential Supply	7.2%
Population Density	6.5%

Table 5.3: Result of AHP-Delphi Analysis Second Iteration Round

The weights as a result from the initial round are displayed in table 5.1. From this ranking, experts consider major transport node as the most important factor to locate UAM ground infrastructure, followed by POI factor. The initial round reached consensus of 47.9% with a consistency ratio of 0.7%. Since the aimed consensus level is 70%, the initial round consensus value leads to another iteration round of AHP-Delphi analysis.

Calculating by means of geometric mean, the ADM value is the aggregation of all values (responses) from all experts (respondents), acting as a benchmark for all experts. Further information is explained in chapter 2.6. The ADM value of the initial round table in the appendix A also shows that there are no significant preferences generated by the experts. Most of the ADM value were around 1.5 to 2.4. This ADM value might happened because one expert choose factor A over factor B for value of 5, while another expert choose factor B over factor A for value of 5. The experts were shown this ADM table and asked to reconsider their answer according to the ADM value, as another attempt to increase higher consensus percentage in the next round of AHP-Delphi analysis.

New considered pairwise comparison and importance values were filled by the experts during the iteration process. Table 5.2 displays new results after the first iteration process. Notable adjustments are founded in the job density, number of extreme commuters and existing noise factors. After the first iteration process, experts were accommodating the ADM value and the consensus value increased to 54.4% with a consistency ratio of 0.8%. The targeted consensus value is 70%, yet the adjusted consensus value is still below the target (54.5%). Therefore, another iteration round was performed. The experts were once again asked to reconsider and adjust their valuation and preferred factors.

In this final round of AHP-Delphi analysis, the pairwise comparison had been refilled by the experts during the second iteration process. The result showed several changes, for example the average total transport cost factor declined 3 places, the number of extreme commuter increased 2 places, and the major transport node gained more weight. However, the consensus value was still below the target, showing only a slight increase to 58.1% with consistency ratio of 0.9%. Considering time limitation, the real-time AHP-Delphi analysis was forced to dismiss and take the ADM value as weights for the criteria. The outcome of the AHP-Delphi analysis, like low ADM value and not achieving the targeted Shannon entropy value are not as expected beforehand.

5.2 Expert Interview

To enhance real-time AHP-Delphi result, this thesis conducts deeper forecasting method by interviewing the so-called "super-experts" or expert with more than 15 years of experience. This interview aims to get more insights about UAM operation and other factors that might be taken into UAM ground infrastructure analysis.

The first expert has more than 15 years in aircraft designing, especially Unmanned Aerial Vehicle (UAV). Expert 1 fulfilled the similar pairwise comparison questionnaire like the one in real-time AHP-Delphi, as well as getting consistency index calculated. The difference is expert 1 does not have to reconsider his answer according to other experts in the iteration round. The answers from expert 1 has 13% of consistency ratio, which is accepted. As shown in table 5.4, expert 1 put big percentage on median income criterion, as he thinks that people with enough money are the most potential passenger and will help the first implementation of UAM operation. Due to company ability to give high salary and operational budget, especially for transportation in a daily basis, office rent price is the second most important criterion according to the expert 1.

Additionally, the expert 1 spoke his thought that UAM ground infrastructure placement analysis should be different one city to another. It depends on the restriction and rules applied. The placement analysis also depends on another existing transport mode. For example, if a city has good public transportation system then the urge of having UAM and eVTOL vehicles tend to be less to certain extent, compare to a city that has chaotic surface-level transport and poor public transport service.

Factor	Weight
Median Income	24%
Office Rent Price	17%
Average Total Transport Cost	12%
Major Transport Node	10%
Potential Supply	10%
Point of Interest	8%
Existing Noise	6%
Jobs Density	5%
Number of Extreme Commuters	5%
Population Density	3%

Table 5.4: Result of Expert Interview 1

Factor	Weight
Point of Interest	25%
Average Total Transport Cost	22%
Median Income	13%
Office Rent Price	10%
Jobs Density	8%
Major Transport Node	8%
Existing Noise	6%
Number of Extreme Commuters	4%
Population Density	3%
Potential Supply	2%

Table 5.5: Result of Expert Interview 2

The second expert has more than 15 years of experience in operational aspects of aviation subject. Expert 2 also did the same questionnaire procedural with real-time AHP-Delphi participant, except the iteration round. With 14% of consistency ratio, which is a practicable value according to Goepel (2013), expert 2 puts 25% weight on POI. The tourism is generating traffic demand for UAM operation, especially for sightseeing purpose in a time sensitive manner. He also underlined the slight difference between current transportation mode and UAM operation, if the average total transport cost is high. Meaning, with high transport cost, people could switch transport mode without thinking complexly. Those statement can be inferred from table 5.5.

According to expert 2's opinion, another important factor for placing UAM ground infrastructure would be the public perception towards technological advancement in a certain area. To give an illustration, Silicon Valley, where a lot of IT-companies based might have better reception of UAM operation and subsequently allows the construction of UAM ground infrastructure. Another thing that might be taken into further consideration is the vertical accessibility of elevated UAM ground infrastructure. Since UAM is a time-sensitive mode of transport, then the first- and last-mile process for getting into the eVTOL vehicle does matter. If a vertiport is built atop tall building and it takes sometimes for the vertical movement, then the advantage of flying in UAM is not significant compare to other modes.

5.3 Result

To summarize, experts from real-time AHP-Delphi analysis have a different perspective on the initial UAM operation compared to two "super-experts". Although the consensus had not been achieved, the experts from real-time AHP Delphi analysis tend to perceive non-commuting trip as the main trip generator for the initial phase of UAM operation. The conclusion is drawn from table 5.3, where major transport node and point of interest topped the table.

On the contrary, two "super-experts" favors commuting trip as trip generator. Even though POI is atop the expert 2's ranking, transport cost as the second best factor in this ranking has only a slight difference than POI. Furthermore, the rest of top factors in both expert's rankings display a resemblance in opting for commuting trip as the early demand of UAM operation.

Chapter 6

Case Study Implementation

The general methodology employed in this thesis is GIS MCDA. Specifically, this thesis performs GIS-based suitability analysis, in which each factor will be multiplied with a certain weight based on its importance in influencing UAM ground infrastructure. The outcome of GIS-based suitability analysis portrays suitable particular areas to build UAM ground infrastructure. Another advantage from using GIS-based analysis is that the visualization of the outcome would be more clear and could be understood easily, especially for people who recognize case study areas.

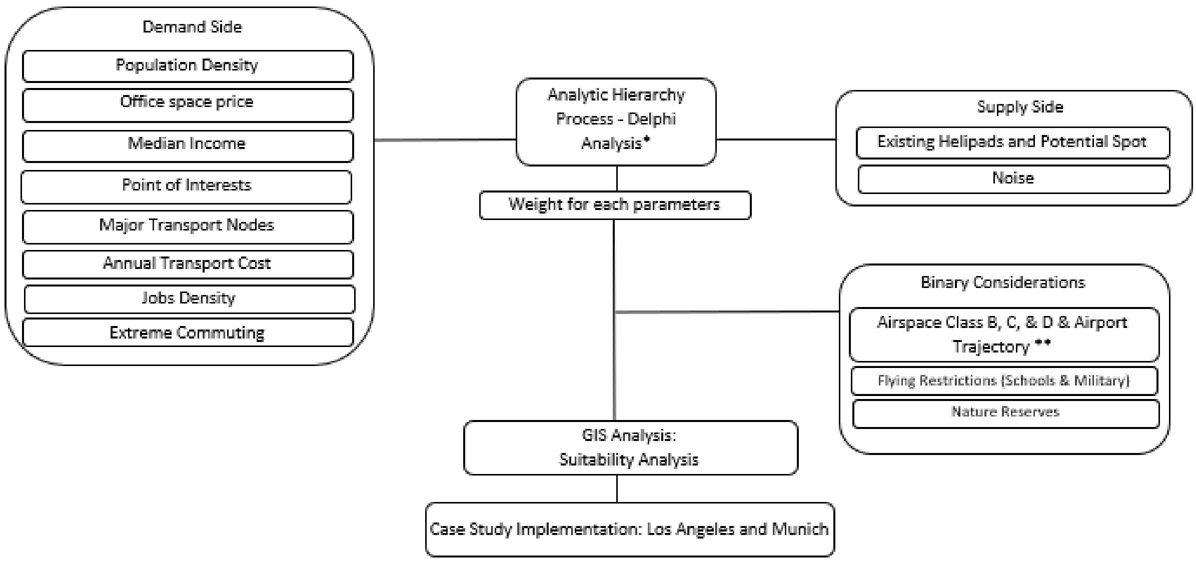


Figure 6.1: Thesis Flowchart

6.1 Case Study: Los Angeles

There are several factors why this study takes Los Angeles as one of case study cities. The tremendous inhabitants of LA metropolitan area is one determined factor, which leads to further rationales, like commuter flow and weather. According to a study conducted by Rapino and Fields (2012) and using 5-year American Community Survey data as a basis, the LA metropolitan area is ranked fifth in the highest percentage of mega commuters in metropolitan areas. The authors also composed a ranking of Top 10 mega county commuter flows based on mean travel time and mean distance for commuting purposes, in which two counties in the LA metropolitan area peak the ranking. Those are San Bernadino county to Los Angeles county and Riverside county to Los Angeles county trips. LA also has 76.7% growth in super-commuter (super-commuter depicts a person who lives beyond boundaries of a metropolitan area but works in the central location of that metropolitan area) from 2002 - 2009, the second highest compared to other super-commuter growth rate in metropolitan areas in the USA. (Moss & Qing, 2012).

Considering the impact of weather in UAM operation, a case study city should have considerable weather for all year round operation. High speed winds, severe rains, and cold temperatures are significant weather characteristics that may disturb daily UAM operation. LA's consistent year-round weather is another reason why it was chosen as a case study. Any disturbance caused by weather may only affect UAM operation for less than 20 days a year in LA (Vascik & Hansman, 2017). The boundary for LA case study is 80 kilometer or 50 miles, as it represents minimum distance for a commuter to be considered as a long-distance commute (Rapino & Fields, 2012).

The area of the first case study in this thesis covers five counties: the Los Angeles county, San Bernadino county, Orange county, Ventura county and Riverside county. Not every census tract and census block group is included in this thesis, only those which are located within the 80-kilometer distance from the downtown of LA. In total, there are 9,879 census block groups involved in this Los Angeles metropolitan area case study. Appendix B displays detailed maps for each factor in this case study.

6.1.1 GIS Database Building

This section gives an explanation on how to collect and classify required data. As explained previously, the factors are divided into three categories: demand side, supply side, and binary consideration. Like other American cities, LA has several open access database, which can be utilized by this research. This database provides up-to-date data or at least estimation of recent situation. The open access database mostly publishes data up to census block group level, which covers data within a few city blocks. The GIS shapefiles for the basic polygons are provided by the U.S. Census Bureau under its flagship 2010 TIGER/Line shapefiles (U.S. Census Bureau, 2010).

6.1.1.1 Demand Side

Population Density

Population density data in this research is obtained from the American Community Survey 2016 5 year estimation (U.S. Census Bureau, 2016). The population per census block data are collected online, through advanced search mode in a U.S. Census Bureau website. To create population density data, the obtained data are divided by area of census block. The data are then inserted into GIS application and are attached to the corresponding polygon of a certain shapefile layer. By doing so, the vector map of population density is successfully created.

Afterwards, the vector map is converted to raster format and is standardized, by means of equation 2.7. To make sure that the standardization process had been implemented correctly, raster layer statistics function checked the maximum and minimum raster value. The latter should have a value of 0 and the former should have a value of 10.

The vector map shows that the densely populated areas (20th percentile) are located in the down town LA, as well as south LA and north Hollywood. Following behind are the city center in the surrounding counties, for example Oxnard, Anaheim, and San Bernardino.

Median Income

Similar with population density data, median income data is obtained from the American Community Survey 2016 5-year estimation (U.S. Census Bureau, 2016). However, there are several census blocks without median income data, including dense area in downtown LA and LAX Airport. This noData value influence the WLC calculation further because noData value is deliberately converted to 0 or very low median income within census block. To avoid that, this thesis employs several interpolation methods and set up a comparison of the results afterwards.

As explained in section 2.8, there are three interpolation methods for estimating noData value, namely IDW, NN, and TPS. The vector layer of median income creates a centroid for representing every census block, and thus is converted to raster format. The initial vector map is also converted to raster format, so the interpolated maps can be compared by means of RMSE. Table 6.1 shows RMSE comparison for median income data, where NN has the smallest RMSE value, compared to other interpolated raster maps. NN also has the most related minimum and maximum value to actual rasterized layer, according to the table 6.2. Subsequently, the NN interpolation method is chosen for the further WLC analysis. From the interpolated map we can infer that high median income inhabitants (20th percentile) live in the peripheral area of LA, for example Simi Valley, Thousand Oaks, Malibu, and Mission Viejo. Before this raster data is able to proceed into further step, the standardization process should be performed with the help of Raster Calculator function in QGIS.

Table 6.1: Result of RMSE Calculation

	Square Error	Total cells	Mean Square Error	RMSE
IDW	7,565,100,478,450,000	14,721,000	513,898,544.83	22,669.33
NN	7,147,443,535,980,000	14,721,000	485,527,038.65	22,034.68
TPS	12,489,442,840,600,000	14,721,000	848,409,947.73	29,127.48

Table 6.2: Comparison Result between Interpolation Methods and Actual Raster

	Actual Rasterized Data	TPS	NN	IDW
Min Value	0	- 235,870	6,875	13,050
Max Value	248,000	595,930	248,000	242,334
Mean	39,991	90,640	86,204	74,369
Std. Dev	49,199	45,347	38,363	15,710

Office Leasing Price

To estimate the office rent value in LA, this thesis collects office leasing prices from various property websites, such as cityfeet (Cityfeet, 2018) and loopnet (LoopNet, 2018) and interpolates the collected data is the best effort to estimate office rent value in Los Angeles. These selected office leasing data are inserted into QGIS with the help of supplementary website, called Geoplaner (Nathansen, 2018) whose function is to generate .gpx file from the given addresses. Subsequently Geoplaner creates point of the given address using Google Maps as basemap in .gpx format. In total, there is a random number of 428 sample points of office rent advertisement gathered from both websites, with minimum office price $83.96 up to $1,227.13 per square meter per year.

Although the IDW interpolation method is not optimal in estimating real estate value compared to Kriging method, as explained in section 2.8, this thesis chose to perform the IDW method due to its simplicity and ability to take distance between points into calculation. The interpolation result shows that the high leasing price offices are located along the Pacific shore side, for example in Malibu, Santa Monica, and Newport Beach. In addition to that, downtown Los Angeles also has high office leasing price. Before this raster data able to proceed into further step, standardization process should be undertaken with the help of Raster Calculator function in QGIS.

Points of Interest

Tourist attractions or POI data are obtained from the Trip Advisor website (TripAdvisor, 2018) for top 40 attractions within case study area. Each county has at least one top tourist attraction included in the list. This source relies heavily on Trip Advisor's algorithm on the ranking process. Nevertheless, this selection could represent trip generation and trip destination by tourists. Next, the list of the selected 40 POIs act as an input for the aforementioned Geoplaner website and subsequently resulting .gpx files which consist of POIs points.

Heatmap function in the QGIS software allows this thesis to locate areas with the most POI and is taken into WLC calculation afterwards. All the POI points are given a 1.5 km radius, as 40% of Americans tend to walk at least 0.9 mile (1.5 km) in recreational occasion (Yang & Diez-Roux, 2012). By having a heatmap, two nearby POIs may join the usage of one UAM ground infrastructure. For example, The Getty Center and University California Los Angeles which is only separated by 3.45 km can be conjoined, resulting in a higher demand for UAM ground infrastructure than a single POI.

This heatmap raster map has noData value in between points, which causes miscalculation in the WLC analysis. Therefore, the grid resampling function in SAGA GIS helps by adjusting this noData value and fills it with a 0 value. POI layer differs from previously explained layers. Instead of being standardized, this layer is reclassified based on percentile distribution of raster value. By doing so, an area in a certain buffer zone will have the same value instead of continuous value. Despite of the different methods, standardization and reclassification are both suitable for the WLC analysis in the next step.

Major Transport Node

The criteria of major transport node depends on the size of the city of case study. For LA, this thesis looks up top 5 airports and top 5 intercity train stations. The top 5 airports are described from enplanement ranking in the USA for commercial service airports in 2016 published by FAA (FAA, 2017a). Los Angeles International (LAX), John Wayne Airport (SNA) in Santa Ana, Ontario International (ONT), Bob Hope (BUR) in Burbank, and Daughtry Field (LGB) in Long Beach are the top 5 airports in case study area according to the FAA publication. This data is incorporated into QGIS by adding up additional points manually by editing vector map.

The top 5 intercity train stations are acquired from the Amtrax station's ridership reports in California created by Rail Passengers Association (Rail Passengers Association, 2018). The train stations belonging in this category are the Los Angeles Union station, Irvine transportation center, Fullerton transportation center, San Juan Capistrano depot, and Anaheim. This data is incorporated into QGIS by taking open street map (OSM) data via Geofabrik (OpenStreetMap, 2018a).

Heatmap function in QGIS converts point data into a heatmap area with incremental values within radius of 1 km. Major transport node map encounters noData value problem when converting from vector map to raster map, similar to POI layer. By doing the same grid resampling process in SAGA GIS software, the problem is solved. Then, major transport node raster map is now allowed to proceed to the reclassification step.

Annual Transport Cost

The Center for Neighborhood Technology (2017) provides this thesis with an online database of the average annual transportation cost in census block scale. Annual transportation cost comprises of total auto ownership cost, total public transportation cost, and driving cost per mile (auto use cost). This data is part of the Housing and Transportation Index (H+T Map), which gives a comprehensive understanding of the affordability of location. Annual transport cost in case study area varies from the minimum of $5,075 per year to the maximum $19,846 per year. As this data is on census block level, the compiling process with census block GIS shapefile from U.S. Census Bureau (U.S. Census Bureau, 2010) is straight forward.

However, this data is not fully completed. There are noData value in some census blocks, leaving this thesis with no option but interpolation. After the centroids were ready, three interpolation methods were executed. Three raster maps as a result from three different interpolation methods are compared against the initial raster annual transport cost data. Among them, the NN method creates a raster map with the minimum RMSE from the initial raster map, as shown in table 6.3. Moreover, table 6.4 displays that NN has the similarity in minimum and maximum value towards the actual rasterized data. Afterwards, the selected NN method is standardized, as a preparation step for WLC analysis. From the result of the standardization process, it is shown that census blocks with high transport costs are situated in the periphery area of Los Angeles city.

Table 6.3: Result of RMSE Calculation

	Square Error	Total cells	Mean Square Error	RMSE
IDW	235,006,993,529,000	40,900,000	5,745,892.26	2,397.06
NN	105,306,917,465,000	40,900,000	2,574,741.26	1,604.60
TPS	116,137,186,319,000	40,900,000	2,839,540.01	1,685.09

Table 6.4: Comparison Result between Interpolation Methods and Actual Raster

	Actual Rasterized Data	TPS	NN	IDW
Min Value	0	4,759	5,075	6,325
Max Value	19,846	34,478	19,846	19,722
Mean	8,022	16,640	16,366	14,554
Std. Dev	8,471	2,330	2,128	958

Job Density

Job density data are acquired from The Origin-Destination Employment Statistics (LODES) from U.S. Census Bureau (U.S. Census Bureau, 2015). This source provides origin and destination up to census blocks level. As this thesis only looks for job density data, the origin home-office trip data can be excluded and increase the processing speed. Later, the job density data are incorporated with GIS shapefile from U.S. Census Bureau (U.S. Census Bureau, 2010) and are divided with area of the census blocks. The densest census block has 12,0810 jobs/km^2 and is located in the downtown LA.

Eventually, there are some unknown data in several census blocks, similar to the median income and annual transport layer. To solve the problem, again, the noData census block should be interpolated to find the estimated value using three interpolation methods, IDW, NN and TPS. Table 6.5 shows that the TPS result presents better RMSE value than other methods, yet its minimum raster value is negative (table 6.6), meaning it is not appropriate to be standardized. Therefore, the NN method as the second best in RMSE value and the most similar minimum and maximum value with an actual rasterized data is standardized and is taken into further analysis.

Table 6.5: Result of RMSE Calculation

	Square Error	Total cells	Mean Square Error	RMSE
IDW	161,283,012,678	14,721,000	10,955.98	104.67
NN	79,062,171,455	14,721,000	5,370.71	73.29
TPS	69,021,389,511	14,721,000	4,688.63	68.47

Table 6.6: Comparison Result between Interpolation Methods and Actual Raster

	Actual Rasterized Data	TPS	NN	IDW
Min Value	0	- 1,230.8	0	0
Max Value	12,081	11,851.6	12,081	11,056
Mean	19	34.7	38	82
Std. Dev	119	144.7	154	62

Extreme Commuting

The 5-year estimates survey data from the U.S. Census Bureau U.S. Census Bureau (2016) provides another category, which is relevant to UAM operation. Travel time to work place, this category name, has different number of inhabitants in census block level who travels in various travel times. According to subsection 4.1.8, extreme commuters endure more than 90 minutes to get to the office from home. The maximum number of extreme commuter is 522 inhabitants in a census block, located at the outermost of case study area.

Combined with GIS shapefile from U.S. Census Bureau, extreme commuter layer is successfully incorporated to GIS. Next, rasterize function in QGIS transforms this vector map into a raster map. To make extreme commuting raster map able to be combined with other maps, standardization process using equation 2.7 is a prerequisite step to be executed.

6.1.1.2 Supply Side

Existing Helipads and Potential Spots

Existing helipads and potential spots vector layer is made up from points of the exact locations. Despite the aim of this thesis is searching for suitable areas (not as detailed as the exact location using site search modelling analysis), supply point acts as the exact location and provides a value at the exact location for further analysis. By using heatmap function in QGIS with a radius of 250 m, this exact location point turns into several levels of buffer area with the point as its center, of which contains gradual value.

This layer is a combination between existing helipads and potential spots, which for this thesis is the rooftop from gasoline stations. There are 343 helipads and 809 gas station within case study area of LA. Both data, existing helipads points and gasoline station points are extracted from OSM data, via Geofabrik. Both are merged and the final vector layer is rasterized using heatmap function. As the problem of noData value occurs, SAGA GIS helps by resampling the extent, as well as filling a 0 value to the noData space within points. Later, the heatmap is reclassified to an ordinal value from 0 to 10.

Existing Noise

Existing noise data of surface-level and aviation transportation is acquired from The National Transportation Noise Map created by the U.S. Department of Transportation (U.S. Department of Transportation, 2017). This map has equal classification of decibels, from 35 db to 95 db nationwide. For case study area, it ranges from 36 to 85 db with the highest noise occurring around the airport, especially those with a high enplanement number, for instance Los Angeles International airport, Bob Hope Airport in Burbank and John Wayne airport in Santa Ana.

Consequently, this equal classification raster map is reclassified from a 1 to 10 scale, according to percentile distribution. standardization could work, but unfortunately there are two different minimum and maximum raster value from two different function in QGIS, raster layer statistics and raster information. Taking raster information minimum and maximum value into the standardization formula, the result exceeds 10 as the maximum standardized value. Hence, using reclassification based on percentile is the best option for this thesis.

6.1.1.3 Binary Consideration

According to Vascik and Hansman (2017), LA has an existing law prohibiting helicopter pad in the vicinity of K-12 education facilities. It is the California Public Utility Code (PUC) § 21662.5 which restricts a VTOL vehicle to land and depart within 1000 ft (300 m) from K-12 school buildings. This leads to further analysis in this thesis. Extracting all the K-12 education points from OSM database through Geofabrik and combined with a building footprint of K-12 education facilities from OSM database through bbbike (OpenStreetMap, 2018c), a new vector layer has been established.

Another restricted flying area within case study area is the military base camp. This data is collected from the FAA map, published in ArcGIS website format (FAA, 2017b). The source does not have a Web Map Service (WMS) address that can be accessed or shapefile format that can be downloaded. Therefore, this thesis manually digitize the base map (OSM map) in QGIS.

Airspace class B, C, and D or around airports vicinity are also frequently debated, whether eVTOL vehicles are allowed to operate there. This is still in discussion and development, but one thing for sure, referring to section 4.3, eVTOL vehicles and UAM operation are able to fly in the airport vicinity as long as the advanced communication system is able to coordinate all the parties (ATC, aircraft, and eVTOL vehicles).

Another thing that is still in debate is nature reservation area. By far, this thesis have performed detailed research about this limitation in case study area, but have come to no conclusion. Several existing helipads within a nature reservation boundary are a sign that landing and take-off within the area is allowed as long as it's registered to the authority.

School restriction and military base camp restriction (binary constraints) vector layers are then superimposed with boundary vector layer to create the permitted flying zone. To make the calculation time faster, the result of WLC analysis (scenario A, B and C) are clipped with the permitted flying zone vector raster, thus create the final result of WLC analysis raster maps in this thesis for case study LA.

6.1.2 Suitability Analysis

All the criteria layers, now either have been standardized or reclassified, are in raster format maps. The OWA function in SAGA GIS is also able to perform WLC analysis. Connection of SAGA GIS in QGIS makes the WLC analysis possible to be executed directly in QGIS. However, the immense size of this case study shapefile and raster file makes the process end up with an error message.

Before executing the OWA function in SAGA GIS, it is important to set all raster layers in the same extent. Else, the OWA function will return an error message and decline to execute the function. To set all rasters in the identical extent, first this thesis creates a virtual layer by using the build virtual raster (catalog) menu in QGIS. Afterwards, with the help of raster calculator, all the raster layers are re-adjusted according to the virtual raster extent.

Importing all the re-adjusted raster layer to SAGA GIS is necessary because of the inability of QGIS to execute OWA function successfully. In SAGA GIS too, all the result from previous analysis by AHP-Delphi will be combined and become the weight for the WLC analysis. Table

5.3 acts as the coefficient for all the criteria in scenario A, whereas table 5.4 acts as the coefficient for all the criteria in scenario B. Likewise, coefficient for scenario C will be drawn from table 5.5.

According to the first part of equation 2.6, the first part of scenario A calculation is elaborated as follows:

$$\begin{aligned}\sum w_i X_i = {} & (PopulationDensity * 0.065) + (MedianIncome * 0.09) \\ & + (OfficeRentPrice * 0.095) + (JobDensity * 0.099) + (ExistingNoise * 0.076) \\ & + (POI * 0.123) + (MajorTransportNode * 0.194) + (ExtremeCommuting * 0.095) \\ & + (AnnualTransportCost * 0.090) + (PotentialSupply * 0.072)\end{aligned} \tag{6.1}$$

The first part of scenario B calculation is elaborated as follows:

$$\begin{aligned}\sum w_i X_i = {} & (PopulationDensity * 0.030) + (MedianIncome * 0.240) \\ & + (OfficeRentPrice * 0.170) + (JobDensity * 0.05) + (ExistingNoise * 0.06) \\ & + (POI * 0.08) + (MajorTransportNode * 0.10) + (ExtremeCommuting * 0.05) \\ & + (AnnualTransportCost * 0.120) + (PotentialSupply * 0.1)\end{aligned} \tag{6.2}$$

The first part of scenario C calculation is elaborated as follows:

$$\begin{aligned}\sum w_i X_i = {} & (PopulationDensity * 0.03) + (MedianIncome * 0.13) \\ & + (OfficeRentPrice * 0.10) + (JobDensity * 0.08) + (ExistingNoise * 0.06) \\ & + (POI * 0.25) + (MajorTransportNode * 0.08) + (ExtremeCommuting * 0.04) \\ & + (AnnualTransportCost * 0.22) + (PotentialSupply * 0.02)\end{aligned} \tag{6.3}$$

After all layers are successfully superimposed, the result map will be subtracted with all the Boolean constraint. This subsequently completes the equation 2.6 by adding the final part of multiplication between result map with Boolean constraint. This applies to each scenario. To simplify the process, the result map from the first part of suitability equation (raster format) will be clipped with the permitted flying zone vector layer (subsection 6.1.1.3).

6.1.3 Results

Figure 6.2 shows the result of the WLC analysis using a weight from the AHP-Delphi analysis. Comprising of 7,593,325 raster cells, this map displays quite depth information. The result map is displayed based on 20-class quantile distribution, meaning that the blue spectrum is divided into 20 different colors from light blue to dark blue. The dark blue color means that it belongs to the 5^{th} quantile and is more suitable for UAM ground infrastructure than the light blue colour. The dark blue colour are mainly located in the downtown Los Angeles, Los Angeles international airport, Santa Monica, East vale, and West Hollywood. On the other hand, except from the constraints, the less suitable location for UAM ground infrastructure are mostly located in less populated areas, for instance Santa Ana mountains, Santa Monica mountains, Santa Clarita Woodlands park, Pine mountains or dessert in the intersection between state route 18 and state route 138. Low suitability also occurs in the industrial or warehousing complex like Terminal island in Long Beach, not to mention green open space, like Whittier Narrows park. Another interesting finding is that not all nearby downtown areas have a high value of suitability. For example, the location where Los Angeles river and surface-level trunk railway tracks intersect at the Soto junction and Redondo junction vicinity.

Figure 6.3 displays the outcome map of the WLC analysis using the weight from expert number 1. The result map is displayed in 20-class quantile distribution, not to mention depth information is provided due to 7,593,325 raster cells. The color scheme also resembles to scenario A and scenario C, which means that the darker the color the more suitable a raster is to build UAM ground infrastructure. Having not many significant difference than scenario A, the suitable areas to site UAM ground infrastructure in the map of scenario B are dispersedly located, mainly in the downtown of LA, surrounding major transport nodes, and along highway towards periphery area. The less suitable area is comparable to that displayed in the outcome map of scenario A, as no significant changes take place. From the perspective of raster statistics, outcome map of scenario B has lesser maximum value, yet bigger minimum value and mean value.

The result of WLC analysis using weights from expert number 2 is shown in the figure 6.4. Comprising of similar 7,593,325 raster cells, scenario C is divided into 20-class based on quantile distribution and uses the same color scheme as the aforementioned scenarios. According color scheme comparison, the prominent area for UAM ground infrastructure is still located similarly like scenario A and B. However, there is a significant difference between outcome map of scenario C with the map of scenario A. Although there are some less suitable areas nearby the city center, for example Whittier Narrows park, it is not categorized as the least suitable for UAM ground infrastructure, as shown in the outcome map of scenario A. The least suitable areas are located more dispersedly, for instance in the dessert near route 138, as well as along route 126. From the statistic's perspective, the map of scenario C has the lowest minimum value and mean value from all the outcome maps.

For the first implementation of UAM operation, scenario A offers various locations as shown in the figure 6.5. This thesis takes the top 5 percent of converted vector features into the creation of new layer process. 265,094 features belong to this vector layer with a total area of 637,568,908 m^2. To give an illustration, major transport nodes, both inter city train stations and major airports are affiliated to this layer. Affluent residential area, for example Bel Air, Palos Verdes, and Sierra Lakes have the potential to hold the first implementation of UAM operation. Downtown Los Angeles and Central Los Angeles, where many offices are located there, are also reach the 5^{th} percentile.

Figure 6.6 depicts the 5^{th} percentile of scenario B having lesser area in Santa Monica and West Hollywood, as well as downtown LA and Irvine. The changes between scenario A and B tends to happen because of the staggering increase of median income weight. This also leads to smaller areas of scattered top 5% value of UAM ground infrastructure, for example West Corvina and Temple City. Although major transport node weight reduces significantly, all the stations and airports still belong to the 5^{th} percentile. For the initial phase of UAM operation, the outcome raster map of scenario C is translated into a vector map, as shown in figure 6.7. From the comparison with vector maps of scenario B and scenario A, the significant differences are located in La Habra heights and Montebello, where a small area of 5^{th} percentile appear. Not only there but also in Lynwood, Hawthrone and Carson. Those scattered areas appear might be because of the dramatic increase in POI and annual transport cost weights in scenario C, compared to the rest of the scenarios.

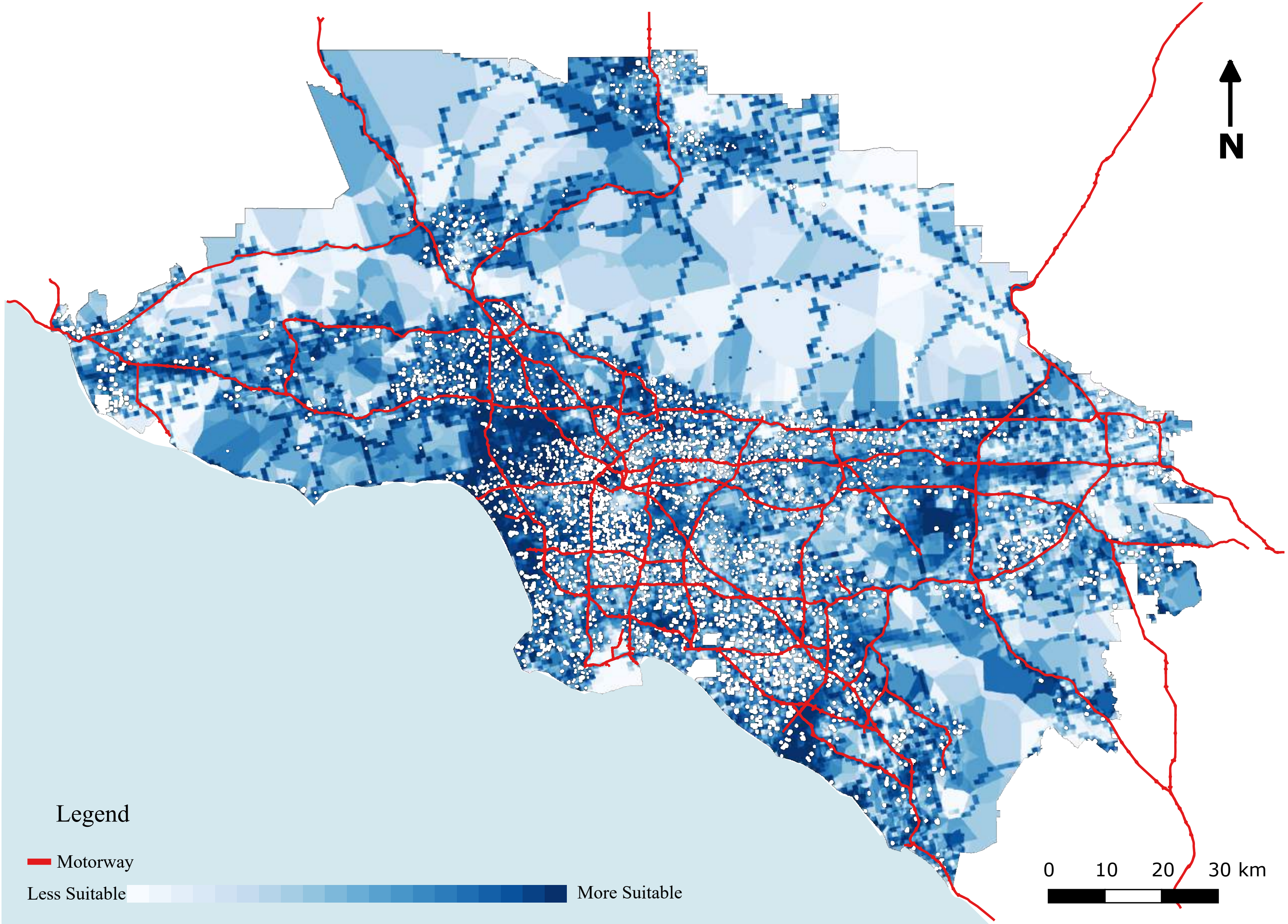


Figure 6.2: Scenario A Los Angeles

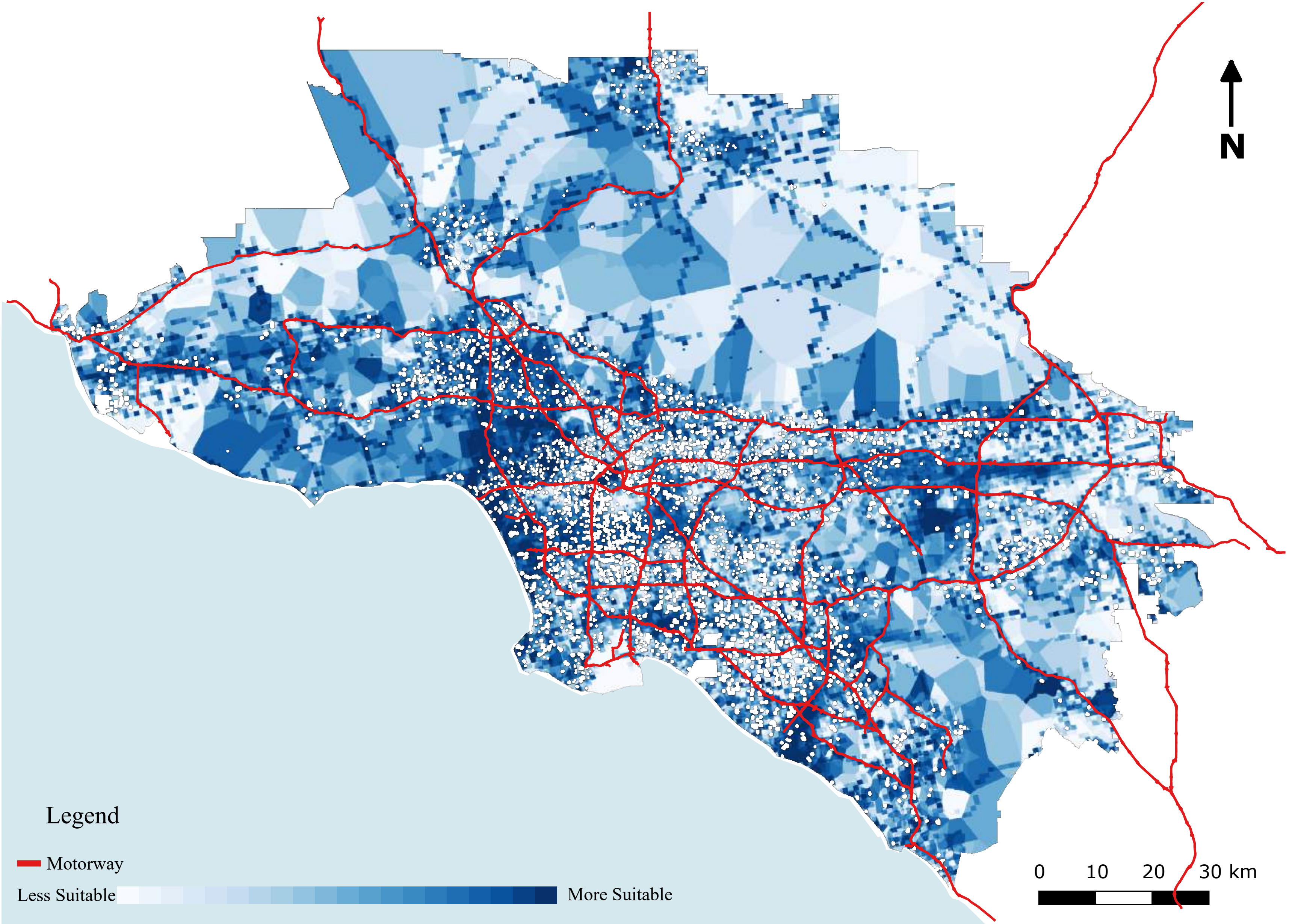


Figure 6.3: Scenario B Los Angeles

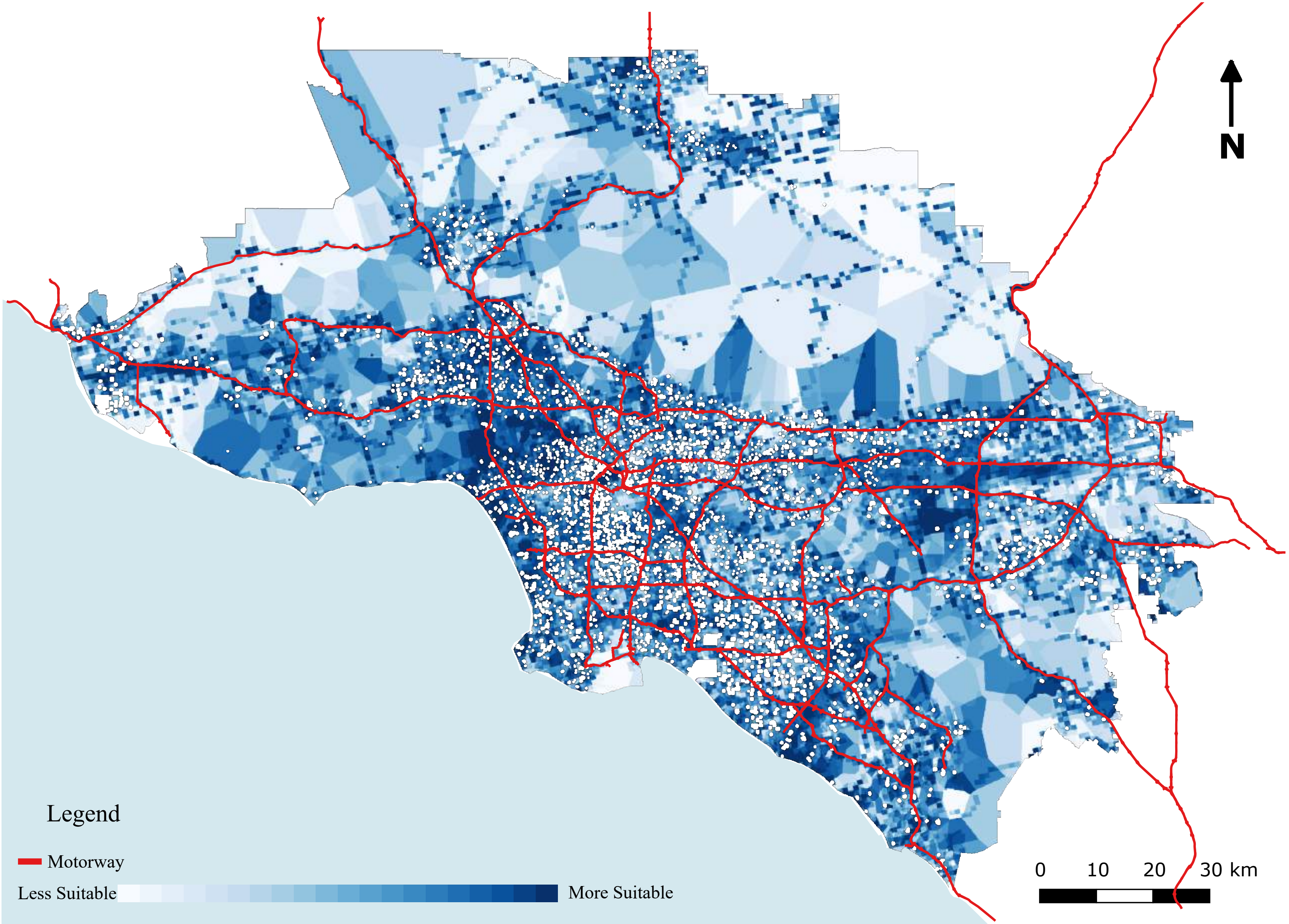


Figure 6.4: Scenario C Los Angeles

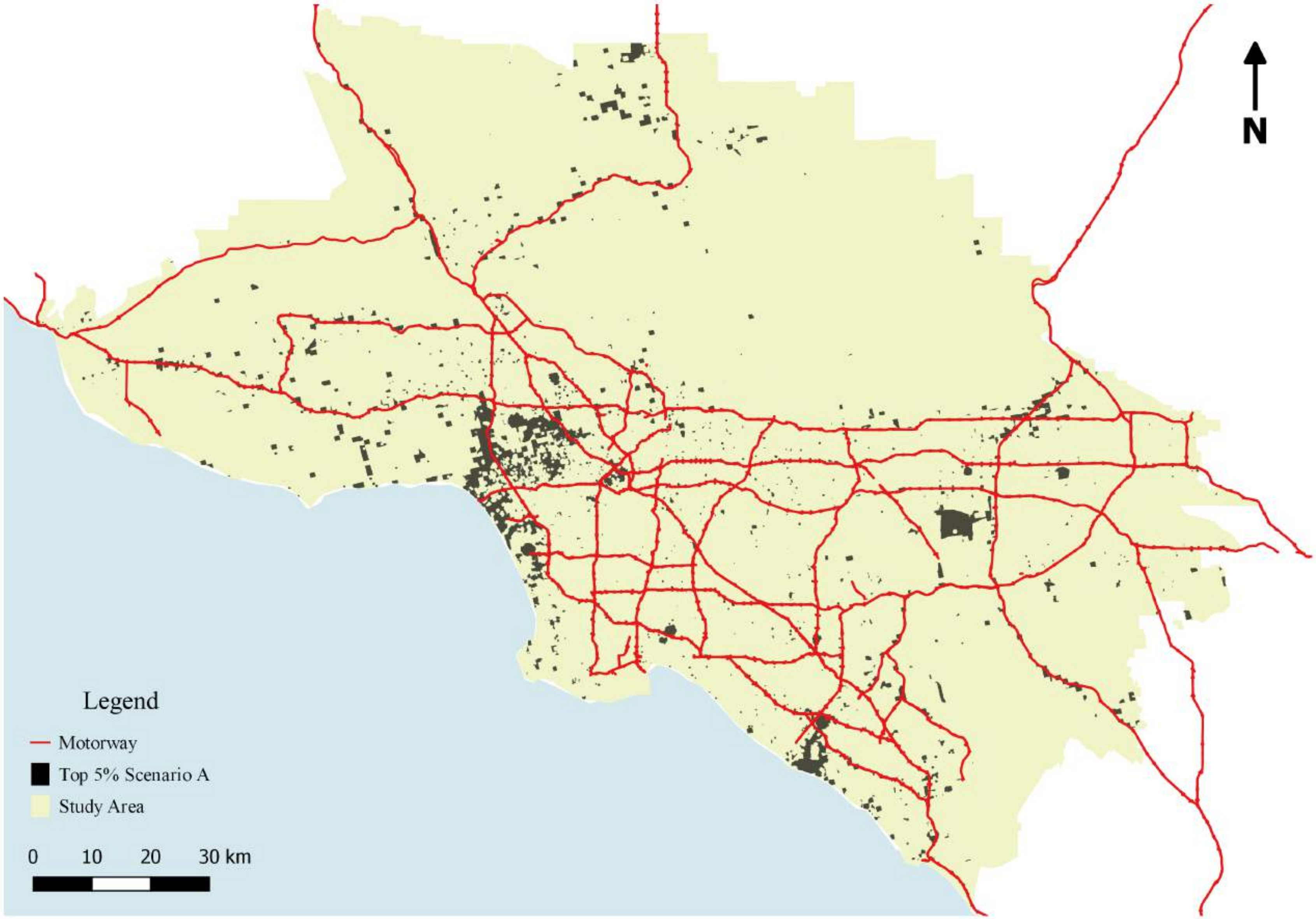


Figure 6.5: Top 5 percent location based on Scenario A Los Angeles

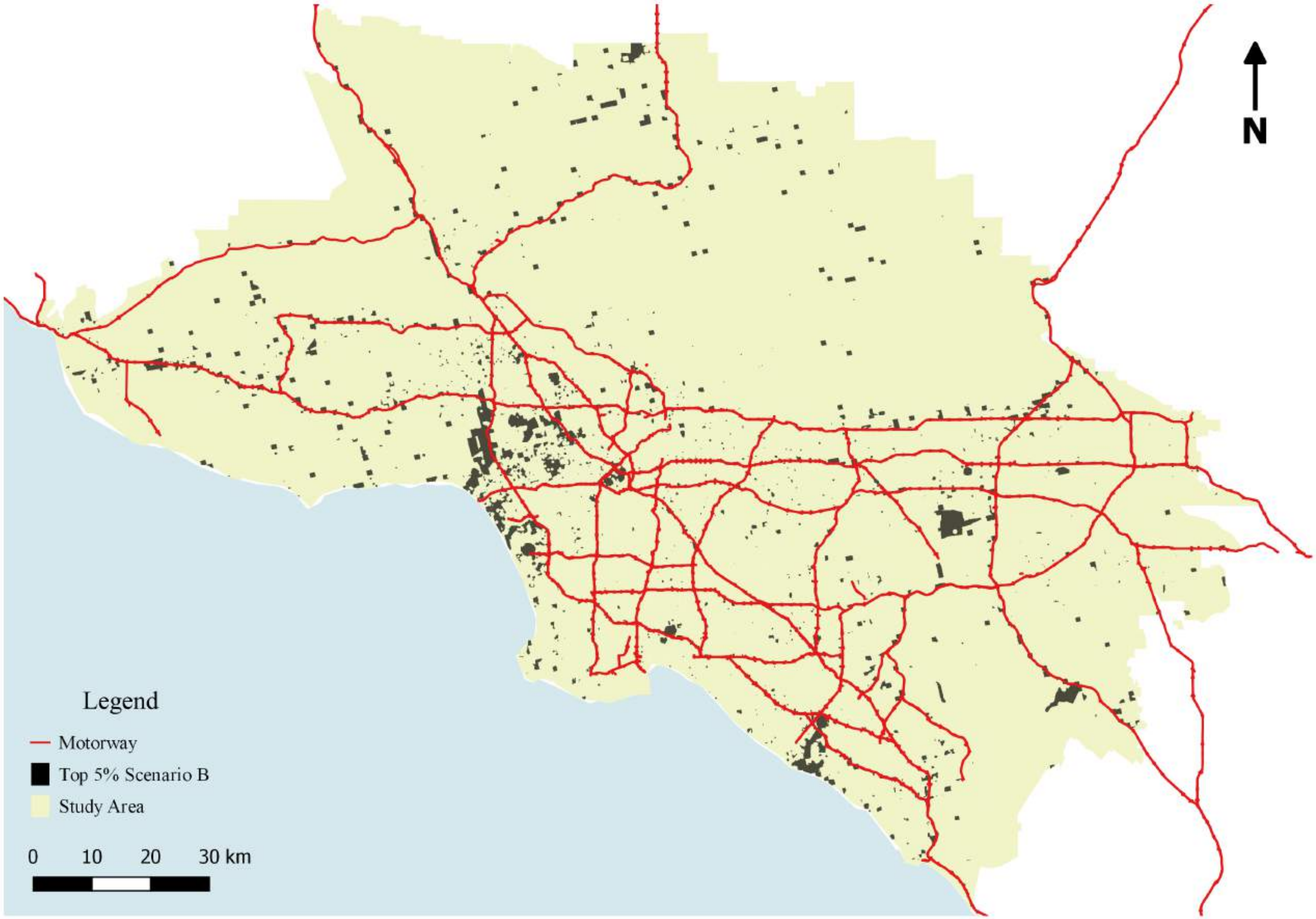


Figure 6.6: Top 5 percent Location based on Scenario B Los Angeles

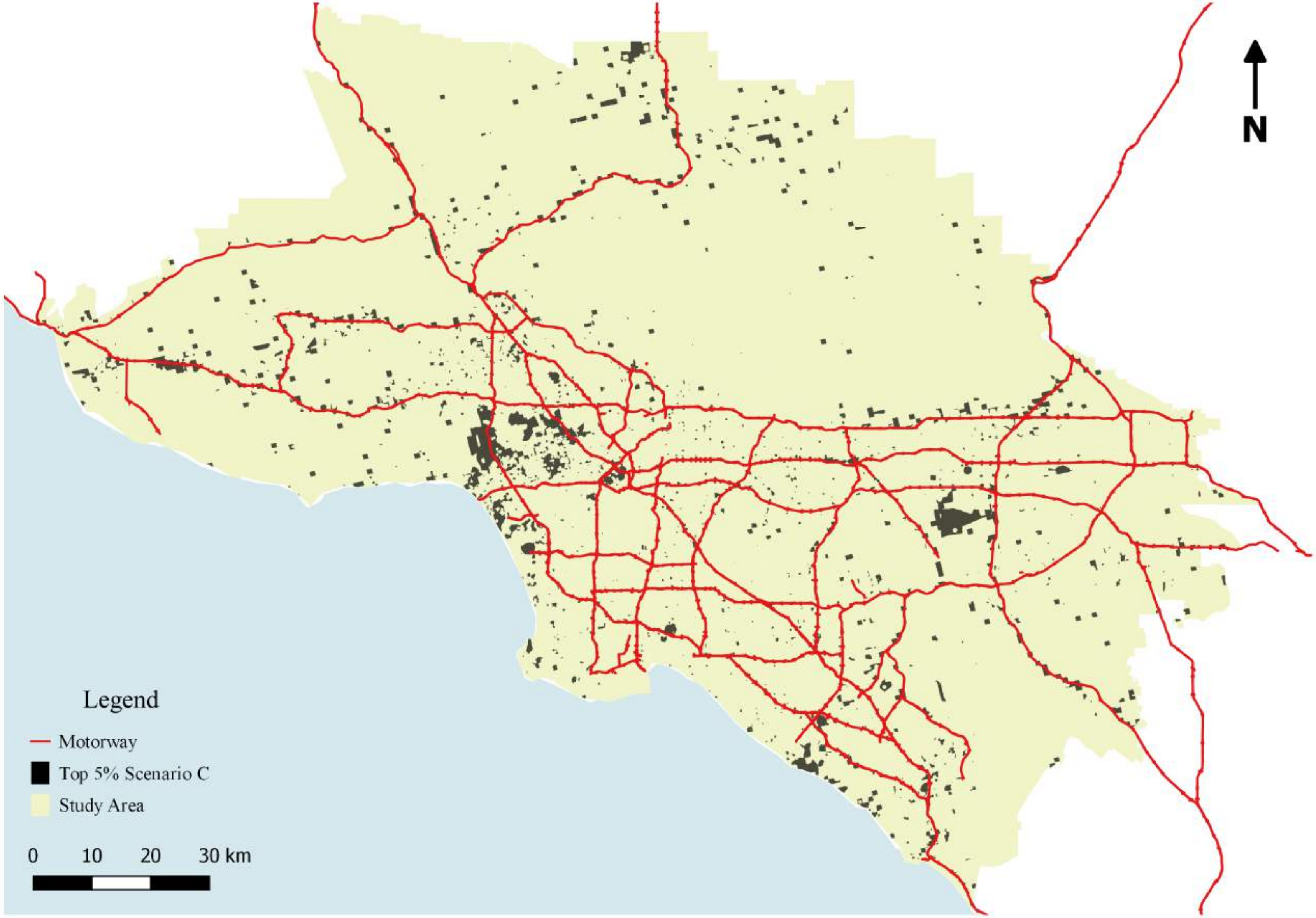


Figure 6.7: Top 5 percent Location based on Scenario C Los Angeles

6.2 Case Study: Munich

Munich, the capital of Bavaria province, topped the chart of global traffic scorecard from all the cities in Germany (INRIX, 2017). Being known as the most congested city in Germany, the government of Munich encouraged the citizen to choose public transit mode for their daily commuting activity. While the percentage of trips done by public transport only reached 15%, share of trips are done by private car in areas where München Verkehrs- und Tarifverbund (MVV) (public transport operator in Munich and its sub urban area) operated is double the previous mode share with 35% (Referat für Stadtplanung und Bauordnung, 2010). Munich is also known as the capital of commuters, where over 368,000 employees travel to the city of Munich daily (Merkur, 2017). The high level of congestion and low level of public transport utilization mean that in Munich, UAM has potential to deliver its passengers faster than private car and more comfortable than surface-level public transportation mode for commuting purpose or non-commuting purpose.

The boundary of case study is limited within Munich and seven Landkreis (counties) adjacent to it, namely Dachau, Ebersberg, Erding, Fürstenfeldbruck, Freising, county of Munich, and Starnberg. Based on Bundesministerium für Verkehr Bau und Stadtentwicklung (2010), a cumulative of 98% of commuters in Munich travel from 0 km to 100 km and cumulatively 81.1% of them travel up to 25 km daily. The minimum coverage of this study area reaches 30 km radius from the city center of Munich. Appendix C displays detailed maps for each factor in this case study.

6.2.1 GIS Database Building

This section comprises of several subsections which explains the required data collection process. Alike the Los Angeles case study, factors are divided into three categories: demand side, supply side, and binary consideration.

On the other hand, Munich does not provide many open access data like LA. As a consequence, annual transport cost and extreme commuting criteria should be disregarded in this academic work. With help from the professorship of Modelling Spatial Mobility of Technical University Munich, which provided basic data from its model, job density and income factor data can be attained (Moreno & Moeckel, 2018). The basic shapefiles are downloaded from the Federal Agency for Cartography and Geodesy (Bundesamt für Kartographie und Geodäsie, 2017). Similar to the Los Angeles case study, all of the rasterized layers should be standardized using raster calculator before proceeding to the WLC analysis.

6.2.1.1 Demand Side

Population Density
Population data is obtained from Zensus 2011, a census organized by the German Federal Statistical Office (Statistische Ämter des Bundes und der Länder, 2014). The resolution of this data is in detailed format, in a 100 meter x 100 meter grid. Although the initial data is in a comma separated value (CSV) format, it has an x and y coordinate that can be exported into QGIS software as a point layer with particular value. Afterwards, this point layer is rasterized by the vector to raster function in QGIS and is standardized with the help of the raster calculator function.

Income
Due to limited data availability, case study Munich does not use median income within a particular area to see where the affluent people live. This is different from the case study Los Angeles. From the synthetic population data of Munich, the modeled income data are classified in €5,000 intervals for each zone (Moreno & Moeckel, 2018).

Furthermore, this classified data is weighted by the composition of household income from another study about app-based on-demand ride services in San Francisco (Rayle, Shaheen, Chan, Dai, & Cervero, 2014). The study has income level distribution of on-demand ride services in San Francisco, which can be a proxy for income level of UAM operation. The income data are reclassified based on the study classification. Unlike income data in the U.S, which has an inconsistent interval, especially when reaching above US$ 50,000, the synthetic population data in Munich has a consistent income data interval. Although the study uses U.S. Dollar as currency, the given income data can be simply converted to U.S. Dollar class. The converted weight after normalization can be seen in table 6.7. Furthermore, the weighted result will be calculated and inserted into shapefiles for each zone in QGIS. Before this criterion is able to proceed to the WLC analysis, the rasterized layer needs to be standardized using equation 2.7.

Table 6.7: Converted Income Classification from (Rayle, Shaheen, Chan, Dai, & Cervero, 2014)

Income Class	Normalized Percentage	Converted Income Class
US$ 30K or less	10%	€ 0 - € 25,000 (US$ 29,943)
US$ 30K - US$ 70K	26%	€ 25,000 - € 55,000 (US$ 65,876)
US$ 71K - US$ 100K	20%	€ 55,000 - € 80,000 (US$ 95,820)
US$ 100K - US$ 200K	43%	€ 80,000 - € 100,000

Office Leasing Price
Similar to the case study Los Angeles, there is no open access data about office leasing price. Therefore, this study obtained 121 sample points data from Jonas Lang Lacsalle (Jones Lang

LaSalle, 2018) and Immobilo (Immobilo, 2018) to be the input value for IDW interpolation. With the maximum value of €42 per square meter per month to the minimum value of €5 per square meter per month, the sample data are collected dispersedly in the central city and periphery area of Munich. These sample points are spatially converted into x and y coordinates with the help of Geoplaner website (Nathansen, 2018).

Despite of the explanation in section 2.8 about IDW not being the most optimal interpolation method to predict unknown real estate price compared to the Krigig method, this thesis performs IDW to benefit from its simplicity and ability to take distance between sample points into calculation.

Points of Interest
Top 50 POI within Munich and its surrounding data are gathered from Tripadvisor (TripAdvisor, 2018). Alike the Los Angeles case study, this data collection process relies heavily on TripAdvisor's algorithm on the ranking process. The Geoplaner web-based tool assists in converting the list into x and y coordinates.

This point layer is converted into heatmap raster layer to locate areas with many tourist attraction sites which can be a potential to be served by UAM. The distance between each buffer ring is not constant, because of the reclassification process of heatmap value is based on quantile distribution. Taking the example of the Los Angeles case study, the heatmap radius is assigned to 1.5 km radius (Yang & Diez-Roux, 2012).

The heatmap raster has noData value between points, which causes miscalculation in the WLC analysis. Therefore, grid resampling function in SAGA GIS adjusts this noData value and converts into 0 value. Moving into further analysis, this heatmap is reclassified instead of being standardized. This aims to make sure each buffer area in heatmap has the same value, which gradually changes as the distance gets closer to the center point.

Major Transport Node
As the criteria for major transport node are different from one city to another, this thesis incorporates the Munich international airport (Franz Joseph Strauss (MUC)) and three major intercity train stations in the Munich vicinity. These location are selected manually in QGIS using the vector editing mode.

These points are converted into heatmap with 1 km radius using heatmap function in QGIS. Major transport node map encounters noData value problem when converting vector map into raster map. To cope with this problem, grid resampling function in SAGA GIS can be an option. Similar to POI layer, major transport node is not standardized, but rather reclassified before proceeding into further analysis.

Job Density
Job density data are obtained from synthetic population model of Professorship Modelling Spatial Mobility, TU Munich (Moreno & Moeckel, 2018). The model can go into fine-grain spatial resolution of 300 x 300 meter, with a total of 3090 raster zones. Subsequently, the shapefile is also provided by the model. As the model divides jobs into 10 categories, this thesis aggregates into one general category. In spite of that, the input data from model outcome is a coarse estimation, not an actual surveyed data.

6.2.1.2 Supply Side

Existing Helipads and Potential Spots
Combining between existing helipads and potential spots, the database source of this layer is extracted from OSM data, via Geofabrik (OpenStreetMap, 2018b). Potential spots are translated as gas stations in this thesis. There are 316 gas stations and 38 helipads exist within case study area of Munich. Both existing helipads and gas stations point locations are merged and the final vector layer is rasterized using heatmap function. As the problem of noData value occurs, SAGA GIS function called resampling grid helps to adjust the extent and fill a 0 value to the noData space within points. Later, the heatmap is reclassified to ordinal value from 0 to 10.

Existing Noise
Open access data from Geoportal Bayern provides two kinds of existing noise, street-level transport noise and aviation noise (Bayerisches Landesamt für Umwelt, 2013, 2017). Noise value ranges from 50 dB to above 75 dB. The format is web map service (WMS) then converted into raster image format through QGIS additional layer function. Using the RGB to PCT function, the multicolor band format turns into an optimal pseudo-color table. Afterwards, the pseudo-color layer is reclassified according to table 6.8 into an ordinal scale from 0 to 10 for both layers, based on decibel class in the source.

The reclassification process also rearranges that the loudest locations are the most suitable site for UAM ground infrastructure, since the aim is to overlay the noise of eVTOL vehicle with the existing noise. Later, the result layer for both street-level transport and aviation are multiplied using rastercalc function. Since the joined layer between street-level transport noise and aviation noise has a value of more than 10 after classification, it should be standardized to be on the same ordinal scale (0 to 10) with other raster layers.

6.2.1.3 Binary Consideration

Binary constraints in UAM ground infrastructure could be an airspace in a busy airport vicinity, nature reservation, and military base. Because of the language barrier, this thesis is not able to perform a comprehensive and thorough literature research about flying and landing restrictions

Decibel Value Range	Reclassification Value
55 - 60 dB	2
60 - 65 dB	4
65 - 70 dB	6
70 - 75 dB	8
Above 75 dB	10

Table 6.8: Existing Noise Reclassification

in Munich. In spite of that, there is an aeronautical chart available online that defines EDR (restricted area for flight operations) around the case study area (SkyVector, 2018). There are two EDR within case study area, one is the EDR-60 in Oberpfaffenhofen and another one is EDR-1 in Garching.

The restricted area vector layer is superimposed with boundary vector layer and result in the permitted flying zone. To make the calculation time faster, the result of WLC analysis (scenario A, B and C) are clipped with the permitted flying zone vector raster thus creating the final result of WLC analysis raster maps in this thesis for case study Munich.

6.2.2 The WLC Analysis

After all the raster layer have been standardized, located and sized in the same extent, case study Munich proceeds to the WLC analysis using OWA function in SAGA GIS. The core of this analysis is superimposing all the raster layer and summing up all the weighted values. The weights are gained from AHP-Delphi analysis and expert interviews.

As this case study does not obtain prerequisite data for all criteria, the weights are necessary to be normalized according to the remaining criteria with available data. Table 5.1 acts as the coefficient for all the criteria in scenario A, whereas table 5.2 acts as the coefficient for all the criteria in scenario B. Likewise, the coefficient for scenario C will be drawn from table 5.3. According to the equation 2.6, the first part of it is composed of the multiplication of raster value with the normalized coefficients, which are elaborated in the following equations:

$$\begin{aligned}\sum w_i X_i = & (PopulationDensity * 0.08) + (MedianIncome * 0.111) \\ & + (OfficeRentPrice * 0.117) + (JobDensity * 0.122) + (ExistingNoise * 0.093) \\ & + (POI * 0.151) + (MajorTransportNode * 0.238) + (PotentialSupply * 0.088)\end{aligned} \tag{6.4}$$

The first part of scenario B calculation is elaborated as follows:

$$\begin{aligned}\sum w_i X_i = &(PopulationDensity * 0.034) + (MedianIncome * 0.288) \\ &+ (OfficeRentPrice * 0.208) + (JobDensity * 0.058) + (ExistingNoise * 0.068) \\ &+ (POI * 0.095) + (MajorTransportNode * 0.124) + (PotentialSupply * 0.122)\end{aligned} \tag{6.5}$$

The first part of scenario C calculation is elaborated as follows:

$$\begin{aligned}\sum w_i X_i = &(PopulationDensity * 0.046) + (MedianIncome * 0.170) \\ &+ (OfficeRentPrice * 0.137) + (JobDensity * 0.103) + (ExistingNoise * 0.075) \\ &+ (POI * 0.334) + (MajorTransportNode * 0.103) + (PotentialSupply * 0.038)\end{aligned} \tag{6.6}$$

6.2.3 Results

Figure 6.8 portrays a raster map as the outcome of WLC analysis using the AHP-Delphi analysis. Comprising of 10,979,093 raster cells, this map gives deep information about the WLC analysis result. Based on a 20-class quantile distribution, the map of scenario A map has a color range from dark blue to white, with the darkest blue colour means the suitable location for UAM ground infrastructure. This map displays the inner city part, major transport nodes, and highway ring road as suitable sites for UAM ground infrastructure. On the other hand, parks and city forests (Perlacher Forst and Forstenrider Park), as well as some low density residential areas in the periphery (Puchheim, Aich, and Egenhofen) have a low suitability score.

Figure 6.9 exhibits a raster map as the result from WLC analysis using weights which are generated from expert number 1. Alike other scenario outcome maps, the outcome value of the WLC analysis in this map is divided into 20 classes following a percentile distribution. In comparison to scenario A's result, the areas in some part of the periphery turned into a white and pale blue color (meaning less suitable value), for example in the west side of Fürstenfeldbruck and north eastern Dachau. The areas that are suitable (covered by a dark blue color) in the city center are also reduced. Yet, some part of the periphery are also getting darker, for example in north western Dachau. The difference can be seen along the ringroad highway, where the color is a light blue, as noise criterion is less significant than in scenario A.

Figure 6.10 depicts 10,979,093 raster cells of the outcome of WLC analysis using the weights from expert 2. Following the same displaying option, this map is divided into 20 classes based on percentile distribution. The color range is from dark blue to white. Compared to scenario A and scenario B, the area in the boundary area of the city of Munich has a darker color (more suitable) in the scenario C outcome map. Scenario C is more similar to scenario A, as both has strong influence of point-based raster map. Scenario C put one-third of the total weight on POI criterion, while scenario A put one-fourth of the total weight on major transport node criterion.

The location that suits the first implementation of UAM operation are selected from the 5^{th} percentile of the WLC outcome raster map, which is composed from a total of 492,634 raster cells (figure 6.11). To that end, the raster map is converted to vector map format and selects the top 5^{th} based on the WLC analysis outcome value. Almost every space within the city center of Munich belongs to this category. Additionally, the airport and intercity train stations also reach the 5^{th} percentile, as well as convention centers, such as Messestadt Riem and MOC. Residential areas with high income level are also suitable for the first implementation of UAM operation, for instance Stetten and Gauting.

The vector map of scenario B has 424,113 raster cells reaching the 5^{th} percentile (figure 6.12). Many periphery areas which has high a income classification climb up to the 5^{th} percentile. To give an illustration, the area between Olching and Eichenau, the area in the western side of Schwabhausen, and the area in the southern of Erding now belongs to the 5^{th} percentile. According to the result of scenario B, the city center of Munich has less area in the 5^{th} percentile compared to the scenario A and scenario C. The outermost part of inner city of Munich, for example Mittelsendling and Bogenhausen, have lesser area in the 5^{th} percentile compared to scenario A and scenario C. However, this scenario still incorporates major transport nodes, old town area in the city center and convention centers, similar to scenario A and scenario C.

To figure out the location within the 5^{th} percentile, the outcome raster map is converted into a vector format (figure 6.13). As scenario C has the biggest value in point-based layer (POI) with over 33% (twice than scenario A and almost four times than scenario B), the 5^{th} percentile areas are located nearby POIs. The area that has a high income classification and are located along the highway also compose the 5^{th} percentile. Despite all the differences between scenario C and other scenarios, major transport nodes, old town area in the city center and convention centers belong to the 5^{th} percentile, which is similar to scenario A and scenario B.

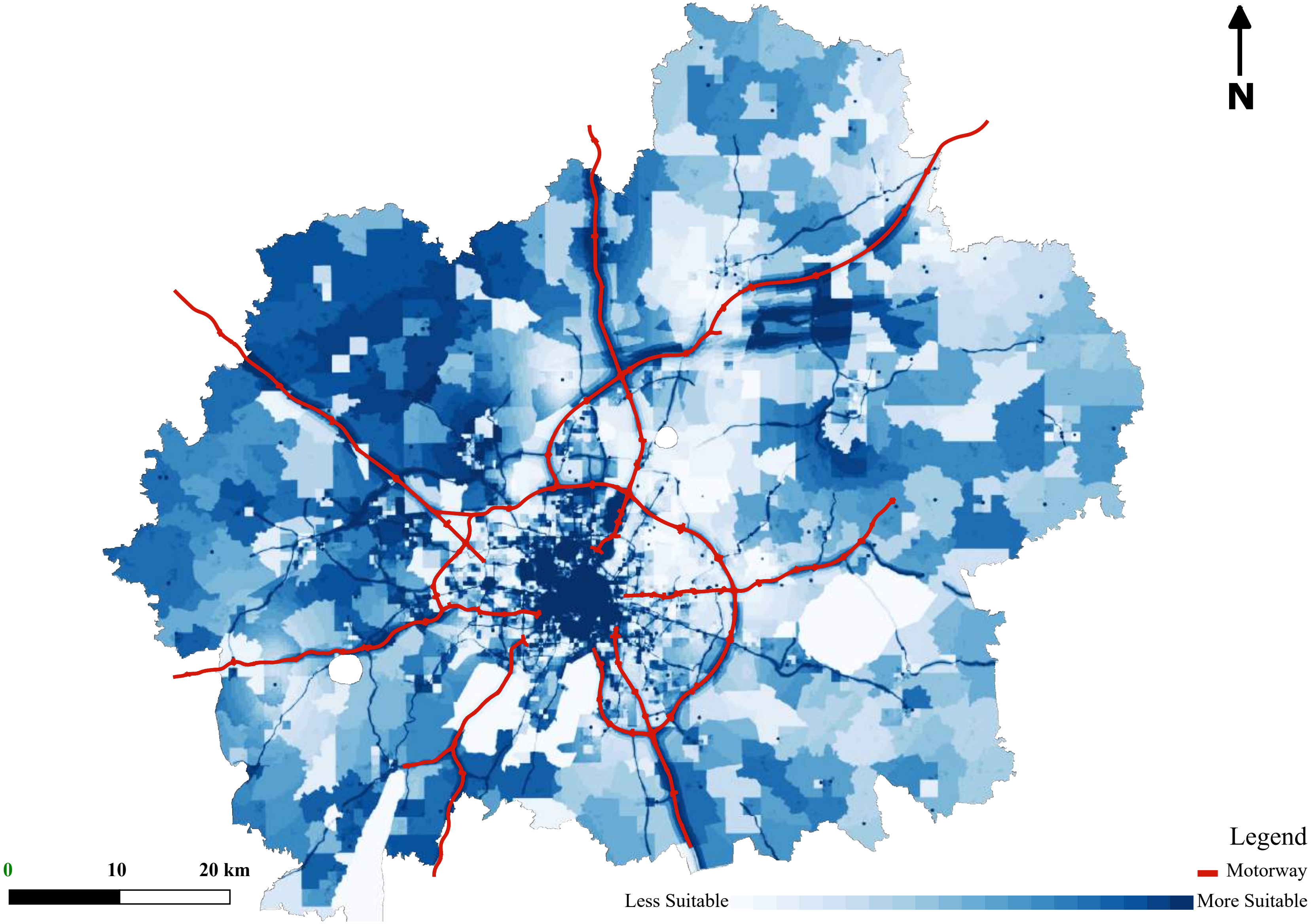


Figure 6.8: Scenario A Munich

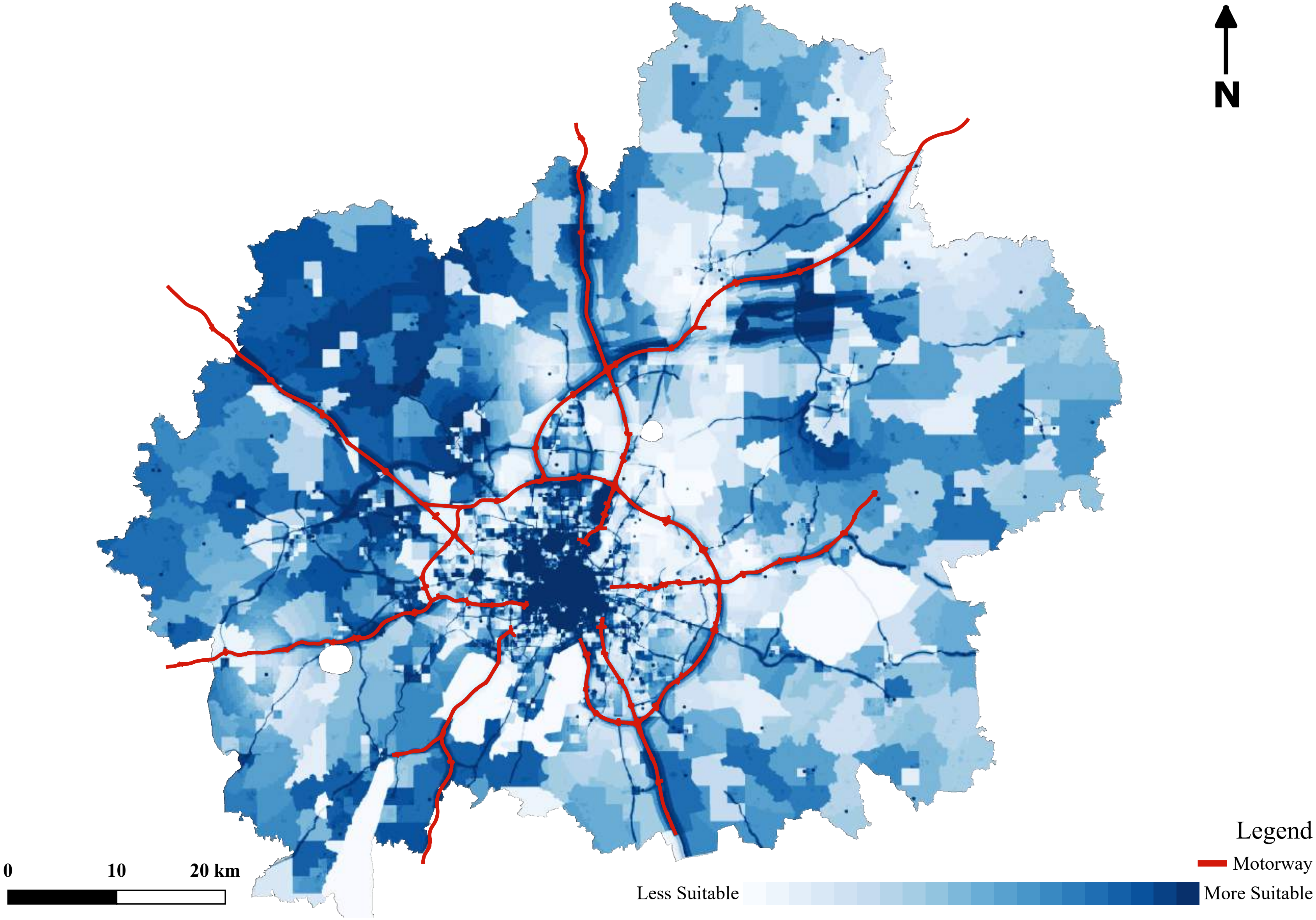


Figure 6.9: Scenario B Munich

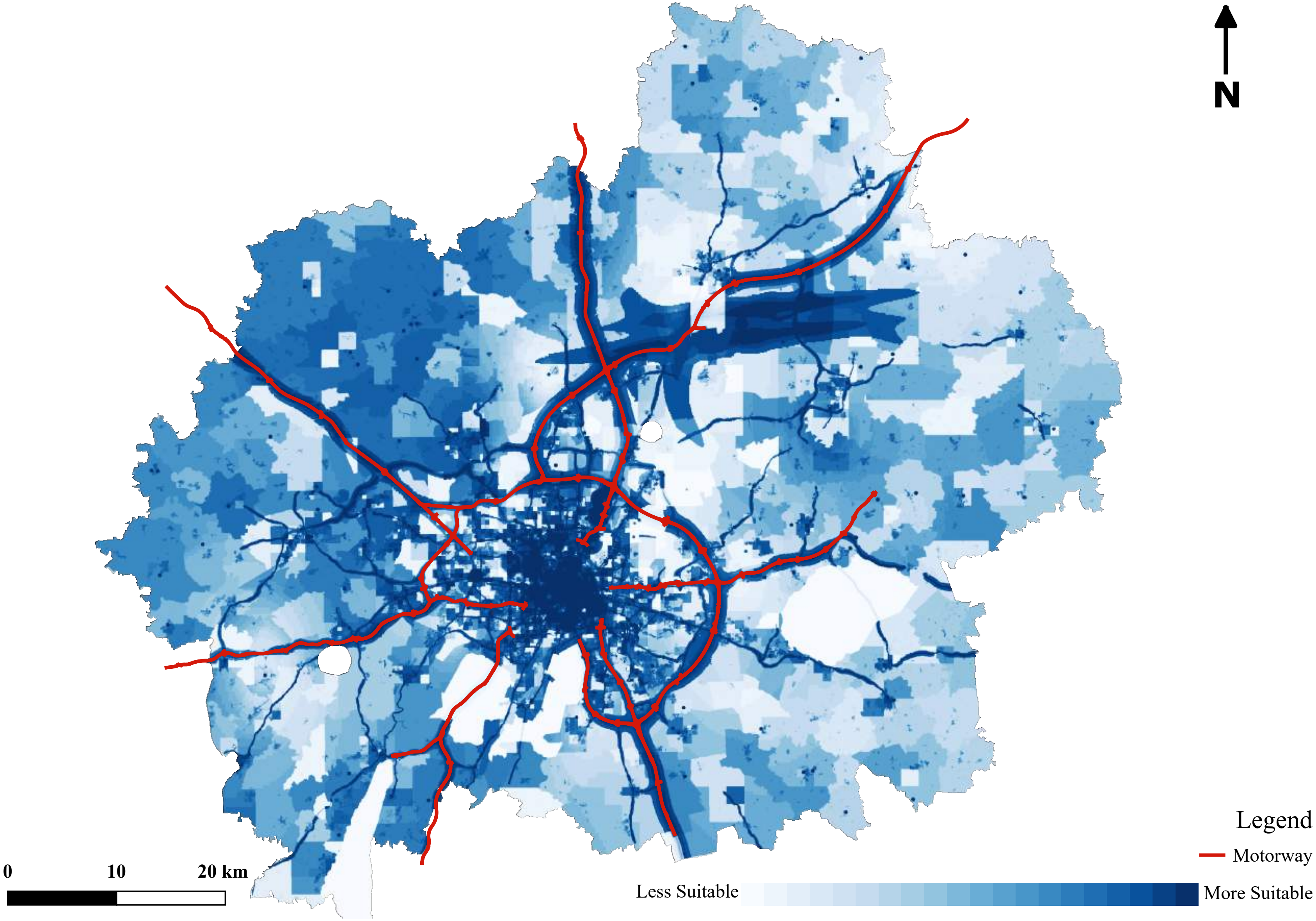


Figure 6.10: Scenario C Munich

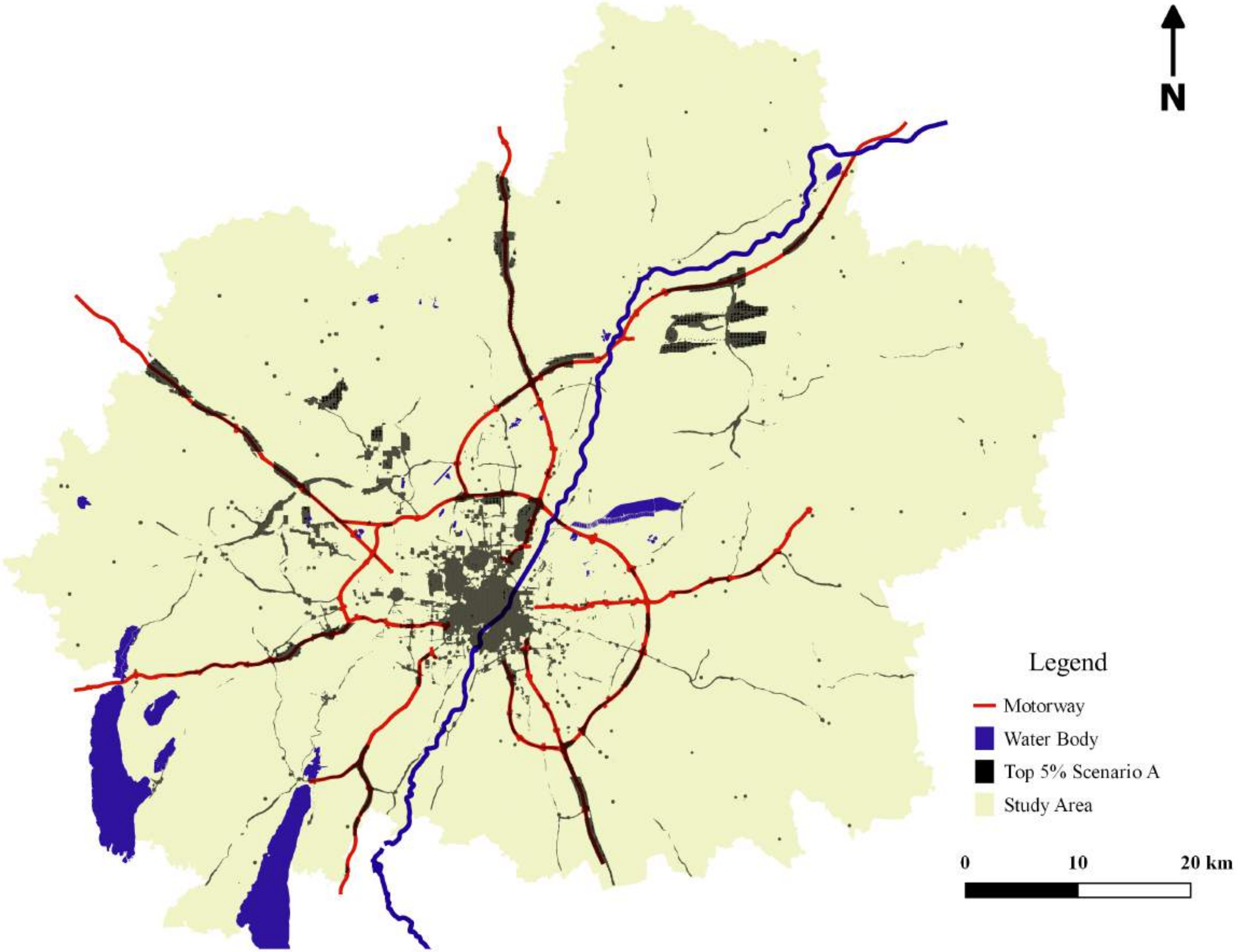


Figure 6.11: Top 5% Location based on Scenario A Munich

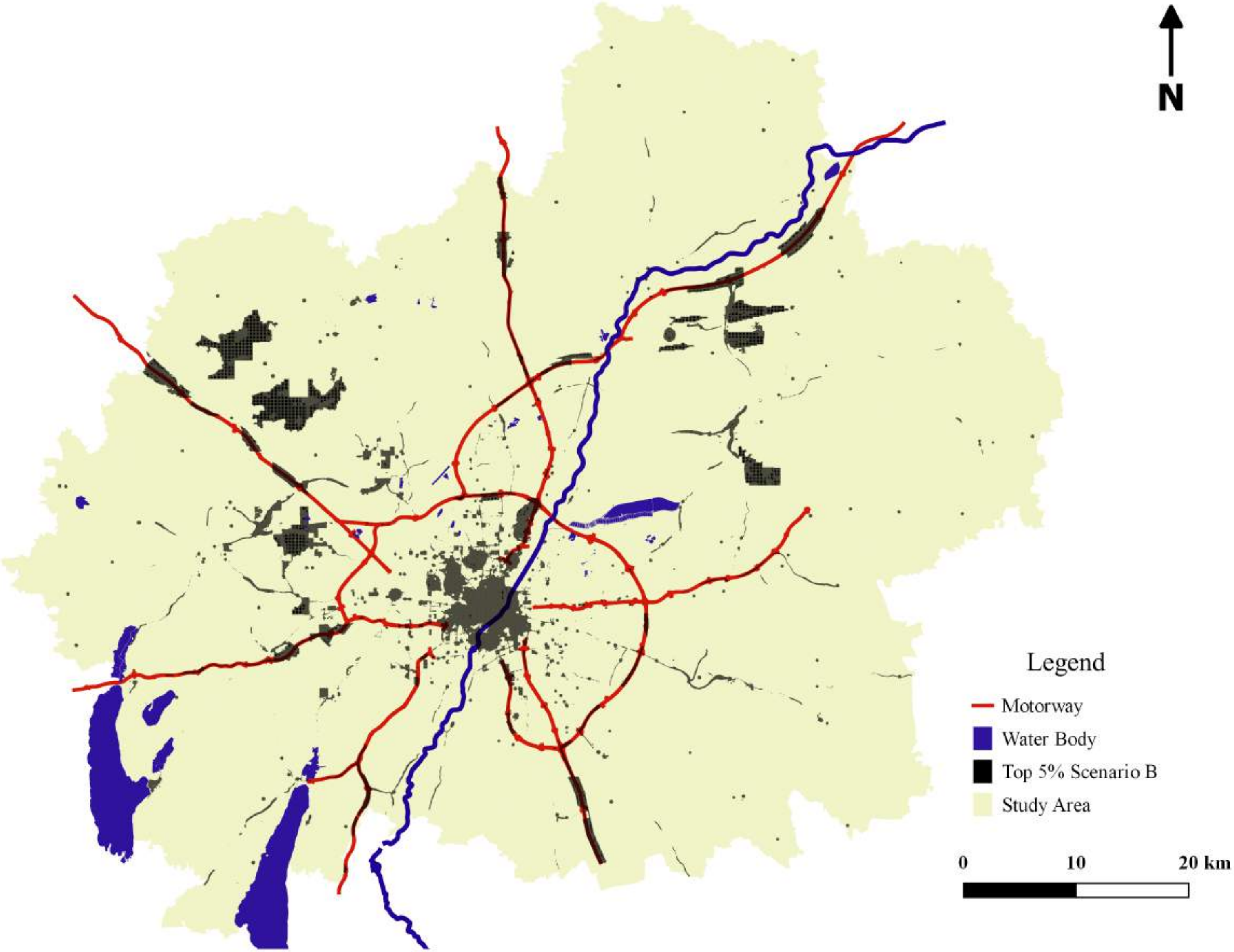


Figure 6.12: Top 5% Location based on Scenario B Munich

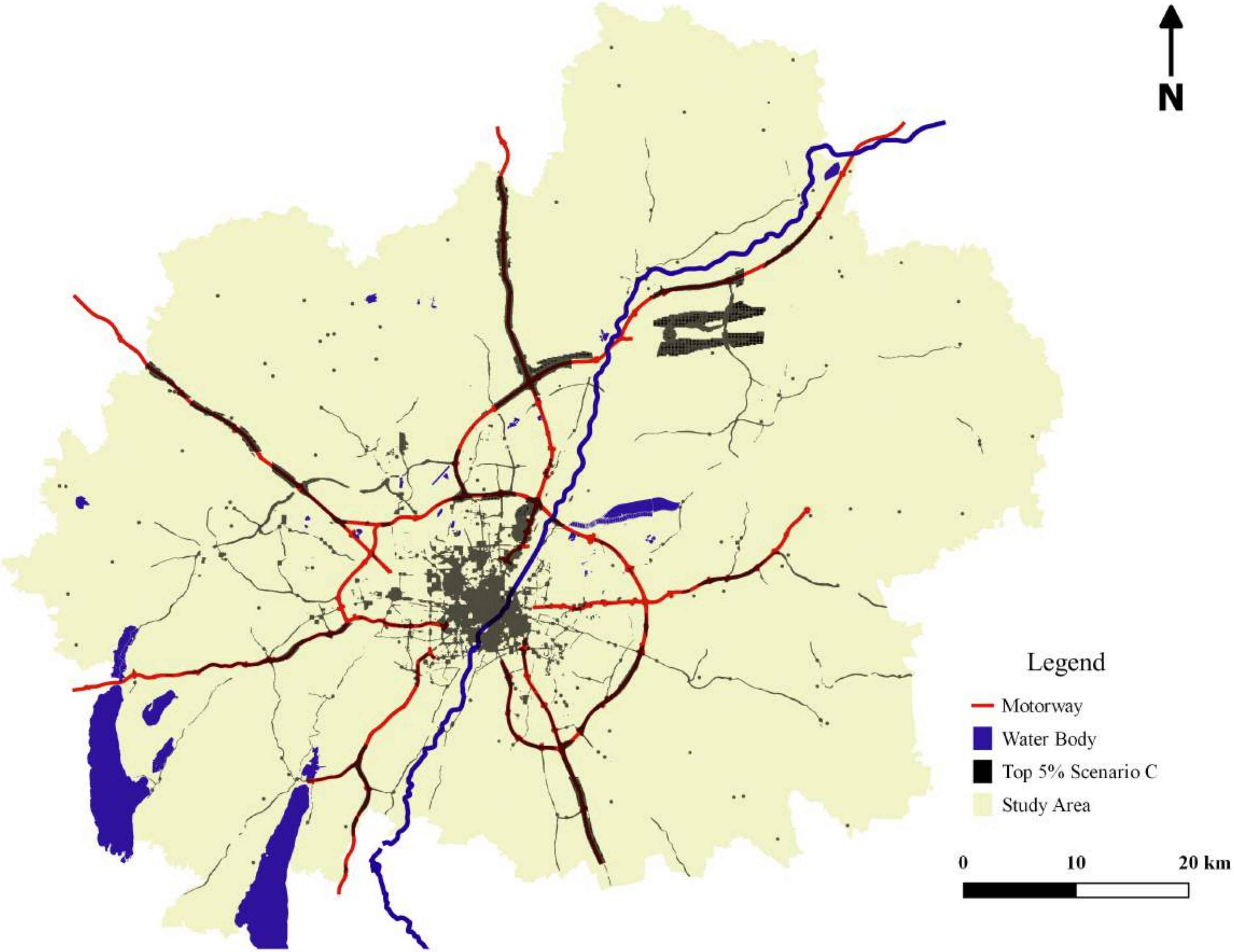


Figure 6.13: Top 5% Location based on Scenario C Munich

Chapter 7

Conclusion

This chapter presents the result of the analysis process and to discover whether the research questions have been answered. This chapter is divided into several parts. Firstly, all the outcome, from the AHP-Delphi analysis, expert interviews, and the WLC analysis (both LA and Munich) are discussed here. The second part is the limitation from any kind of analysis in this academic work. Further research possibility comes afterwards, explaining what kind of future work can be done. The concluding remarks close this chapter.

7.1 Overview of Results

Despite any uncertainty in UAM and eVTOL vehicle development, this thesis might act as a stepping stone towards UAM implementation. The minimum requirement for UAM ground infrastructure offers a novel idea about what kind of technologies can be maximized for UAM operation. By combining many literature, papers, work reports, presentation slides and regulations, this thesis attempts to grasp all the current development in UAM and creates a comprehensive summary of the minimum requirement of UAM ground infrastructure. Any type of UAM ground infrastructure requires a landing pad which consist of a TLOF, FATO, and safety area. In total, using the current biggest eVTOL design, one landing pad can consume at least 361 m^2. For operational purpose, any type of UAM ground infrastructure demands a charging station, which can fastly recharge eVTOL batteries. Another important aspect related to spatial needs of UAM ground infrastructure is parking assistance. To reduce the space needed by a parking stand, automation in parking eVTOL vehicle should be implemented. Otherwise, eVTOL vehicle needs to hover from the landing pad to the parking stand and therefore requiring more space for safety buffer.

Taking the summary as a starting point, this thesis illuminates the UAM realm with seven proposed variants of UAM ground infrastructure design for any type of UAM ground infrastructure. One important consideration for designing seven proposed variants of UAM ground infrastructure is the approach and departure surface. To provide safe continuous operation at UAM ground infrastructure, six variants of UAM ground infrastructures are designed following the FAA recommendation with at least a 135 degree separation between approach and departure surface (FAA, 2012). Nevertheless, Alexander and Syms (2017) uses 120 degree separation in their proposed vertiport. Following that and the assumption that eVTOL vehicles use steeper glideslope during take-offs and landing process to limit total ground area exposed by eVTOL vehicle noise (Helicopter Association International, 2009), variant 7 is designed using 120 degree separation to allow more parking stands. If one landing pad is not enough, these variants could be build in combination, altogether with other variants to create a new variation which has two or more landing pads.

Despite of limited literature sources, this thesis still carries out literature review to figure out the second research question. The result infers that there are 10 criteria influencing UAM ground infrastructure placement, which are divided into three categories: supply, demand and restrictions. These criteria are then brought into a panel of experts in real-time AHP-Delphi analysis to see the importance of each criterion. Expert interview process also validate these findings. Expert 1 and expert 2 agree on the criteria list, meaning that those are important criteria for determining where to build UAM ground infrastructure in a different degree. For example, Boolean constraint (flying restriction), average transport cost, and office rent price are criteria they both agree on, but on a different importance to each other. However, to some degree they did not reach agreement. For example, expert 1 considers POI as a niche market, which generates limited demand. On the other hand, expert 2 sees POI as a major criterion which could generate demand.

In contrast with theories, the AHP-Delphi analysis does not reach the consensus. Not a single collected ADM value from all the experts reached a value of 3. Meaning that the experts are split into two different ends of continuum. This might be caused by the novelty of UAM topic, various academic backgrounds of the experts (engineering, economics, and geography), different years of experiences and different perceptions on UAM and eVTOL vehicle. As the experts foresee eVTOL vehicles initially serving non-daily trips such as commuting trip or business trip, major transport node and POI overcome other criteria. This is a contrary to the expert 1, who states median income is the most important criterion and tourism trip is niche for UAM.

The outcome of WLC analysis in three different scenarios in both Los Angeles and Munich shows that initial UAM ground infrastructure should be placed in major transport nodes, city center, POI and periphery area with high income inhabitants. These locations are suggested by many literature to have potential passengers in the initial operation of UAM, for both commuting and non-commuting mode. Expert opinions also seconded these initial placement of UAM ground infrastructure.

Besides intercity train stations and international airports, the case study in Los Angeles shows that initial UAM ground infrastructure are located along the pacific coast, for example Malibu, Santa Monica, and Newport Beach, as well as downtown Los Angeles, Bel Air, Palos Verdes, and Simi Valley, where high income residents live and expensive office prices are located. Tourist attractions criterion also has a potential for initial location of UAM operation, as seen along pacific coast and in the downtown Los Angeles. Similar situation are also seen in Munich, where the outcome of the WLC analysis favors major transport nodes to be the initial location of UAM ground infrastructure. High office rent prices and a high job density in the surrounding of major transport nodes, both in Munich and LA, make the outcome value of major transport node bigger than in other areas. High income residential areas along the noisy highway are also a preferred location for the initial UAM ground infrastructure in Munich. For example Fasangarten, Geisebullach and Oberallershausen. It can be concluded that the result of case studies in two metropolitan cities and three different scenarios show that the city center (which has high office rent prices in Munich and LA), airports and inter city train station are suitable for initial operation of UAM, not to mention high income residential areas in the outskirt of the city. POIs can also be an enhancement for these areas, trying to catch niche market of tourism trip.

7.2 Limitations

There are many limitations along the working process. The UAM ground infrastructure design process in chapter 3 does not take physical structure into account. Despite of the complexity of WLC analysis, the exact location of UAM ground infrastructure is not be able to be determined. Narrowing down the scope of where to build UAM ground infrastructure by means of WLC method is the best impact this thesis might contribute to the development of UAM. There is still a need to find a way on how to determine the exact location to build UAM ground infrastructure. To that end, a new study should be conducted.

Physical structure of UAM ground infrastructure is not taken into consideration in this thesis. However, the other minimum ground infrastructure factors refer to more complex and detail works. To give an illustration, minimum requirement for communication infrastructure is obtained from another working paper. Likewise, minimum requirement for parking infrastructure is also taken from manufactured products, without any further examination or review.

Data availability is also another issue encountered by this thesis. Although U.S. Census data is quite complete, there are some census blocks without any data in median income, job density, and annual transportation cost. To cope with that issue, the interpolation method was undergone, as well as for office rent price data. In absence of office rent price data, this thesis collects some sample points from real estate property websites and interpolates them to examine office price within both case studies area. The interpolation method itself, due to time limitation, did not use the best interpolation method as other paper have recommended. The availability of private data in Munich is not as much as in LA. For example, income data and job density are not openly published.

This thesis also exaggerates the potential supply criterion, as not every gas station, both in Munich and Los Angeles, has square flat rooftop where eVTOL vehicle can landed on. Similarly, this thesis also exaggerates the permitted flying zone in Munich, as no detailed law and regulation assessment had been conducted. To simplify the analysis process, the details about flying restriction in Munich and LA are not brought into analysis. No elaboration of private space definition and impact of tress-passing eVTOL vehicle above private grounds could be another hurdle for this thesis to help stakeholders in shaping UAM operation.

7.3 Future Work

In the future, research topic about UAM ground infrastructure placement aiming for the exact site shall be conducted, following the outcome of this thesis. For example, using the site search modeling as recommended by (Cova & Church, 2000). K-means clustering to filter out UAM ground infrastructure from 5$^{\text{th}}$ percentile location might also be useful for determining exact location for the initial phase, as this algorithm provides clustering function of neighboring sites. Qualitative and quantitative analysis (Anderson et al., 2015) perhaps are other methodologies to locate exact site for UAM ground infrastructure. Detailed analysis in regulations and standards could make the further research more pragmatic. Compliance towards valid legal grounds and translating it into spatial format might return a better and accurate location, where eVTOL vehicle is allowed to land and departure. Different cities' characteristics also should be taken into account when locate an UAM ground infrastructure. To that end, criteria weight should embody the real preference and characteristic of potential UAM user.

7.4 Concluding Remarks

The burgeoning development of eVTOL vehicle forces transport planners, transport engineers, transport modelers, and urbanists into thinking how this mode will play an important role in future urban mobility. This thesis offers an approach in determining ground infrastructure location for UAM, by combining supply and demand criteria, as well as restrictions in a spatial methodology. Overall, this thesis contributes to the field of transportation planning, particularly UAM. Ground infrastructure location selection by means of GIS-based analysis has been achieved in this thesis, as well as various designs of UAM ground infrastructure. By having a GIS-based analysis, UAM ground infrastructure can be spatially planned, thus construct a more accurate investment calculation and operational simulation for the UAM industry.

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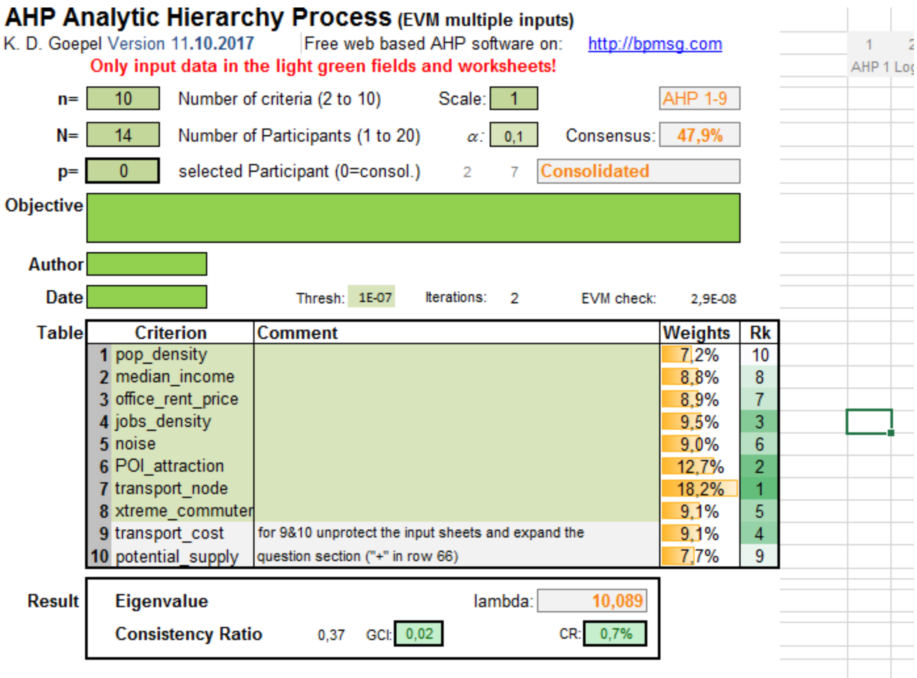
Appendix A

AHP-Delphi Analysis

A.1 Result of the Previous Rounds



AHP Analytic Hierarchy Process (EVM multiple inputs)
K. D. Goepel Version 11.10.2017 | Free web based AHP software on: http://bpmsg.com
Only input data in the light green fields and worksheets!

n= 10 Number of criteria (2 to 10) Scale: 1 AHP 1-9
N= 14 Number of Participants (1 to 20) α: 0,1 Consensus: 47,9%
p= 0 selected Participant (0=consol.) 2 7 Consolidated

Objective
Author
Date Thresh: 1E-07 Iterations: 2 EVM check: 2,9E-08

Table	Criterion	Comment	Weights	Rk
1	pop_density		7,2%	10
2	median_income		8,8%	8
3	office_rent_price		8,9%	7
4	jobs_density		9,5%	3
5	noise		9,0%	6
6	POI_attraction		12,7%	2
7	transport_node		18,2%	1
8	xtreme_commuter		9,1%	5
9	transport_cost	for 9&10 unprotect the input sheets and expand the	9,1%	4
10	potential_supply	question section ("+" in row 66)	7,7%	9

Result
Eigenvalue lambda: 10,089
Consistency Ratio 0,37 GCI: 0,02 CR: 0,7%

(a) Screen shot of the result of the AHP-Delphi Analysis Initial Round

Matrix		pop_density	median_income	office_rent_price	jobs_density	noise	POI_attraction	transport_node	xtreme_commuter	transport_cost	potential_supply	normalized principal Eigenvector
		1	2	3	4	5	6	7	8	9	10	
pop_density	1	-	0,76	0,79	0,66	0,88	0,52	0,44	0,87	0,79	1,03	7,20%
median_income	2	1,32	-	0,93	0,73	1,15	0,63	0,45	0,81	1,26	1,26	8,77%
office_rent_price	3	1,27	1,08	-	1,17	1,20	0,76	0,44	0,82	0,81	1,06	8,90%
jobs_density	4	1,51	1,36	0,86	-	1,09	0,66	0,43	1,07	1,15	1,20	9,46%
noise	5	1,13	0,87	0,83	0,92	-	0,77	0,54	1,27	1,19	0,99	8,96%
POI_attraction	6	1,93	1,58	1,32	1,52	1,30	-	0,63	1,27	1,71	1,45	12,67%
transport_node	7	2,26	2,23	2,27	2,31	1,87	1,58	-	2,02	1,60	2,29	18,17%
xtreme_commuter	8	1,15	1,24	1,22	0,93	0,78	0,79	0,50	-	1,00	1,12	9,07%
transport_cost	9	1,27	0,79	1,24	0,87	0,84	0,59	0,62	1,00	-	1,59	9,11%
potential_supply	10	0,97	0,79	0,94	0,83	1,01	0,69	0,44	0,89	0,63	-	7,68%

(b) Comparison Matrix of the AHP-Delphi Analysis Initial Round

Criteria				more important	ADM
i	j	A	B	A or B	(1-9)
1	2	pop_density	median_income	b	1,32
1	3	pop_density	office_rent_price	b	1,27
1	4	pop_density	jobs_density	b	1,51
1	5	pop_density	noise	b	1,13
1	6	pop_density	POI_attraction	b	1,93
1	7	pop_density	transport_node	b	2,26
1	8	pop_density	xtreme_commuter	b	1,15
2	3	median_income	office_rent_price	b	1,08
2	4	median_income	jobs_density	b	1,36
2	5	median_income	noise	a	1,15
2	6	median_income	POI_attraction	b	1,58
2	7	median_income	transport_node	b	2,23
2	8	median_income	xtreme_commuter	b	1,24
3	4	office_rent_price	jobs_density	a	1,17
3	5	office_rent_price	noise	a	1,20
3	6	office_rent_price	POI_attraction	b	1,32
3	7	office_rent_price	transport_node	b	2,27
3	8	office_rent_price	xtreme_commuter	b	1,22
4	5	job_density	noise	a	1,09
4	6	job_density	POI_attraction	b	1,52
4	7	job_density	transport_node	b	2,31
4	8	job_density	xtreme_commuter	a	1,07

Criteria				more important	ADM
i	j	A	B	A or B	(1-9)
5	6	noise	POI_attraction	b	1,30
5	7	noise	transport_node	b	1,87
5	8	noise	xtreme_commuter	a	1,27
6	7	POI_attraction	transport_node	b	1,58
6	8	POI_attraction	xtreme_commuter	a	1,27
7	8	transport_node	xtreme_commuter	a	2,02
1	9	pop_density	transport_cost	b	1,27
1	10	pop_density	potential_supply	a	1,03
2	9	median_income	transport_cost	a	1,26
2	10	median_income	potential_supply	a	1,26
3	9	office_rent_price	transport_cost	b	1,24
3	10	office_rent_price	potential_supply	a	1,06
4	9	job_density	transport_cost	a	1,15
4	10	job_density	potential_supply	a	1,20
5	9	noise	transport_cost	a	1,19
5	10	noise	potential_supply	b	1,01
6	9	POI_attraction	transport_cost	a	1,71
6	10	POI_attraction	potential_supply	a	1,45
7	9	transport_node	transport_cost	a	1,60
7	10	transport_node	potential_supply	a	2,29
8	9	xtreme_commuter	transport_cost	a	1,00
8	10	xtreme_commuter	potential_supply	a	1,12
9	10	transport_cost	potential_supply	a	1,59

(c) ADM Value after initial round

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version 11.10.2017 | Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n= 10 Number of criteria (2 to 10) Scale: 1 AHP 1-9

N= 14 Number of Participants (1 to 20) α: 0,1 Consensus: 54,4%

p= 0 selected Participant (0=consol.) 2 7 Consolidated

Objective

Author

Date Thresh: 1E-07 Iterations: 2 EVM check: 6,0E-08

Table

	Criterion	Comment	Weights	Rk
1	pop_density		6,8%	10
2	median_income		9,0%	7
3	office_rent_price		9,1%	5
4	jobs_density		10,0%	3
5	noise		8,4%	8
6	POI_attraction		12,6%	2
7	transport_node		18,0%	1
8	xtreme_commuter		9,0%	6
9	transport_cost	for 9&10 unprotect the input sheets and expand the	9,3%	4
10	potential_supply	question section ("+" in row 66)	7,8%	9

Result

Eigenvalue lambda: 10,106

Consistency Ratio 0,37 GCI: 0,03 CR: 0,8%

(d) Screen shot of the result of the AHP-Delphi Analysis First Iteration

i	j	Criteria A	Criteria B	more important A or B	ADM (1-9)
1	2	pop_density	median_income	b	1,82
1	3	pop_density	office_rent_price	b	1,47
1	4	pop_density	jobs_density	b	1,75
1	5	pop_density	noise	b	1,13
1	6	pop_density	POI_attraction	b	1,83
1	7	pop_density	transport_node	b	2,07
1	8	pop_density	xtreme_commuter	b	1,27
2	3	median_income	office_rent_price	b	1,09
2	4	median_income	jobs_density	b	1,22
2	5	median_income	noise	a	1,23
2	6	median_income	POI_attraction	b	1,50
2	7	median_income	transport_node	b	2,40
2	8	median_income	xtreme_commuter	b	1,34
3	4	office_rent_price	jobs_density	a	1,19
3	5	office_rent_price	noise	a	1,26
3	6	office_rent_price	POI_attraction	b	1,30
3	7	office_rent_price	transport_node	b	2,31
3	8	office_rent_price	xtreme_commuter	b	1,18
4	5	job_density	noise	a	1,14
4	6	job_density	POI_attraction	b	1,43
4	7	job_density	transport_node	b	1,99
4	8	job_density	xtreme_commuter	a	1,32

i	j	Criteria A	Criteria B	more important A or B	ADM (1-9)
5	6	noise	POI_attraction	b	1,60
5	7	noise	transport_node	b	1,99
5	8	noise	xtreme_commuter	a	1,22
6	7	POI_attraction	transport_node	b	1,58
6	8	POI_attraction	xtreme_commuter	a	1,27
7	8	transport_node	xtreme_commuter	a	1,85
1	9	pop_density	transport_cost	b	1,36
1	10	pop_density	potential_supply	a	1,01
2	9	median_income	transport_cost	a	1,13
2	10	median_income	potential_supply	a	1,18
3	9	office_rent_price	transport_cost	b	1,24
3	10	office_rent_price	potential_supply	a	1,01
4	9	job_density	transport_cost	a	1,25
4	10	job_density	potential_supply	a	1,27
5	9	noise	transport_cost	a	1,13
5	10	noise	potential_supply	b	1,07
6	9	POI_attraction	transport_cost	a	1,65
6	10	POI_attraction	potential_supply	a	1,40
7	9	transport_node	transport_cost	a	1,68
7	10	transport_node	potential_supply	a	2,33
8	9	xtreme_commuter	transport_cost	b	1,12
8	10	xtreme_commuter	potential_supply	a	1,07
9	10	transport_cost	potential_supply	a	1,56

(e) ADM Value after first iteration

Matrix		pop_density 1	median_income 2	office_rent_price 3	jobs_density 4	noise 5	POI_attraction 6	transport_node 7	xtreme_commuter 8	transport_cost 9	potential_supply 10	normalized principal Eigenvector
pop_density	1	-	0,55	0,68	0,57	0,89	0,55	0,48	0,79	0,73	1,01	6,78%
median_income	2	1,82	-	0,92	0,82	1,23	0,66	0,42	0,74	1,13	1,18	8,96%
office_rent_price	3	1,47	1,09	-	1,19	1,26	0,77	0,43	0,85	0,81	1,01	9,09%
jobs_density	4	1,75	1,22	0,84	-	1,14	0,70	0,50	1,32	1,25	1,27	10,03%
noise	5	1,13	0,81	0,79	0,88	-	0,63	0,50	1,22	1,13	0,94	8,42%
POI_attraction	6	1,83	1,50	1,30	1,43	1,60	-	0,63	1,27	1,65	1,40	12,58%
transport_node	7	2,07	2,40	2,31	1,99	1,99	1,58	-	1,85	1,68	2,33	17,97%
xtreme_commuter	8	1,27	1,34	1,18	0,76	0,82	0,79	0,54	-	0,89	1,07	9,02%
transport_cost	9	1,36	0,88	1,24	0,80	0,89	0,61	0,60	1,12	-	1,56	9,29%
potential_supply	10	0,99	0,85	0,99	0,79	1,07	0,72	0,43	0,94	0,64	-	7,85%

(f) Comparison Matrix of the AHP-Delphi Analysis First Iteration

A.2 Final Responses from Experts

http://bpmsg.com AHP 14/05/2018

AHP Analytic Hierarchy Process n= 10 Input 1

Objective: 0

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	pop_density	population density of a particular area	3%
2	median_income	median income of the population living in a particular area	24%
3	office_rent_price	interpolated rent price of office in a particular area	17%
4	jobs_density	number of jobs available in a particular area	5%
5	noise	existing noise level	6%
6	POI_attraction	most visited places by tourist	8%
7	transport_node	major transport nodes (train stations, bus stations, airports, and ferry)	10%
8	xtreme_commuter	number of commuters who travel more than 90 minutes	5%
9	transport_cost	average total cost of household transportation of a certain population	12%
10	potential_supply	number of existing helipads and petrol stations	10%

Area of expertise Years of Experience α: 0.1 CR: 13% Consistency Ratio 1 Scale

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)		
1	2	pop_density	median_income	B	6		
1	3	pop_density	office_rent_price	B	6		
1	4	pop_density	jobs_density	B	4		
1	5	pop_density	noise	A	2	2	B2
1	6	pop_density	POI_attraction	B	3		
1	7	pop_density	transport_node	B	4		
1	8	pop_density	xtreme_commuter	B	3		
2	3	median_income	office_rent_price	A	3		
2	4	median_income	jobs_density	A	2		
2	5	median_income	noise	A	4		
2	6	median_income	POI_attraction	A	4		
2	7	median_income	transport_node	A	2		
2	8	median_income	xtreme_commuter	A	4		
3	4	office_rent_price	jobs_density	A	6		
3	5	office_rent_price	noise	A	3		
3	6	office_rent_price	POI_attraction	A	5		
3	7	office_rent_price	transport_node	B	1		
3	8	office_rent_price	xtreme_commuter	A	4		
4	5	job_density	noise	B	3		
4	6	job_density	POI_attraction	B	2		
4	7	job_density	transport_node	B	2		
4	8	job_density	xtreme_commuter	A	2		
5	6	noise	POI_attraction	B	2		
5	7	noise	transport_node	B	3		
5	8	noise	xtreme_commuter	A	1		
6	7	POI_attraction	transport_node	B	2		
6	8	POI_attraction	xtreme_commuter	A	2		
7	8	transport_node	xtreme_commuter	A	1		
1	9	pop_density	transport_cost	B	4		
1	10	pop_density	potential_supply	B	5		
2	9	median_income	transport_cost	A	2		
2	10	median_income	potential_supply	A	4		
3	9	office_rent_price	transport_cost	B	2		
3	10	office_rent_price	potential_supply	A	4		
4	9	job_density	transport_cost	B	3		
4	10	job_density	potential_supply	B	4		
5	9	noise	transport_cost	A	2	1	B2
5	10	noise	potential_supply	B	2		
6	9	POI_attraction	transport_cost	A	2	3	B2
6	10	POI_attraction	potential_supply	B	2		
7	9	transport_node	transport_cost	B	3		
7	10	transport_node	potential_supply	B	1		
8	9	xtreme_commuter	transport_cost	B	2		
8	10	xtreme_commuter	potential_supply	B	4		
9	10	transport_cost	potential_supply	A	3		

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,6,8 can be used to express intermediate values		

participant_1-In1

(a) Final Response from Participant 1

http://bpmsg.com AHP 14/05/2018

AHP Analytic Hierarchy Process

n= 10 Input 1

Objective: 0

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	pop_density	population density of a particular area	5%
2	median_income	median income of the population living in a particular area	8%
3	office_rent_price	interpolated rent price of office in a particular area	7%
4	jobs_density	number of jobs available in a particular area	8%
5	noise	existing noise level	14%
6	POI_attraction	most visited places by tourist	16%
7	transport_node	major transport nodes (train stations, bus stations, airports, and ferry)	23%
8	xtreme_commuter	number of commuters who travel more than 90 minutes	8%
9	transport_cost	average total cost of household transportation of a certain population	6%
10	potential_supply	number of existing helipads and petrol stations	6%

Transport Modelling	7	α:	0.1	CR:	3%	1
Area of Expertise	Years of Experience			Consistency Ratio		Scale

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	pop_density	median_income	b	2
1	3	pop_density	office_rent_price	b	3
1	4	pop_density	jobs_density	b	2
1	5	pop_density	noise	b	3
1	6	pop_density	POI_attraction	b	3
1	7	pop_density	transport_node	b	4
1	8	pop_density	xtreme_commuter	b	1
2	3	median_income	office_rent_price	b	1
2	4	median_income	jobs_density	b	1
2	5	median_income	noise	b	3
2	6	median_income	POI_attraction	b	2
2	7	median_income	transport_node	b	4
2	8	median_income	xtreme_commuter	b	1
3	4	office_rent_price	jobs_density	a	2
3	5	office_rent_price	noise	b	3
3	6	office_rent_price	POI_attraction	b	3
3	7	office_rent_price	transport_node	b	4
3	8	office_rent_price	xtreme_commuter	b	2
4	5	job_density	noise	b	2
4	6	job_density	POI_attraction	b	2
4	7	job_density	transport_node	b	3
4	8	job_density	xtreme_commuter	a	1
5	6	noise	POI_attraction	b	2
5	7	noise	transport_node	b	2
5	8	noise	xtreme_commuter	a	2
6	7	POI_attraction	transport_node	b	2
6	8	POI_attraction	xtreme_commuter	a	2
7	8	transport_node	xtreme_commuter	a	2
1	9	pop_density	transport_cost	a	1
1	10	pop_density	potential_supply	a	1
2	9	median_income	transport_cost	a	2
2	10	median_income	potential_supply	a	2
3	9	office_rent_price	transport_cost	b	1
3	10	office_rent_price	potential_supply	a	1
4	9	job_density	transport_cost	a	2
4	10	job_density	potential_supply	a	2
5	9	noise	transport_cost	a	2
5	10	noise	potential_supply	a	2
6	9	POI_attraction	transport_cost	a	2
6	10	POI_attraction	potential_supply	a	2
7	9	transport_node	transport_cost	a	3
7	10	transport_node	potential_supply	a	3
8	9	xtreme_commuter	transport_cost	a	1
8	10	xtreme_commuter	potential_supply	a	1
9	10	transport_cost	potential_supply	a	1

A
B

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

2,4,6,8 can be used to express intermediate values

participant_2-In2

(b) Final Response from Participant 2

http://bpmsg.com AHP 14/05/2018

AHP Analytic Hierarchy Process n= 10 Input 1

Objective: 0

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	pop_density	population density of a particular area	3%
2	median_income	median income of the population living in a particular area	9%
3	office_rent_price	interpolated rent price of office in a particular area	10%
4	jobs_density	number of jobs available in a particular area	4%
5	noise	existing noise level	3%
6	POI_attraction	most visited places by tourist	15%
7	transport_node	major transport nodes (train stations, bus stations, airports, and ferry)	28%
8	xtreme_commuter	number of commuters who travel more than 90 minutes	3%
9	transport_cost	average total cost of household transportation of a certain population	13%
10	potential_supply	number of existing helipads and petrol stations	11%

ght performance and propuls 1 α: 0.1 CR: 11% 1

Area of expertise Years of Experience Consistency Ratio Scale

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)		
1	2	pop_density	median_income	B	6		
1	3	pop_density	office_rent_price	B	5		
1	4	pop_density	jobs_density	B	3		
1	5	pop_density	noise	A	2		
1	6	pop_density	POI_attraction	B	5		
1	7	pop_density	transport_node	B	5		
1	8	pop_density	xtreme_commuter	A	3		
2	3	median_income	office_rent_price	B	3		
2	4	median_income	jobs_density	A	4		
2	5	median_income	noise	A	4		
2	6	median_income	POI_attraction	B	4		
2	7	median_income	transport_node	B	4		
2	8	median_income	xtreme_commuter	A	3		
3	4	office_rent_price	jobs_density	A	5		
3	5	office_rent_price	noise	A	5		
3	6	office_rent_price	POI_attraction	B	2		
3	7	office_rent_price	transport_node	B	4		
3	8	office_rent_price	xtreme_commuter	A	4		
4	5	job_density	noise	B	1		
4	6	job_density	POI_attraction	B	5		
4	7	job_density	transport_node	B	5		
4	8	job_density	xtreme_commuter	A	3		
5	6	noise	POI_attraction	B	3		
5	7	noise	transport_node	B	5		
5	8	noise	xtreme_commuter	A	3		
6	7	POI_attraction	transport_node	B	4		
6	8	POI_attraction	xtreme_commuter	A	4		
7	8	transport_node	xtreme_commuter	A	4	2	A9
1	9	pop_density	transport_cost	B	3		
1	10	pop_density	potential_supply	B	3		
2	9	median_income	transport_cost	B	3		
2	10	median_income	potential_supply	A	2	3	B1
3	9	office_rent_price	transport_cost	B	3		
3	10	office_rent_price	potential_supply	B	3	1	B1
4	9	job_density	transport_cost	B	3		
4	10	job_density	potential_supply	B	3		
5	9	noise	transport_cost	B	4		
5	10	noise	potential_supply	B	4		
6	9	POI_attraction	transport_cost	A	1		
6	10	POI_attraction	potential_supply	A	1		
7	9	transport_node	transport_cost	A	4		
7	10	transport_node	potential_supply	A	3		
8	9	xtreme_commuter	transport_cost	B	3		
8	10	xtreme_commuter	potential_supply	B	3		
9	10	transport_cost	potential_supply	A	1		

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,6,8 can be used to express intermediate values		

participant_3-In3

(c) Final Response from Participant 3

http://bpmsg.com AHP 14/05/2018

AHP Analytic Hierarchy Process n= 10 Input 1

Objective: 0

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	pop_density	population density of a particular area	7%
2	median_income	median income of the population living in a particular area	4%
3	office_rent_price	interpolated rent price of office in a particular area	3%
4	jobs_density	number of jobs available in a particular area	8%
5	noise	existing noise level	2%
6	POI_attraction	most visited places by tourist	40%
7	transport_node	major transport nodes (train stations, bus stations, airports, and ferry)	10%
8	xtreme_commuter	number of commuters who travel more than 90 minutes	3%
9	transport_cost	average total cost of household transportation of a certain population	17%
10	potential_supply	number of existing helipads and petrol stations	6%

Area of Expertise	Years of Experience	α:	Consistency Ratio	Scale
Maintenance Repair Overhau	<1	0.1	CR: 8%	1

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	pop_density	median_income	B	1
1	3	pop_density	office_rent_price	A	3
1	4	pop_density	jobs_density	B	2
1	5	pop_density	noise	A	2
1	6	pop_density	POI_attraction	B	9
1	7	pop_density	transport_node	B	1
1	8	pop_density	xtreme_commuter	A	5
2	3	median_income	office_rent_price	B	2
2	4	median_income	jobs_density	B	2
2	5	median_income	noise	A	3
2	6	median_income	POI_attraction	B	9
2	7	median_income	transport_node	B	5
2	8	median_income	xtreme_commuter	A	3
3	4	office_rent_price	jobs_density	B	3
3	5	office_rent_price	noise	A	4
3	6	office_rent_price	POI_attraction	B	8
3	7	office_rent_price	transport_node	B	3
3	8	office_rent_price	xtreme_commuter	B	3
4	5	job_density	noise	A	3
4	6	job_density	POI_attraction	B	7
4	7	job_density	transport_node	B	1
4	8	job_density	xtreme_commuter	A	4
5	6	noise	POI_attraction	B	8
5	7	noise	transport_node	B	4
5	8	noise	xtreme_commuter	A	2
6	7	POI_attraction	transport_node	A	4
6	8	POI_attraction	xtreme_commuter	A	9
7	8	transport_node	xtreme_commuter	A	3
1	9	pop_density	transport_cost	B	2
1	10	pop_density	potential_supply	A	1
2	9	median_income	transport_cost	B	4
2	10	median_income	potential_supply	A	1
3	9	office_rent_price	transport_cost	B	5
3	10	office_rent_price	potential_supply	B	2
4	9	job_density	transport_cost	B	4
4	10	job_density	potential_supply	B	1
5	9	noise	transport_cost	B	7
5	10	noise	potential_supply	B	4
6	9	POI_attraction	transport_cost	A	5
6	10	POI_attraction	potential_supply	A	8
7	9	transport_node	transport_cost	B	5
7	10	transport_node	potential_supply	A	4
8	9	xtreme_commuter	transport_cost	B	4
8	10	xtreme_commuter	potential_supply	B	2
9	10	transport_cost	potential_supply	A	3

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

2,4,6,8 can be used to express intermediate values

participant_4-In4

(d) Final Response from Participant 4

http://bpmsg.com AHP 14/05/2018

AHP Analytic Hierarchy Process n= 10 Input 1

Objective: 0

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	pop_density	population density of a particular area	3%
2	median_income	median income of the population living in a particular area	3%
3	office_rent_price	interpolated rent price of office in a particular area	10%
4	jobs_density	number of jobs available in a particular area	3%
5	noise	existing noise level	4%
6	POI_attraction	most visited places by tourist	13%
7	transport_node	major transport nodes (train stations, bus stations, airports, and ferry)	15%
8	xtreme_commuter	number of commuters who travel more than 90 minutes	13%
9	transport_cost	average total cost of household transportation of a certain population	8%
10	potential_supply	number of existing helipads and petrol stations	27%

New mobility concepts	2	α: 0.1	CR: 10%	1
Area of Expertise	Years of Experience		Consistency Ratio	Scale

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	pop_density	median_income	B	1
1	3	pop_density	office_rent_price	B	6
1	4	pop_density	jobs_density	B	1
1	5	pop_density	noise	B	1
1	6	pop_density	POI_attraction	B	6
1	7	pop_density	transport_node	B	6
1	8	pop_density	xtreme_commuter	B	6
2	3	median_income	office_rent_price	B	2
2	4	median_income	jobs_density	B	1
2	5	median_income	noise	B	1
2	6	median_income	POI_attraction	B	6
2	7	median_income	transport_node	B	6
2	8	median_income	xtreme_commuter	B	6
3	4	office_rent_price	jobs_density	A	6
3	5	office_rent_price	noise	A	2
3	6	office_rent_price	POI_attraction	B	1
3	7	office_rent_price	transport_node	B	1
3	8	office_rent_price	xtreme_commuter	B	1
4	5	job_density	noise	A	1
4	6	job_density	POI_attraction	B	4
4	7	job_density	transport_node	B	4
4	8	job_density	xtreme_commuter	B	4
5	6	noise	POI_attraction	B	4
5	7	noise	transport_node	B	3
5	8	noise	xtreme_commuter	B	3
6	7	POI_attraction	transport_node	A	1
6	8	POI_attraction	xtreme_commuter	A	1
7	8	transport_node	xtreme_commuter	A	1
1	9	pop_density	transport_cost	B	6
1	10	pop_density	potential_supply	B	6
2	9	median_income	transport_cost	B	1
2	10	median_income	potential_supply	B	6
3	9	office_rent_price	transport_cost	B	2
3	10	office_rent_price	potential_supply	B	6
4	9	job_density	transport_cost	B	3
4	10	job_density	potential_supply	B	6
5	9	noise	transport_cost	B	1
5	10	noise	potential_supply	B	6
6	9	POI_attraction	transport_cost	A	3
6	10	POI_attraction	potential_supply	B	6
7	9	transport_node	transport_cost	A	2
7	10	transport_node	potential_supply	A	1
8	9	xtreme_commuter	transport_cost	B	2
8	10	xtreme_commuter	potential_supply	B	1
9	10	transport_cost	potential_supply	B	6

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

2,4,6,8 can be used to express intermediate values

participant_5-ln5

(e) Final Response from Participant 5

http://bpmsg.com AHP 14/05/2018

AHP Analytic Hierarchy Process

n= 10 Input 1

Objective: 0

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	pop_density	population density of a particular area	9%
2	median_income	median income of the population living in a particular area	22%
3	office_rent_price	interpolated rent price of office in a particular area	8%
4	jobs_density	number of jobs available in a particular area	8%
5	noise	existing noise level	3%
6	POI_attraction	most visited places by tourist	16%
7	transport_node	major transport nodes (train stations, bus stations, airports, and ferry)	26%
8	xtreme_commuter	number of commuters who travel more than 90 minutes	4%
9	transport_cost	average total cost of household transportation of a certain population	2%
10	potential_supply	number of existing helipads and petrol stations	2%

UAM/ economics (Area of Expertise) | 1 (Years of Experience) | α: 0.1 | CR: 10% (Consistency Ratio) | 1 (Scale)

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	pop_density	median_income	b	4
1	3	pop_density	office_rent_price	b	1
1	4	pop_density	jobs_density	a	2
1	5	pop_density	noise	a	4
1	6	pop_density	POI_attraction	b	4
1	7	pop_density	transport_node	b	6
1	8	pop_density	xtreme_commuter	a	4
2	3	median_income	office_rent_price	a	6
2	4	median_income	jobs_density	a	3
2	5	median_income	noise	a	6
2	6	median_income	POI_attraction	b	1
2	7	median_income	transport_node	a	2
2	8	median_income	xtreme_commuter	a	5
3	4	office_rent_price	jobs_density	b	1
3	5	office_rent_price	noise	a	3
3	6	office_rent_price	POI_attraction	b	2
3	7	office_rent_price	transport_node	b	5
3	8	office_rent_price	xtreme_commuter	a	2
4	5	job_density	noise	a	5
4	6	job_density	POI_attraction	b	5
4	7	job_density	transport_node	b	6
4	8	job_density	xtreme_commuter	a	4
5	6	noise	POI_attraction	b	5
5	7	noise	transport_node	b	5
5	8	noise	xtreme_commuter	b	1
6	7	POI_attraction	transport_node	b	4
6	8	POI_attraction	xtreme_commuter	a	3
7	8	transport_node	xtreme_commuter	a	5
1	9	pop_density	transport_cost	a	5
1	10	pop_density	potential_supply	a	5
2	9	median_income	transport_cost	a	5
2	10	median_income	potential_supply	a	6
3	9	office_rent_price	transport_cost	a	6
3	10	office_rent_price	potential_supply	a	4
4	9	job_density	transport_cost	a	4
4	10	job_density	potential_supply	a	5
5	9	noise	transport_cost	a	4
5	10	noise	potential_supply	a	1
6	9	POI_attraction	transport_cost	a	6
6	10	POI_attraction	potential_supply	a	6
7	9	transport_node	transport_cost	a	8
7	10	transport_node	potential_supply	a	8
8	9	xtreme_commuter	transport_cost	a	5
8	10	xtreme_commuter	potential_supply	a	3
9	10	transport_cost	potential_supply	a	1

A
B

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

2,4,6,8 can be used to express intermediate values

participant_6-ln6

(f) Final Response from Participant 6

http://bpmsg.com AHP 14/05/2018

AHP Analytic Hierarchy Process

n= 10 Input 1

Objective: 0

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	pop_density	population density of a particular area	3%
2	median_income	median income of the population living in a particular area	3%
3	office_rent_price	interpolated rent price of office in a particular area	13%
4	jobs_density	number of jobs available in a particular area	13%
5	noise	existing noise level	7%
6	POI_attraction	most visited places by tourist	1%
7	transport_node	major transport nodes (train stations, bus stations, airports, and ferry)	27%
8	xtreme_commuter	number of commuters who travel more than 90 minutes	27%
9	transport_cost	average total cost of household transportation of a certain population	3%
10	potential_supply	number of existing helipads and petrol stations	3%

Aerospace Engineering — 2

Area of expertise — Years of Experience

α: 0.1 CR: 4% Consistency Ratio — 1 Scale

A
B

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	pop_density	median_income	B	1
1	3	pop_density	office_rent_price	B	3
1	4	pop_density	jobs_density	B	3
1	5	pop_density	noise	B	5
1	6	pop_density	POI_attraction	A	3
1	7	pop_density	transport_node	B	9
1	8	pop_density	xtreme_commuter	B	9
2	3	median_income	office_rent_price	B	5
2	4	median_income	jobs_density	B	5
2	5	median_income	noise	B	5
2	6	median_income	POI_attraction	A	5
2	7	median_income	transport_node	B	9
2	8	median_income	xtreme_commuter	B	9
3	4	office_rent_price	jobs_density	A	1
3	5	office_rent_price	noise	A	3
3	6	office_rent_price	POI_attraction	A	7
3	7	office_rent_price	transport_node	B	3
3	8	office_rent_price	xtreme_commuter	B	3
4	5	job_density	noise	A	3
4	6	job_density	POI_attraction	A	7
4	7	job_density	transport_node	B	3
4	8	job_density	xtreme_commuter	B	3
5	6	noise	POI_attraction	A	5
5	7	noise	transport_node	B	5
5	8	noise	xtreme_commuter	B	5
6	7	POI_attraction	transport_node	B	9
6	8	POI_attraction	xtreme_commuter	B	9
7	8	transport_node	xtreme_commuter	B	1
1	9	pop_density	transport_cost	B	1
1	10	pop_density	potential_supply	B	1
2	9	median_income	transport_cost	A	1
2	10	median_income	potential_supply	A	1
3	9	office_rent_price	transport_cost	A	5
3	10	office_rent_price	potential_supply	A	5
4	9	job_density	transport_cost	A	7
4	10	job_density	potential_supply	A	7
5	9	noise	transport_cost	A	3
5	10	noise	potential_supply	A	3
6	9	POI_attraction	transport_cost	B	3
6	10	POI_attraction	potential_supply	B	3
7	9	transport_node	transport_cost	A	7
7	10	transport_node	potential_supply	A	7
8	9	xtreme_commuter	transport_cost	A	7
8	10	xtreme_commuter	potential_supply	A	7
9	10	transport_cost	potential_supply	A	3

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

2,4,6,8 can be used to express intermediate values

participant_7-ln7

(g) Final Response from Participant 7

http://bpmsg.com AHP 14/05/2018

AHP Analytic Hierarchy Process

n= 10 Input 1

Objective: 0

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	pop_density	population density of a particular area	4%
2	median_income	median income of the population living in a particular area	4%
3	office_rent_price	interpolated rent price of office in a particular area	5%
4	jobs_density	number of jobs available in a particular area	7%
5	noise	existing noise level	9%
6	POI_attraction	most visited places by tourist	20%
7	transport_node	major transport nodes (train stations, bus stations, airports, and ferry)	18%
8	xtreme_commuter	number of commuters who travel more than 90 minutes	22%
9	transport_cost	average total cost of household transportation of a certain population	6%
10	potential_supply	number of existing helipads and petrol stations	5%

Area of Expertise	Years of Experience	α:	Consistency Ratio (CR:)	Scale
Operations	1	0.1	6%	1

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	pop_density	median_income	B	1
1	3	pop_density	office_rent_price	A	3
1	4	pop_density	jobs_density	B	3
1	5	pop_density	noise	B	5
1	6	pop_density	POI_attraction	B	5
1	7	pop_density	transport_node	B	3
1	8	pop_density	xtreme_commuter	B	5
2	3	median_income	office_rent_price	B	3
2	4	median_income	jobs_density	B	3
2	5	median_income	noise	B	1
2	6	median_income	POI_attraction	B	7
2	7	median_income	transport_node	B	5
2	8	median_income	xtreme_commuter	B	9
3	4	office_rent_price	jobs_density	A	1
3	5	office_rent_price	noise	B	1
3	6	office_rent_price	POI_attraction	B	3
3	7	office_rent_price	transport_node	B	5
3	8	office_rent_price	xtreme_commuter	B	5
4	5	job_density	noise	A	1
4	6	job_density	POI_attraction	B	3
4	7	job_density	transport_node	B	3
4	8	job_density	xtreme_commuter	B	5
5	6	noise	POI_attraction	B	3
5	7	noise	transport_node	B	1
5	8	noise	xtreme_commuter	B	1
6	7	POI_attraction	transport_node	B	1
6	8	POI_attraction	xtreme_commuter	B	1
7	8	transport_node	xtreme_commuter	B	1
1	9	pop_density	transport_cost	A	1
1	10	pop_density	potential_supply	A	1
2	9	median_income	transport_cost	A	1
2	10	median_income	potential_supply	A	1
3	9	office_rent_price	transport_cost	B	3
3	10	office_rent_price	potential_supply	B	1
4	9	job_density	transport_cost	B	1
4	10	job_density	potential_supply	B	1
5	9	noise	transport_cost	A	3
5	10	noise	potential_supply	B	1
6	9	POI_attraction	transport_cost	A	3
6	10	POI_attraction	potential_supply	A	3
7	9	transport_node	transport_cost	A	5
7	10	transport_node	potential_supply	A	3
8	9	xtreme_commuter	transport_cost	A	5
8	10	xtreme_commuter	potential_supply	A	5
9	10	transport_cost	potential_supply	A	3

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

2,4,6,8 can be used to express intermediate values

participant_8-ln8

(h) Final Response from Participant 5

http://bpmsg.com AHP 14/05/2018

AHP Analytic Hierarchy Process n= 10 Input 1

Objective: 0

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	pop_density	population density of a particular area	13%
2	median_income	median income of the population living in a particular area	4%
3	office_rent_price	interpolated rent price of office in a particular area	6%
4	jobs_density	number of jobs available in a particular area	12%
5	noise	existing noise level	26%
6	POI_attraction	most visited places by tourist	3%
7	transport_node	major transport nodes (train stations, bus stations, airports, and ferry)	17%
8	xtreme_commuter	number of commuters who travel more than 90 minutes	13%
9	transport_cost	average total cost of household transportation of a certain population	3%
10	potential_supply	number of existing helipads and petrol stations	4%

dministration, Aeronautical E 7 α: 0.1 CR: 8% 1

Area of Expertise Years of Experience Consistency Ratio Scale

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	pop_density	median_income	A	1
1	3	pop_density	office_rent_price	A	1
1	4	pop_density	jobs_density	B	1
1	5	pop_density	noise	B	1
1	6	pop_density	POI_attraction	A	5
1	7	pop_density	transport_node	B	1
1	8	pop_density	xtreme_commuter	B	1
2	3	median_income	office_rent_price	A	1
2	4	median_income	jobs_density	B	5
2	5	median_income	noise	B	9
2	6	median_income	POI_attraction	A	1
2	7	median_income	transport_node	B	5
2	8	median_income	xtreme_commuter	B	5
3	4	office_rent_price	jobs_density	A	1
3	5	office_rent_price	noise	B	4
3	6	office_rent_price	POI_attraction	A	4
3	7	office_rent_price	transport_node	B	5
3	8	office_rent_price	xtreme_commuter	B	4
4	5	job_density	noise	B	5
4	6	job_density	POI_attraction	A	5
4	7	job_density	transport_node	B	2
4	8	job_density	xtreme_commuter	A	1
5	6	noise	POI_attraction	A	5
5	7	noise	transport_node	A	1
5	8	noise	xtreme_commuter	A	5
6	7	POI_attraction	transport_node	B	5
6	8	POI_attraction	xtreme_commuter	B	5
7	8	transport_node	xtreme_commuter	A	1
1	9	pop_density	transport_cost	A	5
1	10	pop_density	potential_supply	A	6
2	9	median_income	transport_cost	A	1
2	10	median_income	potential_supply	B	1
3	9	office_rent_price	transport_cost	B	1
3	10	office_rent_price	potential_supply	A	1
4	9	job_density	transport_cost	A	7
4	10	job_density	potential_supply	A	4
5	9	noise	transport_cost	A	9
5	10	noise	potential_supply	A	5
6	9	POI_attraction	transport_cost	B	1
6	10	POI_attraction	potential_supply	A	1
7	9	transport_node	transport_cost	A	5
7	10	transport_node	potential_supply	A	3
8	9	xtreme_commuter	transport_cost	A	2
8	10	xtreme_commuter	potential_supply	A	5
9	10	transport_cost	potential_supply	A	1

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

2,4,6,8 can be used to express intermediate values

participant_9-ln9

(i) Final Response from Participant 9

http://bpmsg.com AHP 14/05/2018

AHP Analytic Hierarchy Process n= 10 Input 1

Objective: 0

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	pop_density	population density of a particular area	8%
2	median_income	median income of the population living in a particular area	11%
3	office_rent_price	interpolated rent price of office in a particular area	30%
4	jobs_density	number of jobs available in a particular area	18%
5	noise	existing noise level	6%
6	POI_attraction	most visited places by tourist	7%
7	transport_node	major transport nodes (train stations, bus stations, airports, and ferry)	7%
8	xtreme_commuter	number of commuters who travel more than 90 minutes	4%
9	transport_cost	average total cost of household transportation of a certain population	6%
10	potential_supply	number of existing helipads and petrol stations	2%

Economic Geography | 5 | α: 0.1 | CR: 9% | 1

Area of Expertise | Years of Experience | Consistency Ratio | Scale

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	pop_density	median_income	B	5
1	3	pop_density	office_rent_price	B	7
1	4	pop_density	jobs_density	B	2
1	5	pop_density	noise	A	1
1	6	pop_density	POI_attraction	A	1
1	7	pop_density	transport_node	A	3
1	8	pop_density	xtreme_commuter	A	3
2	3	median_income	office_rent_price	B	5
2	4	median_income	jobs_density	B	4
2	5	median_income	noise	A	1
2	6	median_income	POI_attraction	A	2
2	7	median_income	transport_node	A	2
2	8	median_income	xtreme_commuter	A	3
3	4	office_rent_price	jobs_density	A	2
3	5	office_rent_price	noise	A	5
3	6	office_rent_price	POI_attraction	A	5
3	7	office_rent_price	transport_node	A	3
3	8	office_rent_price	xtreme_commuter	A	4
4	5	job_density	noise	A	4
4	6	job_density	POI_attraction	A	3
4	7	job_density	transport_node	A	2
4	8	job_density	xtreme_commuter	A	3
5	6	noise	POI_attraction	B	3
5	7	noise	transport_node	B	1
5	8	noise	xtreme_commuter	A	2
6	7	POI_attraction	transport_node	A	1
6	8	POI_attraction	xtreme_commuter	A	2
7	8	transport_node	xtreme_commuter	A	3
1	9	pop_density	transport_cost	A	3
1	10	pop_density	potential_supply	A	5
2	9	median_income	transport_cost	A	5
2	10	median_income	potential_supply	A	3
3	9	office_rent_price	transport_cost	A	5
3	10	office_rent_price	potential_supply	A	6
4	9	job_density	transport_cost	A	3
4	10	job_density	potential_supply	A	4
5	9	noise	transport_cost	A	1
5	10	noise	potential_supply	A	3
6	9	POI_attraction	transport_cost	A	1
6	10	POI_attraction	potential_supply	A	3
7	9	transport_node	transport_cost	B	1
7	10	transport_node	potential_supply	A	4
8	9	xtreme_commuter	transport_cost	B	3
8	10	xtreme_commuter	potential_supply	A	4
9	10	transport_cost	potential_supply	A	3

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

2,4,6,8 can be used to express intermediate values

participant_10-In10

(j) Final Response from Participant 10

http://bpmsg.com AHP 14/05/2018

AHP Analytic Hierarchy Process

n= 10 Input 1

Objective: 0

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	pop_density	population density of a particular area	4%
2	median_income	median income of the population living in a particular area	17%
3	office_rent_price	interpolated rent price of office in a particular area	3%
4	jobs_density	number of jobs available in a particular area	10%
5	noise	existing noise level	11%
6	POI_attraction	most visited places by tourist	6%
7	transport_node	major transport nodes (train stations, bus stations, airports, and ferry)	17%
8	xtreme_commuter	number of commuters who travel more than 90 minutes	8%
9	transport_cost	average total cost of household transportation of a certain population	19%
10	potential_supply	number of existing helipads and petrol stations	5%

Passenger demand (Area of Expertise) | 7 (Years of Experience) | α: 0.1 | CR: 10% (Consistency Ratio) | 1 (Scale)

i	j	A (Criteria)	B (Criteria)	more important ? A or B	Scale (1-9)
1	2	pop_density	median_income	B	3
1	3	pop_density	office_rent_price	A	3
1	4	pop_density	jobs_density	B	3
1	5	pop_density	noise	B	1
1	6	pop_density	POI_attraction	B	3
1	7	pop_density	transport_node	B	3
1	8	pop_density	xtreme_commuter	B	3
2	3	median_income	office_rent_price	A	5
2	4	median_income	jobs_density	A	3
2	5	median_income	noise	B	1
2	6	median_income	POI_attraction	A	3
2	7	median_income	transport_node	B	1
2	8	median_income	xtreme_commuter	A	3
3	4	office_rent_price	jobs_density	B	3
3	5	office_rent_price	noise	B	3
3	6	office_rent_price	POI_attraction	B	3
3	7	office_rent_price	transport_node	B	5
3	8	office_rent_price	xtreme_commuter	B	5
4	5	job_density	noise	B	3
4	6	job_density	POI_attraction	A	3
4	7	job_density	transport_node	B	3
4	8	job_density	xtreme_commuter	A	3
5	6	noise	POI_attraction	A	5
5	7	noise	transport_node	B	3
5	8	noise	xtreme_commuter	A	1
6	7	POI_attraction	transport_node	B	3
6	8	POI_attraction	xtreme_commuter	B	3
7	8	transport_node	xtreme_commuter	A	3
1	9	pop_density	transport_cost	B	5
1	10	pop_density	potential_supply	B	3
2	9	median_income	transport_cost	A	1
2	10	median_income	potential_supply	A	3
3	9	office_rent_price	transport_cost	B	3
3	10	office_rent_price	potential_supply	A	1
4	9	job_density	transport_cost	A	1
4	10	job_density	potential_supply	A	3
5	9	noise	transport_cost	B	3
5	10	noise	potential_supply	A	3
6	9	POI_attraction	transport_cost	B	3
6	10	POI_attraction	potential_supply	A	3
7	9	transport_node	transport_cost	B	3
7	10	transport_node	potential_supply	A	3
8	9	xtreme_commuter	transport_cost	B	3
8	10	xtreme_commuter	potential_supply	A	1
9	10	transport_cost	potential_supply	A	3

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

2,4,6,8 can be used to express intermediate values

participant_11-ln11

(k) Final Response from Participant 11

http://bpmsg.com AHP 14/05/2018

AHP Analytic Hierarchy Process n= 10 Input 1

Objective: 0

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	pop_density	population density of a particular area	9%
2	median_income	median income of the population living in a particular area	6%
3	office_rent_price	interpolated rent price of office in a particular area	4%
4	jobs_density	number of jobs available in a particular area	12%
5	noise	existing noise level	5%
6	POI_attraction	most visited places by tourist	16%
7	transport_node	major transport nodes (train stations, bus stations, airports, and ferry)	21%
8	xtreme_commuter	number of commuters who travel more than 90 minutes	8%
9	transport_cost	average total cost of household transportation of a certain population	12%
10	potential_supply	number of existing helipads and petrol stations	6%

Area of Expertise	Years of Experience	α:	CR: Consistency Ratio	Scale
Alternative fuels	1	0.1	7%	1

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	pop_density	median_income	A	2
1	3	pop_density	office_rent_price	A	3
1	4	pop_density	jobs_density	B	2
1	5	pop_density	noise	A	1
1	6	pop_density	POI_attraction	B	2
1	7	pop_density	transport_node	B	2
1	8	pop_density	xtreme_commuter	B	1
2	3	median_income	office_rent_price	A	3
2	4	median_income	jobs_density	B	2
2	5	median_income	noise	A	2
2	6	median_income	POI_attraction	B	2
2	7	median_income	transport_node	B	3
2	8	median_income	xtreme_commuter	B	3
3	4	office_rent_price	jobs_density	B	3
3	5	office_rent_price	noise	B	2
3	6	office_rent_price	POI_attraction	B	3
3	7	office_rent_price	transport_node	B	3
3	8	office_rent_price	xtreme_commuter	B	1
4	5	job_density	noise	A	2
4	6	job_density	POI_attraction	B	3
4	7	job_density	transport_node	B	2
4	8	job_density	xtreme_commuter	A	2
5	6	noise	POI_attraction	B	2
5	7	noise	transport_node	B	3
5	8	noise	xtreme_commuter	B	3
6	7	POI_attraction	transport_node	B	3
6	8	POI_attraction	xtreme_commuter	A	2
7	8	transport_node	xtreme_commuter	A	2
1	9	pop_density	transport_cost	B	2
1	10	pop_density	potential_supply	A	2
2	9	median_income	transport_cost	B	2
2	10	median_income	potential_supply	B	1
3	9	office_rent_price	transport_cost	B	2
3	10	office_rent_price	potential_supply	B	2
4	9	job_density	transport_cost	A	1
4	10	job_density	potential_supply	A	2
5	9	noise	transport_cost	B	2
5	10	noise	potential_supply	B	2
6	9	POI_attraction	transport_cost	A	3
6	10	POI_attraction	potential_supply	A	2
7	9	transport_node	transport_cost	A	3
7	10	transport_node	potential_supply	A	3
8	9	xtreme_commuter	transport_cost	B	4
8	10	xtreme_commuter	potential_supply	A	2
9	10	transport_cost	potential_supply	A	2

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

2,4,6,8 can be used to express intermediate values

participant_12-In12

(1) Final Response from Participant 12

http://bpmsg.com AHP 14/05/2018

AHP Analytic Hierarchy Process n= 10 Input 1

Objective: 0

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	pop_density	population density of a particular area	9%
2	median_income	median income of the population living in a particular area	8%
3	office_rent_price	interpolated rent price of office in a particular area	9%
4	jobs_density	number of jobs available in a particular area	10%
5	noise	existing noise level	4%
6	POI_attraction	most visited places by tourist	13%
7	transport_node	major transport nodes (train stations, bus stations, airports, and ferry)	9%
8	xtreme_commuter	number of commuters who travel more than 90 minutes	14%
9	transport_cost	average total cost of household transportation of a certain population	9%
10	potential_supply	number of existing helipads and petrol stations	15%

Area of expertise	Years of Experience	α:	CR: Consistency Ratio	Scale
transport modelling	0.5	0.1	7%	1

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	pop_density	median_income	B	2
1	3	pop_density	office_rent_price	B	2
1	4	pop_density	jobs_density	B	1
1	5	pop_density	noise	A	3
1	6	pop_density	POI_attraction	B	1
1	7	pop_density	transport_node	A	1
1	8	pop_density	xtreme_commuter	B	2
2	3	median_income	office_rent_price	B	1
2	4	median_income	jobs_density	B	2
2	5	median_income	noise	A	3
2	6	median_income	POI_attraction	B	2
2	7	median_income	transport_node	B	2
2	8	median_income	xtreme_commuter	B	3
3	4	office_rent_price	jobs_density	A	2
3	5	office_rent_price	noise	A	3
3	6	office_rent_price	POI_attraction	B	2
3	7	office_rent_price	transport_node	B	1
3	8	office_rent_price	xtreme_commuter	B	2
4	5	job_density	noise	A	3
4	6	job_density	POI_attraction	B	2
4	7	job_density	transport_node	A	2
4	8	job_density	xtreme_commuter	A	1
5	6	noise	POI_attraction	B	2
5	7	noise	transport_node	B	2
5	8	noise	xtreme_commuter	B	2
6	7	POI_attraction	transport_node	A	2
6	8	POI_attraction	xtreme_commuter	A	1
7	8	transport_node	xtreme_commuter	B	1
1	9	pop_density	transport_cost	B	2
1	10	pop_density	potential_supply	A	2
2	9	median_income	transport_cost	B	1
2	10	median_income	potential_supply	B	2
3	9	office_rent_price	transport_cost	B	2
3	10	office_rent_price	potential_supply	B	2
4	9	job_density	transport_cost	A	2
4	10	job_density	potential_supply	B	3
5	9	noise	transport_cost	B	2
5	10	noise	potential_supply	B	3
6	9	POI_attraction	transport_cost	A	2
6	10	POI_attraction	potential_supply	B	2
7	9	transport_node	transport_cost	A	1
7	10	transport_node	potential_supply	B	2
8	9	xtreme_commuter	transport_cost	A	2
8	10	xtreme_commuter	potential_supply	A	1
9	10	transport_cost	potential_supply	B	1

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,6,8 can be used to express intermediate values		

participant_13-In13

(m) Final Response from Participant 13

http://bpmsg.com AHP 26/03/2018

AHP Analytic Hierarchy Process **(EVM multiple inputs)**

K. D. Goepel Version 11.10.2017 Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	10	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	13	Number of Participants (1 to 20)	α:	0.1	Consensus: 58.1%
p=	0	selected Participant (0=consol.)	2	7	Consolidated

Objective

Author

Date Thresh: 1E-07 Iterations: 2 EVM check: 6.3E-08

Table

	Criterion	Comment	Weights	Rk
1	pop_density		6.5%	10
2	median_income		9.0%	6
3	office_rent_price		9.5%	5
4	jobs_density		9.9%	3
5	noise		7.6%	8
6	POI_attraction		12.3%	2
7	transport_node		19.4%	1
8	xtreme_commuter		9.5%	4
9	transport_cost	for 9&10 unprotect the input sheets and expand the	9.0%	7
10	potential_supply	question section ("+" in row 66)	7.2%	9

Result

Eigenvalue		lambda:	10.122
Consistency Ratio	0.37 GCI: 0.03	CR:	0.9%

Matrix

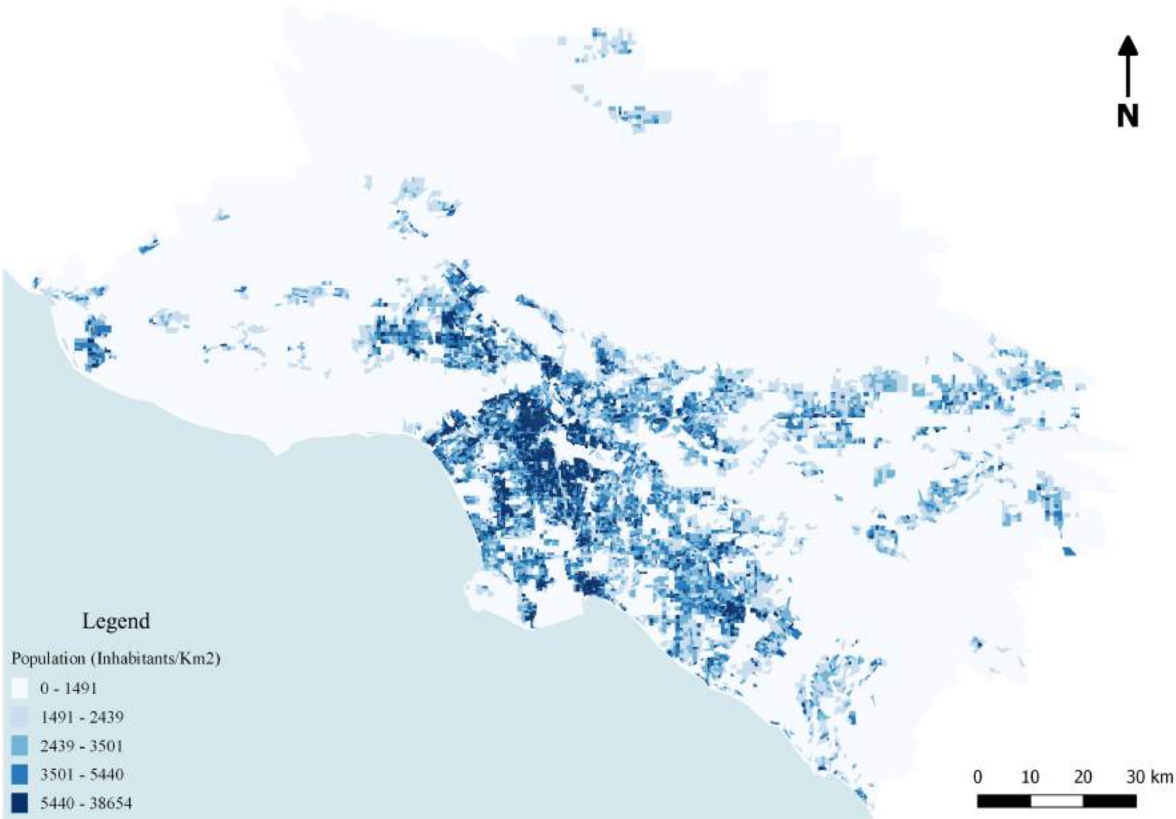
		pop_density 1	median_income 2	office_rent_price 3	jobs_density 4	noise 5	POI_attraction 6	transport_node 7	xtreme_commuter 8	transport_cost 9	potential_supply 10	normalized principal Eigenvector
pop_density	1	-	0.53	0.65	0.55	1.02	0.47	0.40	0.78	0.76	1.06	6.52%
median_income	2	1.90	-	0.91	0.76	1.22	0.70	0.42	0.82	1.12	1.39	9.05%
office_rent_price	3	1.54	1.10	-	1.36	1.52	0.86	0.42	0.77	0.81	1.10	9.46%
jobs_density	4	1.83	1.31	0.74	-	1.21	0.68	0.47	1.29	1.27	1.30	9.93%
noise	5	0.98	0.82	0.66	0.83	-	0.62	0.40	1.02	1.11	0.89	7.64%
POI_attraction	6	2.14	1.43	1.17	1.48	1.63	-	0.54	1.22	1.66	1.39	12.27%
transport_node	7	2.51	2.39	2.40	2.14	2.52	1.86	-	1.81	1.81	2.66	19.37%
xtreme_commuter	8	1.29	1.22	1.29	0.77	0.98	0.82	0.55	-	0.93	1.49	9.52%
transport_cost	9	1.32	0.90	1.23	0.79	0.90	0.60	0.55	1.07	-	1.53	9.03%
potential_supply	10	0.94	0.72	0.91	0.77	1.12	0.72	0.38	0.67	0.66	-	7.22%

by K. Goepel AHPcalc-2017-10-11 - Kopie-Summary

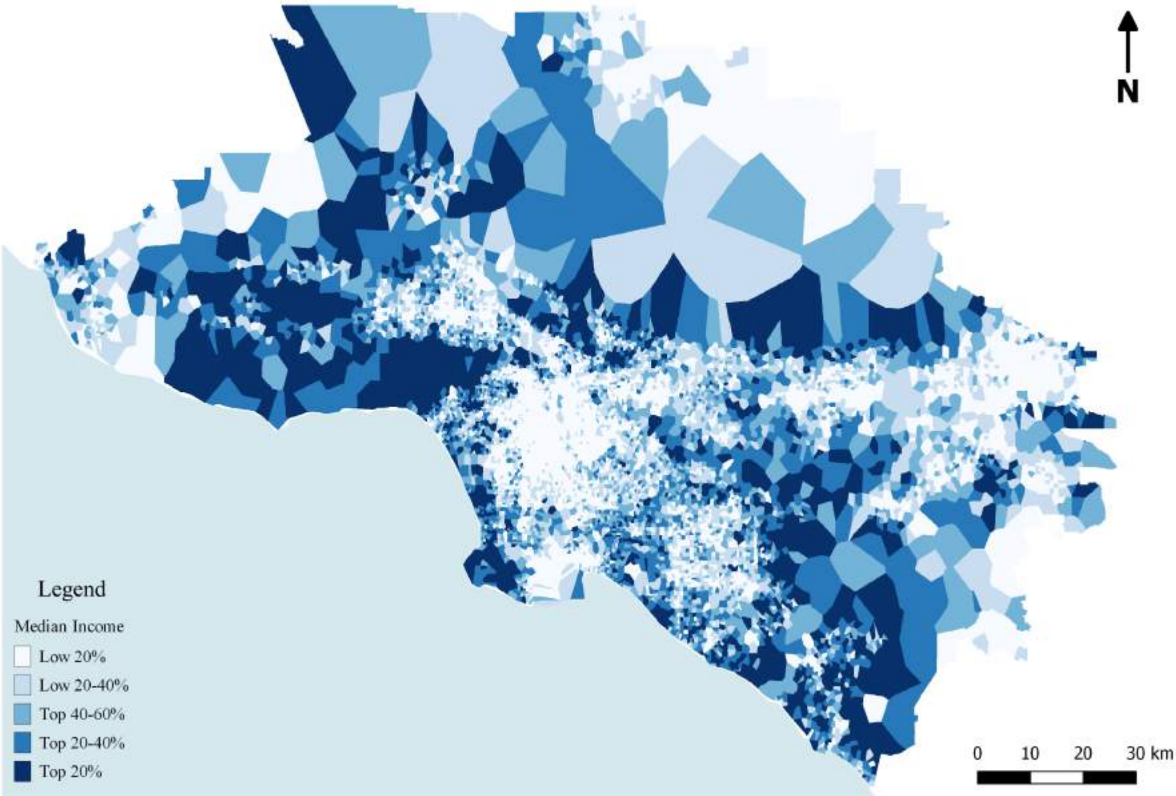
(n) Final Response from All Experts

Appendix B

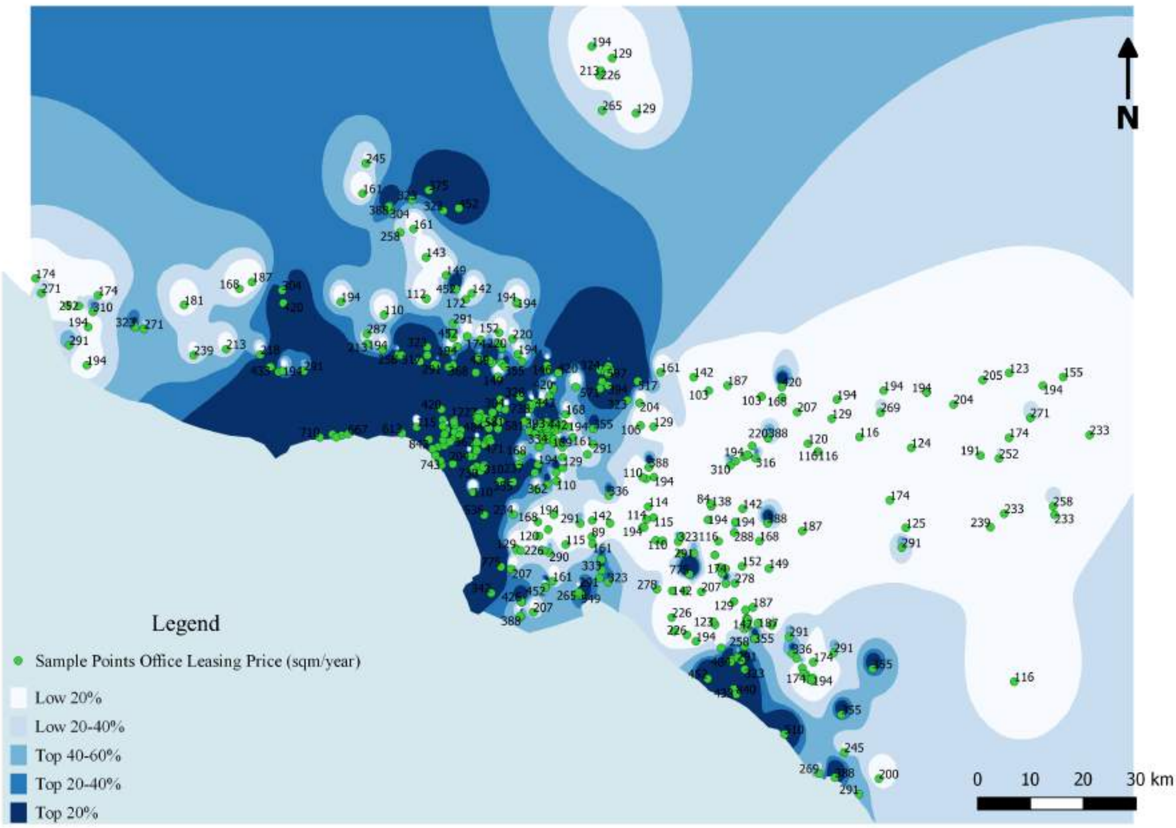
Maps of Case Study: Los Angeles



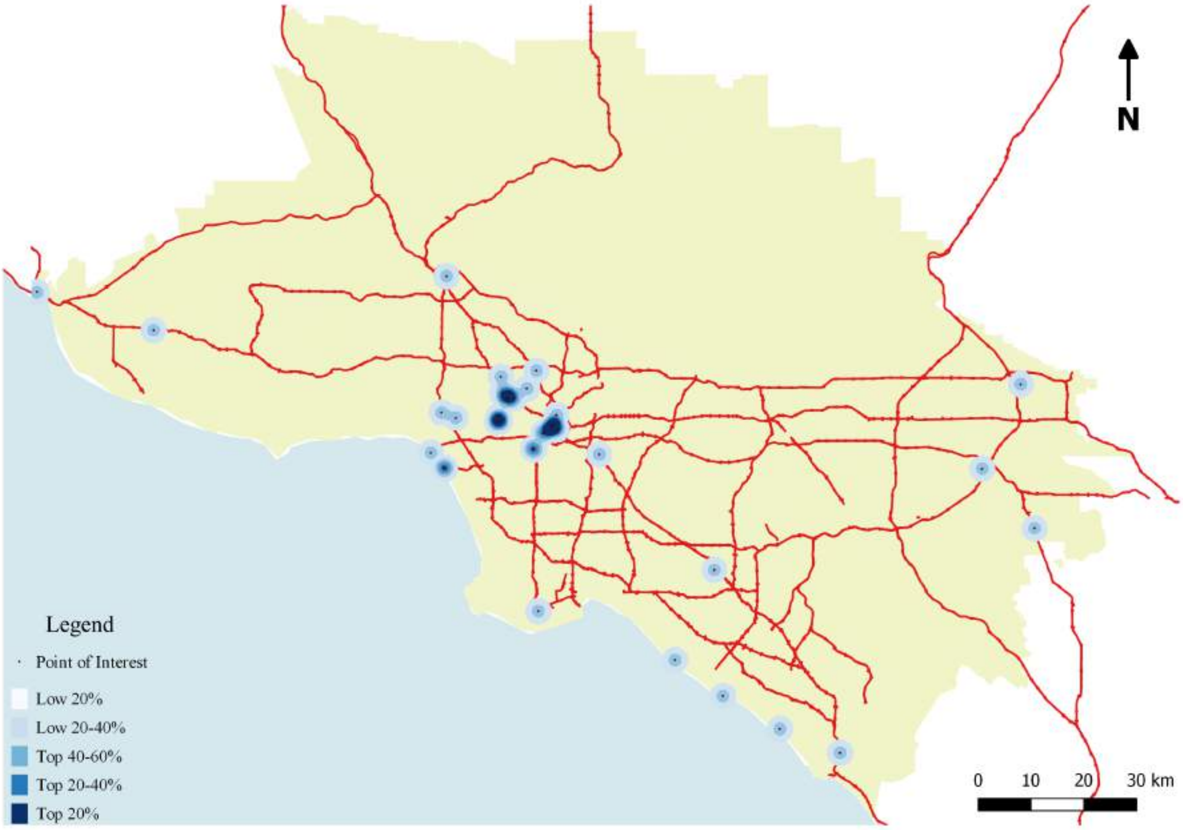
(a) Population Density



(b) Median Income

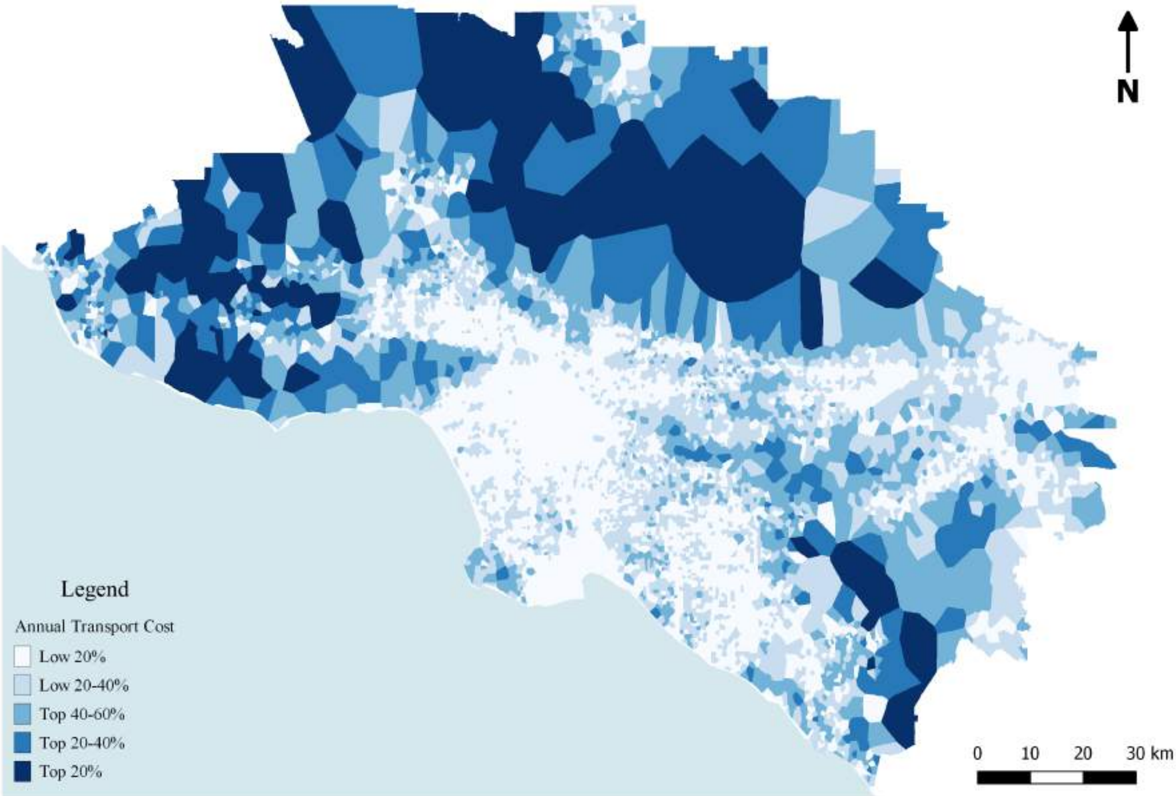


(c) Office Rent Price

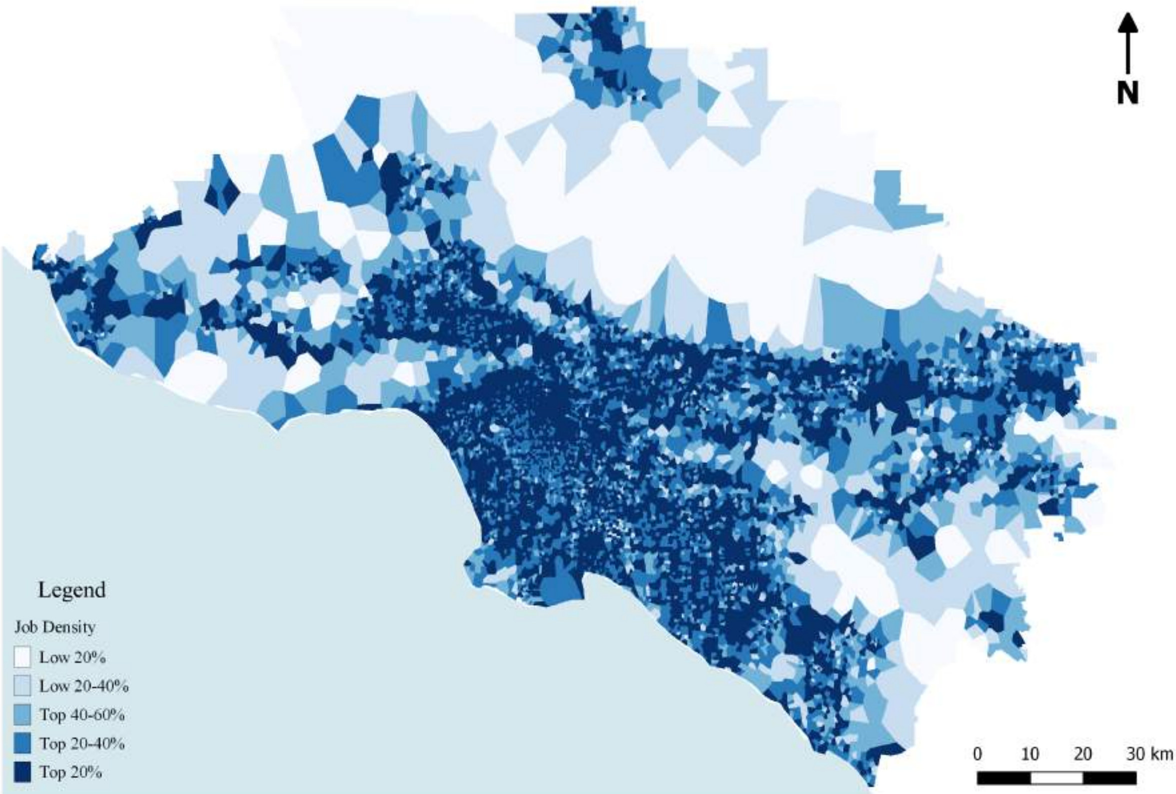


(d) Point Of Interest

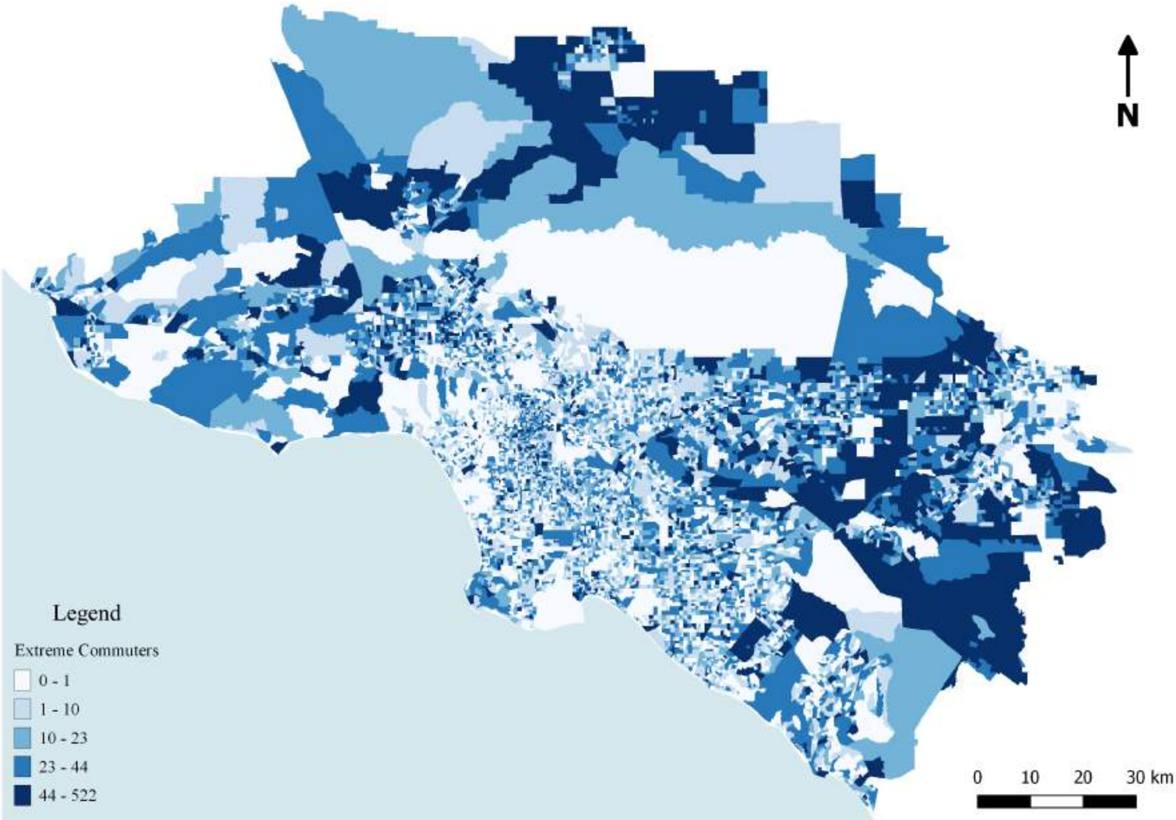
(e) Major Transport Node



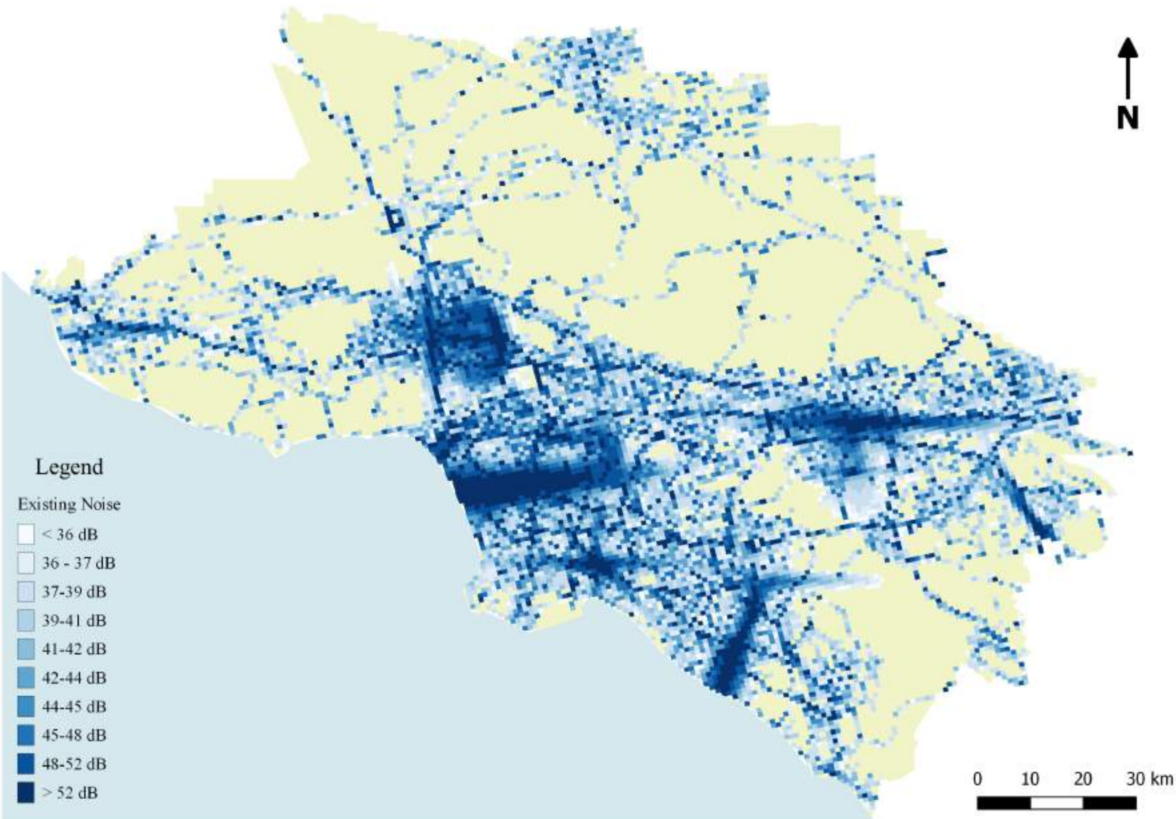
(f) Transport Cost



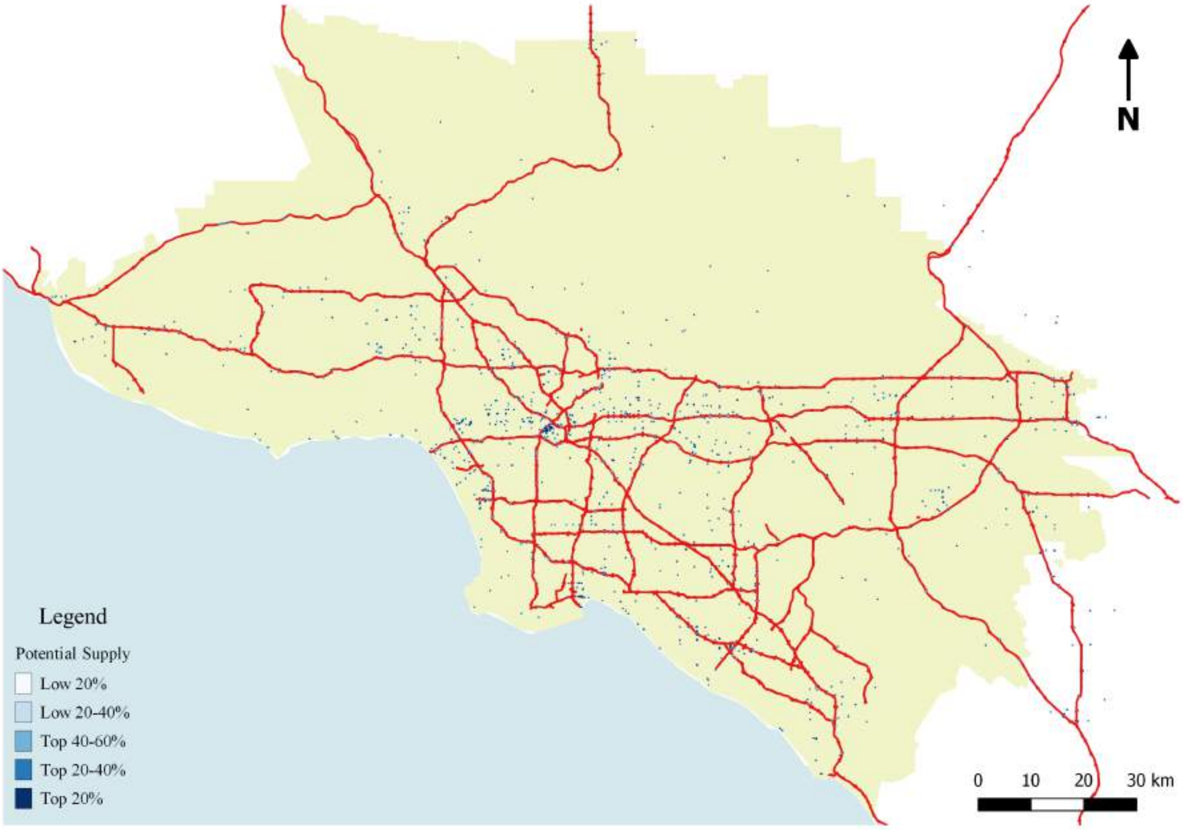
(g) Job Density



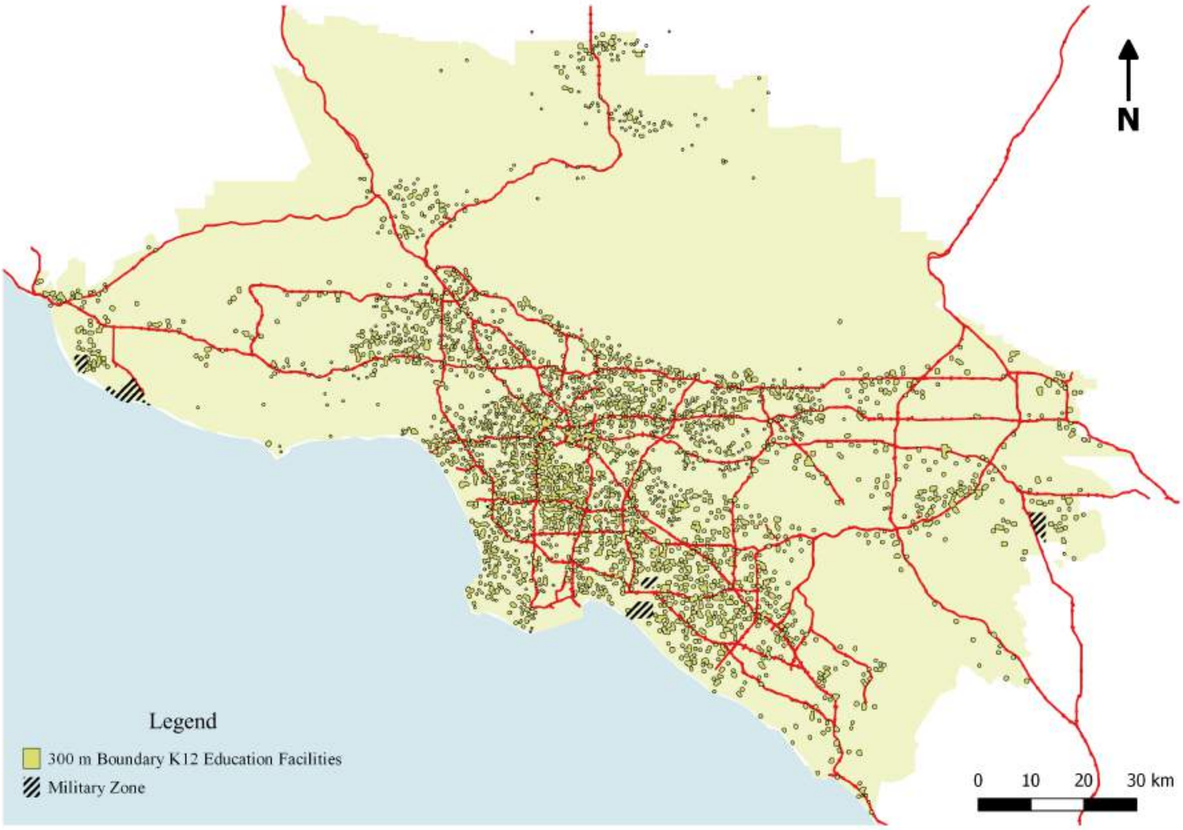
(h) Extreme Commuters



(i) Existing Noise



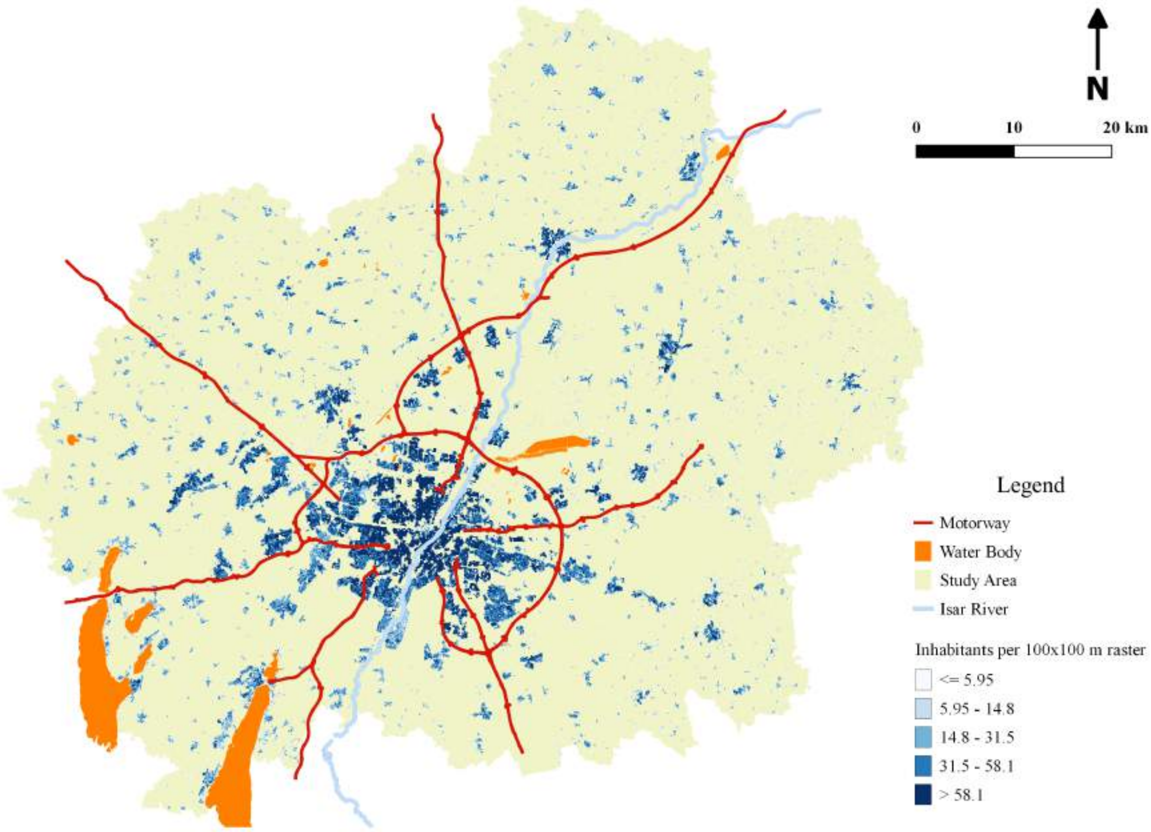
(j) Potential Supply



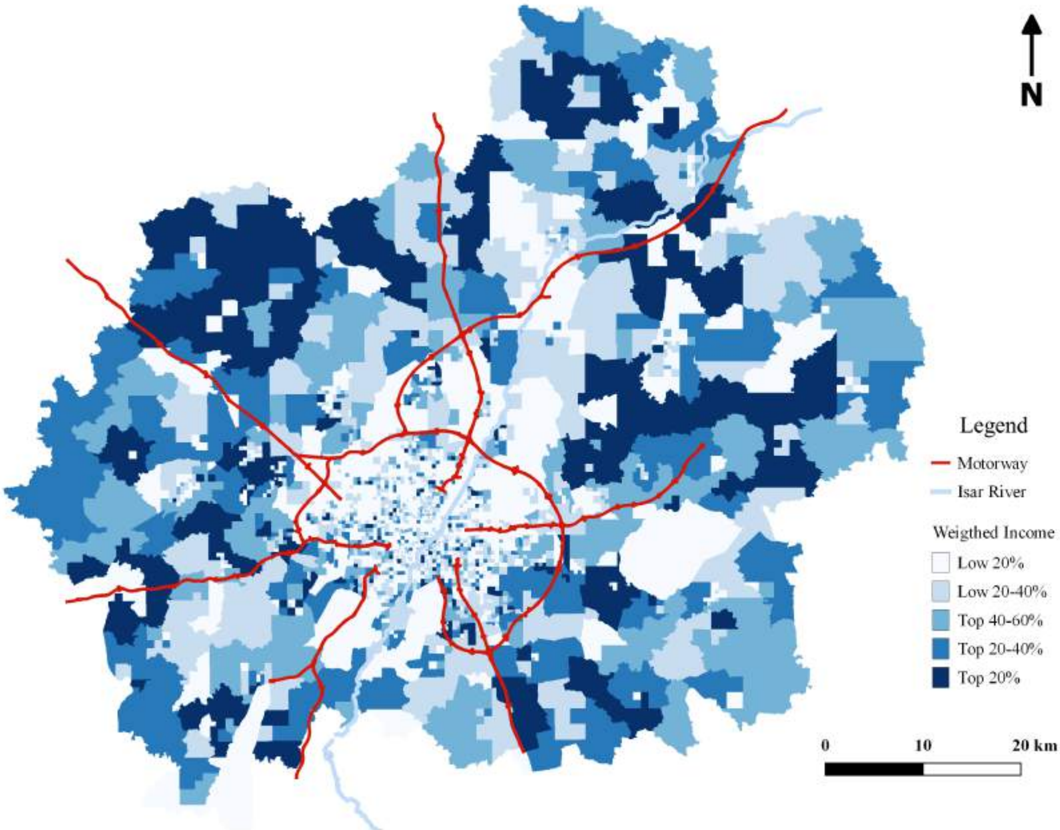
(k) Binary Consideration

Appendix C

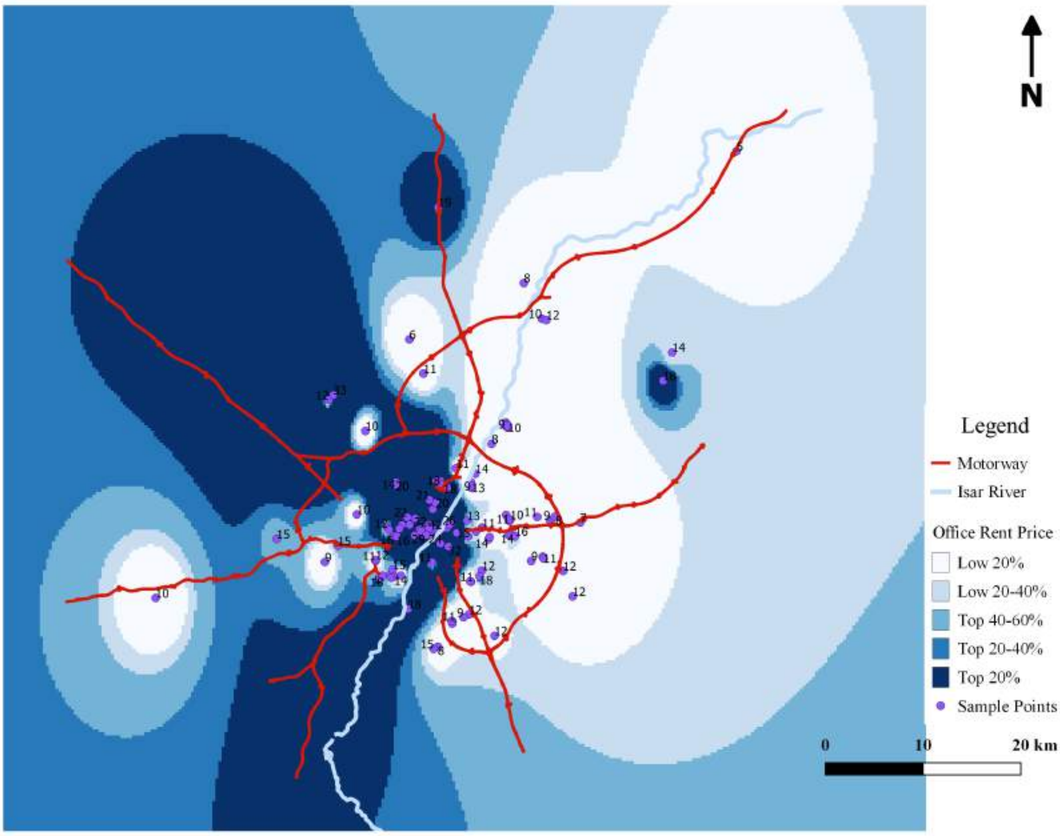
Maps of Case Study: Munich



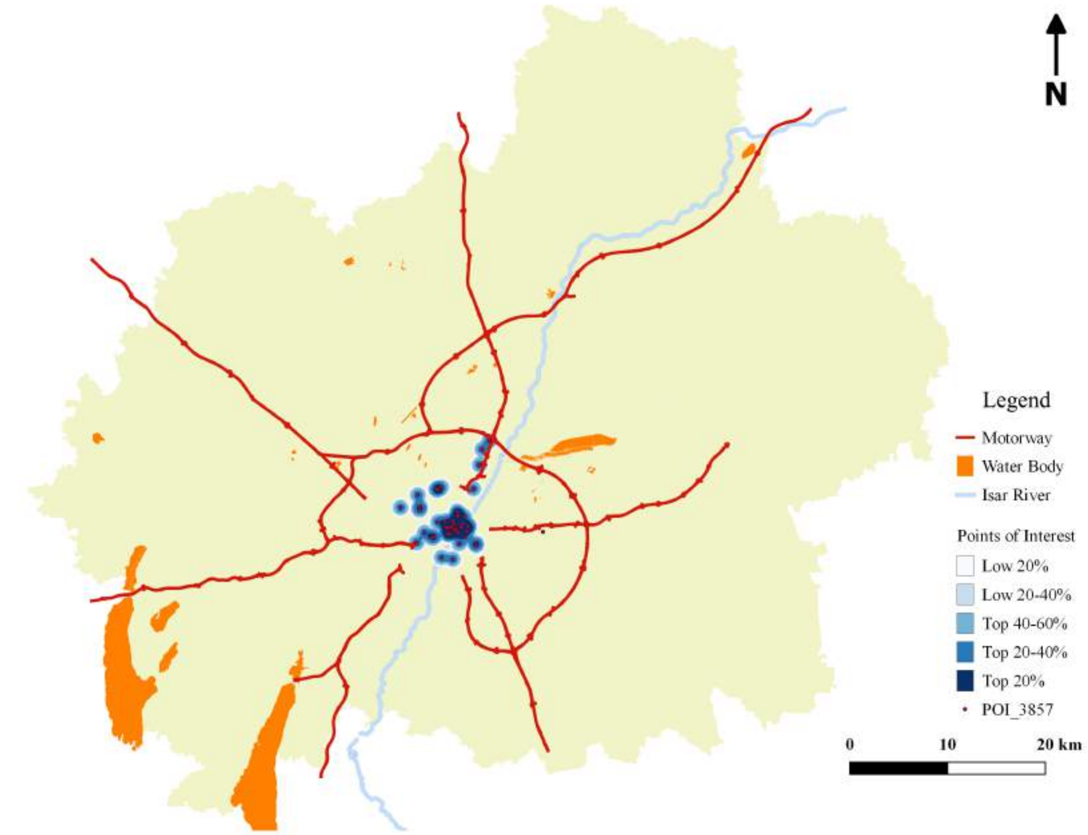
(a) Population Density



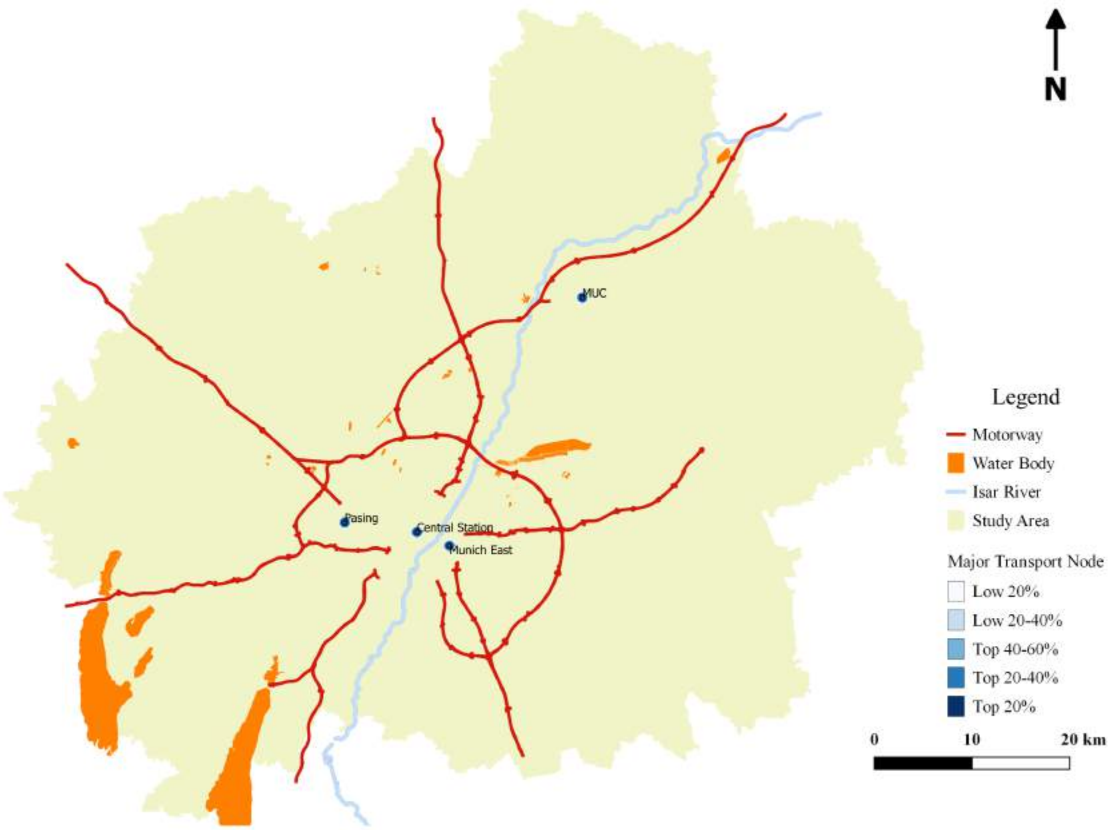
(b) Median Income



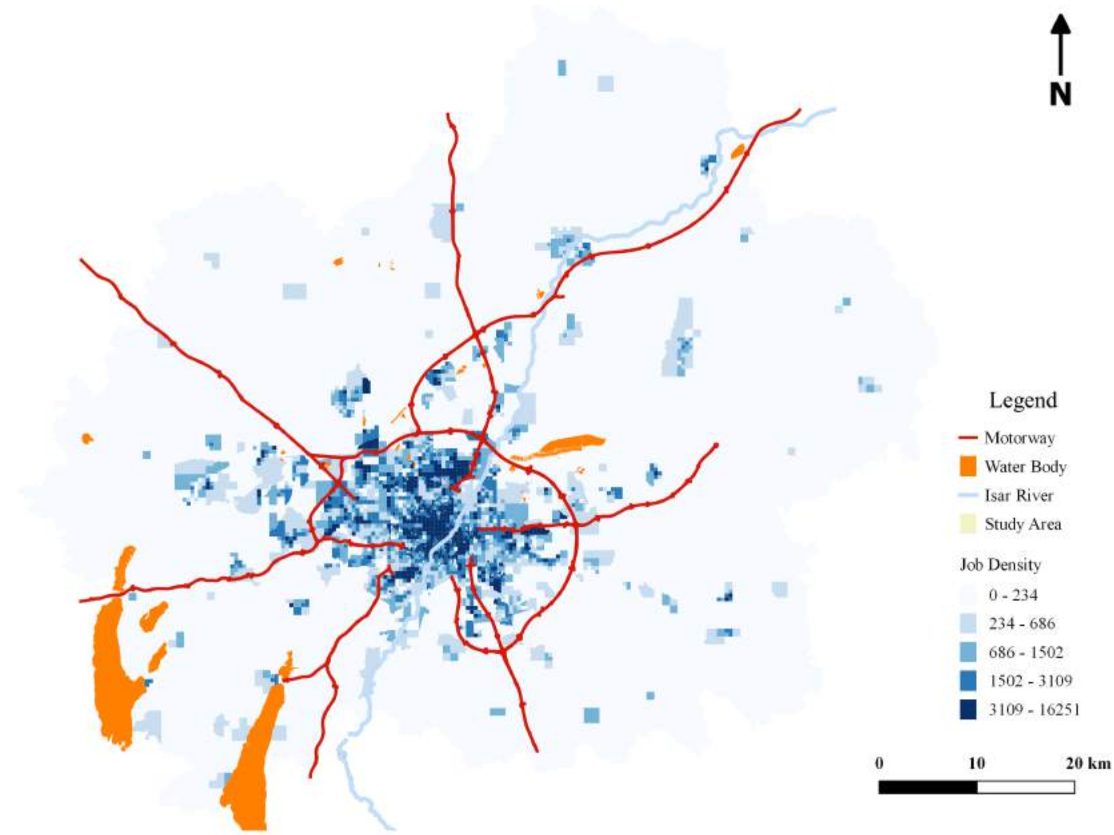
(c) Office Rent Price



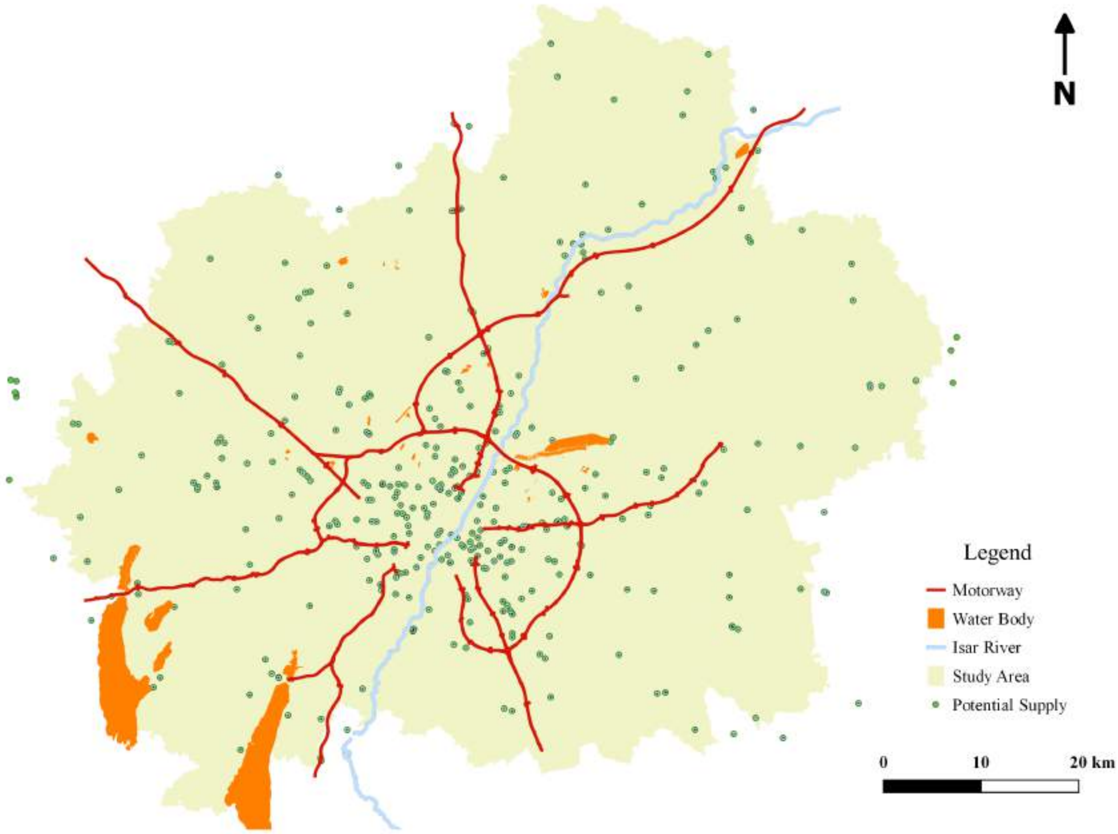
(d) Point Of Interest



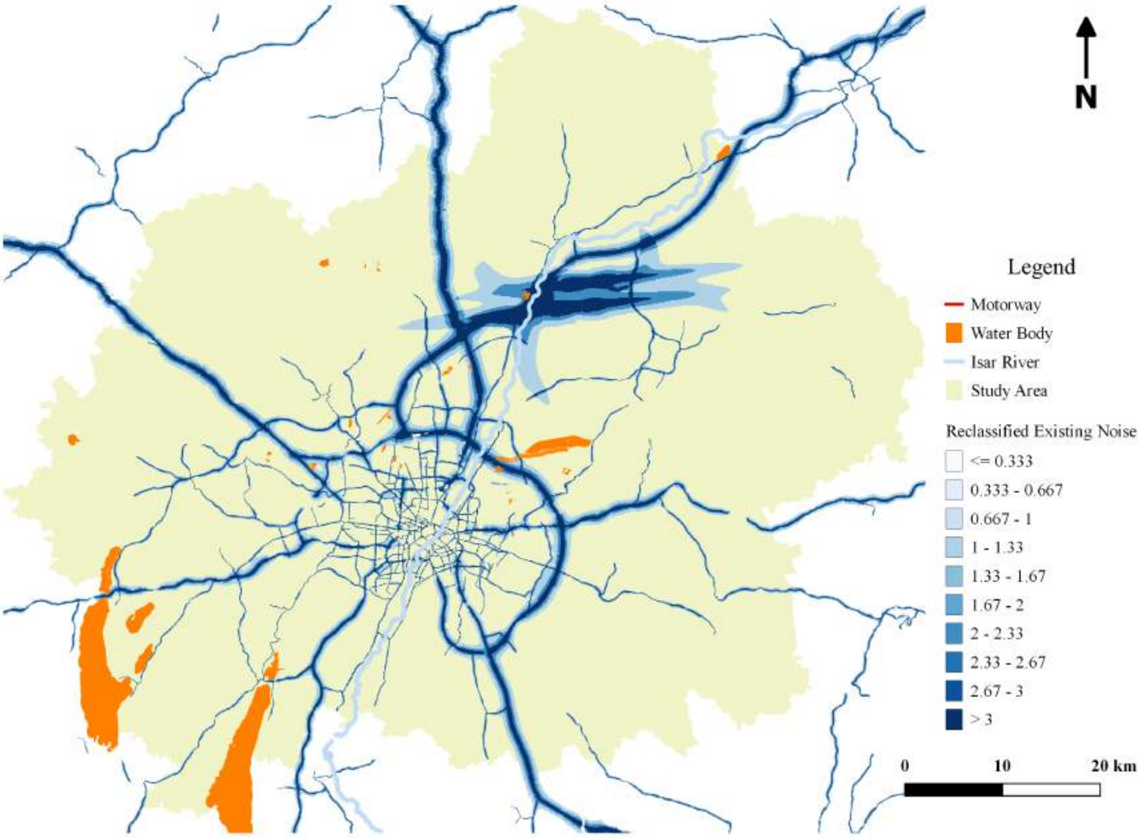
(e) Major Transport Node



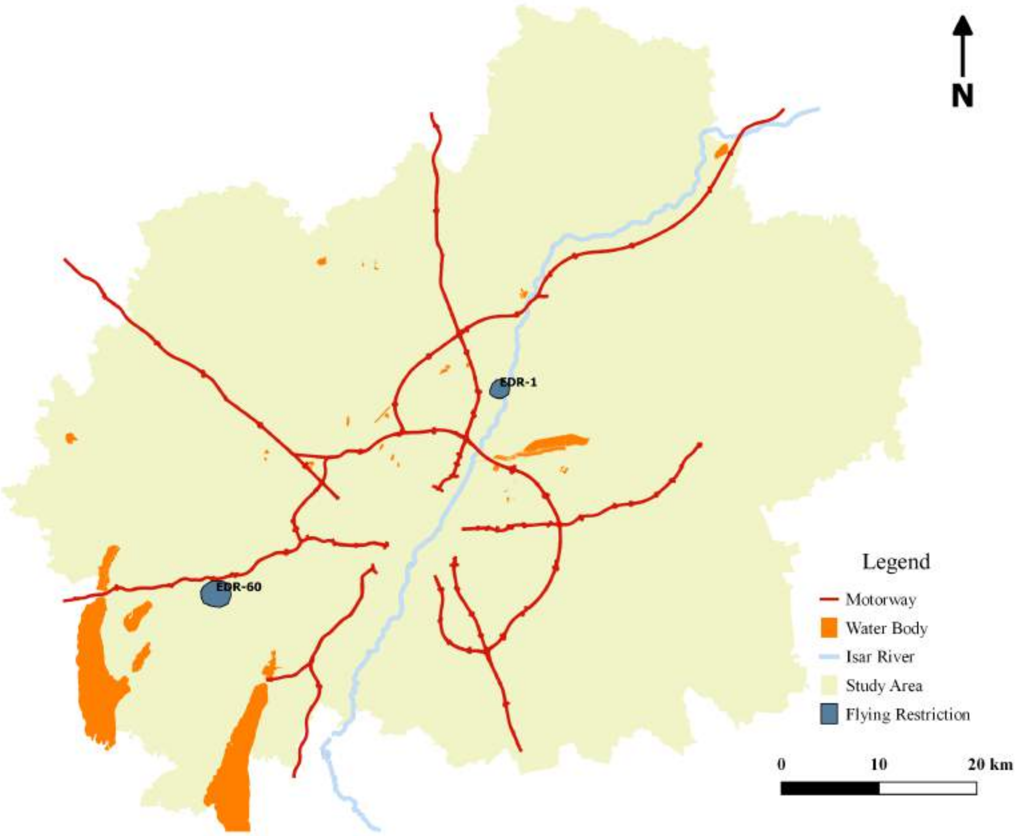
(f) Job Density



(g) Potential Supply



(h) Existing Noise



(i) Binary Consideration

Appendix D

List of Point Interest

Marienplatz	Friedensengel	Hubertusbrunnen
Asamkirche	Isator	Kurt Eisner Monument
Eisbachwelle	Maxmilianeum	Alte Muenze Muenchen
BMW Zentrum	Karlsplatz	Maria Hilf Kirche
Allianz Arena	Siegestor	St. Johannes der Taeufe
Schloss Nymphenburg	Gasteig	St. Markus Kirche
Peterskirhce	Sendlinger Tor	Nordfriedhof
Olympiapark	LMU	Westfriedhof
Olympiaturm	MOC	Sankt Ruppert Kirche
Koenigsplatz	Wittelsbacherplatz	Heidehaus
Bavaria Statue	Herz-Jesu-Kirche	Luitpold Bruecke
Maxmillianstr	Klosterkirche St. Anna	Brudermuehlbrücke
Altes Rathaus	Monopteros	TonHalle
Hofbraeuhaus	Gruenwalder Stadion	Theresienwiese
Max-Joseph-platz	Kultfabrik	Messestadt
Odeonsplatz	Promenadeplatz	Audi Dome
Justizpalast	Spaten Brauerei	

Table D.1: List of Point of Interest in Munich

The Getty Center	Pantages Theatre
Universal Studios Hollywood	Japanese American National Museum
Griffith Observatory	Venice Beach
The Nethercutt Collection	The Hollywood Museum
California Science Center	Los Angeles County Museum of Art
Walt Disney Concert Hall	Disneyland Park (Anaheim)
Petersen Automotive Museum	Heisler Park & Laguna Beach
Staples Center	Mission San Juan Capistrano (San Juan Capistrano)
Santa Monica Bay	Balboa Pier
The Broad	Huntington Beach
Battleship USS Iowa BB-61	Original McDonald's Site and Museum
Natural History Museum of Los Angeles County	March Field Air Museum
Hollywood Bowl Museum	Mission Inn Museum
La Brea Tar Pits and Museum	Camarillo Premium Outlets (Camarillo)
The Grove	Mission San Buenaventura (Ventura)
Runyon Canyon Park	Cathedral of Our Lady of the Angels
University of California, Los Angeles (UCLA)	Citadel Outlets
Venice Canals Walkway	Bradbury Building
Autry Museum of the American West	The Grammy Museum
Dodger Stadium	Madame Tussauds Hollywood

Table D.2: List of Point of Interest in Los Angeles