William Roberto de Paiva

Droneways: building new paths in the skies

Limeira/SP

2021

UNIVERSITY OF CAMPINAS
School of Technology

William Roberto de Paiva

Droneways: building new paths in the skies

Thesis presented to the School of Technology from University of Campinas as part of the requirements to obtain the title of Ph.D. in Technology, on the Information Systems and Communication Research area.

Supervisor: Prof. Dr. André Franceschi de Angelis
Co-supervisor: Regina Lúcia de Oliveira Moraes

This document is the final version of the Ph.D. Thesis presented by William Roberto de Paiva and supervised by Ph.D. André Franceschi de Angelis.

Limeira/SP
2021

Abstract

Several companies are looking for a way to use drones for delivery, but as they seek for efficiency of the operation, personal privacy and safety issues emerge, as drones are usually collect data with sensors and cameras, and are failure prone, which may lead to an accident. This work proposes the droneways: drones airways designed over a city selected subset of streets, aiming to offer a balance between convenience for the drones to fly, and an acceptable level of personal privacy and safety. Two different heuristics to create droneways over street maps modelled as graphs were tested: the Fishbone and Spiderweb. The heuristics were applied on the maps from three locations: the Manhattan borough, U.S.A; the city of Paris, France; and the city of Uruapan, Mexico. The Spiderweb heuristic has provided more efficient droneways than the Fishbone ones for all locations, with a better coverage/efficiency ratio in most cases. The proposed structure can make it easier to guarantee personal privacy and safety, as it would be smaller than the entire street map, requiring less effort to manage and control it. This work also opens news possibilities to solve the problem that companies are facing to use delivery drones in urban areas, providing guidelines to implement efficient paths for them to fly.

Keywords: droneways, drones airways, efficient paths, complex networks, UAV, delivery drones

Resumo

Várias empresas estão procurando por formas de utilizar drones para entregas, mas enquanto seu foco é na efiência na operação, problemas de privacidade segurança das pessoas envolvidas emergem neste cenário. Drones podem coletar dados privados com sensores e câmeras, e são propensos a falhas, o que pode levar a um acidente. Este trabalho propõe as droneways: vias aéreas para drones, projetadas sobre ruas selecionadas em mapas de cidades, buscando oferecer um equilíbrio entre conveniência na operação dos drones e um nível aceitável de privacidade pessoal e segurança. Mapeando as ruas em grafos, duas heurísticas diferentes foram testadas para criar as droneways: A Fishbone, lembrando o formato de uma espinha de peixe, e a Spiderweb, lembrando o formato de uma teia de aranha. As heurísticas foram aplicadas nos mapas de três localidades: o bairro de Manhattan, nos E.U.A.; a cidade de Paris, na França; e a cidade de Uruapan, no México. A heurística Spiderweb entregou droneways mais eficientes que as criadas utilizando a Fishbone para todas as localidades, com uma melhor razão de cobertura/efficiência na maioria dos casos. A estrutura proposta pode ajudar a garantir privacidade e segurança pessoal, já que será menor que o conjunto completo de ruas de uma cidade, exigindo menos esforço para administrá-la e controlá-la. Este trabalho abre novas possibilidades para resolver o problema enfrentado pelas empresas para implementar entregas com drones em áreas urbanas, provendo diretrizes para criar caminhos eficientes para o vôo dos drones.

Palavras-Chave*: droneways, vias para drones, caminhos eficientes, redes complexas, drones entregadores*

Contents

This thesis is dedicated to her. She used her time doing things I should do, so I had time do this work. I freaked out uncountable times, and she was always there to encourage me.

To my lovely wife,

Ana Paula

Acknowledgements

First, I would like to sincerely thank my adviser, André, for all the help, advices, red pen scribbles and patience. I hope someday I'll be as awesome as he is.

I also want to thank my co-adviser, Regina, for all the feedback and the time she has dedicated to help me.

I want to thank my parents, who have supported me my entire life to get here. In return, I gave them headaches.

To all my friends, thank you for pushing the problems away sometimes.

I wish to thank my dog, Roger, who always remembers me to enjoy the little things, like bouncing balls.

Thank you Lord, for the persistence You gave me to keep trying over and over.

"This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001".

List of Figures

List of Tables

Glossary

ANAC: Agência Nacional de Aviação Civil (Brazilian National Civil Aviation Agency).

Betweenness: in a graph, this is a metric which represent the fraction of shortest paths which crosses a given node.

Complex Network: network in wihch the nodes may have different degree among them, commonly used to represent networks and systems.

Random Network: complex network in which the probability of an edge between any pair of nodes is uniform.

Scale-Free Network (Barabási-Albert Model): the Scale-Free network has as striking feature its node degree distribution, which follows a power law. There are many nodes having few edges and few nodes having many edges.

Small-World Network: complex network in which its diameter is relatively small for its size, i.e., starting from a random node it is possible to reach any other node using a few number of steps.

Distance: see Shortest-Path.

EASA: European Union Aviation Safety Agency.

Edge: it is a relationship, a connection between two graph nodes. Edges can be weighted, each one having a different value representing the connection intensity; or simple, when all of them have the same weight.

Arc: directed edge in a graph, i.e., an edge which has defined source and target.

Efficiency: is a measure of how efficiently the network exchanges information.

FAA: Federal Aviation Administration of the United States of America.

Geodesic Path: see Shortest-Path.

Graph Diameter: length of the longest geodesic path between any two nodes, considering only the nodes which have a path between them.

Graph: a node set, in which the nodes can be linked between each other using edges. It can also be referenced as simple graph.

Directed Graph: a graph which has arcs.

Weighted Graph: a graph which has weights on its edges.

Hub: complex network node which has a large number of edges related to the edges average in the network.

Neighbour: when a node is linked to an edge, the node in the other end is called its neighbour.

Node Centrality: it is how much a node is centered in a graph related to the path that crosses it. Some centrality metrics are Clustering Coefficient, Betweenness and Closeness.

Node Degree: number of neighbours for a given node.

In-Degree: in a directed graph, it is the number of arcs whose reach a target node.

Out-Degree: in a directed graph, it is the number of arcs departing from a source node.

Node: an element from a complex network.

Order: number of nodes of a complex network.

Path: a sequence of nodes which has an edge between a node and the next one on the sequence. In an undirected graph, a path can be followed in both directions, while in directed graphs the path follows the source and target of the arcs on it.

Shortest-Path: it is the path between any pair of nodes in which the edges weight sum to reach each other is the lowest one. When there is no path between the nodes, the path length is treated as infinite.

Size: number of edges of a complex network.

UAV: Unmanned Aicraft Vehicle. Also called as drone.

Vertex: see Node.

VLOS: Visual Line of Sight, when is necessary to keep a UAV under direct visual line of sight from the pilot, without using third parties or cameras to do it.

BVLOS: Beyond Visual Line of Sight. It describes when the UAV is not directly visible to the pilot.

EVLOS: Extended Visual Line of Sight, when cameras or third parties are used to the pilot aware of the UAV position.

1 Introduction

The demand for delivery services has increased significantly in recent decades, mainly driven by online shopping. At the same time, consumers' wishes for fast deliveries has also increased. In order to satisfy the client needs and to be competitive, sellers require agility from the delivery companies, which in turn have to adapt and improve their logistics methods. As urban traffic is increasing every day, delaying ground vehicles, speed up deliveries is a challenge faced by those companies, that now seeks for alternative delivery means which could help solve this issue.

One of those alternatives is the use of Unmanned Aerial Vehicles (UAV) - *drones* from now on - to make deliveries. As many packages are small and lightweight, using a little drone to make the task by the air is a very attractive idea.

Drones are a recent technology, initially planned for military and specific applications. The fast development of this technology has driven the construction of light and cheap drones, suitable for individual usage, even in recreation or simple daily tasks. They are now commercially available from retail stores or e-commerce sites. General public is now paying attention to the drones, forecasting new daily applications.

Tests using drones for packages delivery are already being made by some companies, such as Google, Amazon, DHL and Walmart, just to mention few of them, but they are still making it in open areas, far from densely populated places (KHAN, 2018). The reason is that safety and privacy issues are still being discussed. A drone could fall from the sky and hit an object or a person, especially if it has a load. Usually UAV have cameras and/or microphones attached to guide themselves and get environmental information, allowing them to collect private pictures, videos, and conversations from people inside their homes.

Some of national authorities are developing a regulatory framework (European Union Aviation Safety Agency, 2021), but conflicts and inconsistencies are still present in these incipient regulations. For instance, there are operating limits according to the type, weight, and technology of the vehicles, making it difficult to push the frontiers. In some places, there are restrictions to the proximity of people not involved in the drone operation, written authorization requirement, or some sort of bureaucratic procedure to be followed (FLOREANO; WOOD, 2015). This set of restrictions, although being in a changing process, still prevents the hiring of drones for civilian tasks, such as packages delivery, when they need to fly close or over people.

Ensuring personal privacy and safety is going to be a challenge for companies, that will need to follow the rules while aiming to make the full operation efficient and economically viable.

In this work the *droneways* are proposed: air routes overlapping a strategically interconnected street map subset. Droneways are intended to use the smallest fraction of a given street map as its underlying structure, targeting efficient routing, lower costs, controlled conditions for autonomous navigation, risk and privacy issues reduction, and relaxing of hard restricting laws. In summary, droneways could make the autonomous drones feasible to the delivery service over populated areas while also considering the operation safety, security and personal privacy.

To use the droneways, a drone must fulfill some initial requirements, such as the management of fuel/battery levels required for the delivery, communication with the droneways control system, and an embedded GPS to follow the city map. Once the flight is approved, the drone will take off from its starting point. If this point is outside the droneways, it will fly over a common street using the minimal possible distance to the droneways. Once it is within the droneways, it will follow, without leaving it, using the shortest path until reach the closest point from the delivery address. Then, to finish the delivery, the drone leaves the droneways for the shortest time possible, still flying over the streets, finds the package destination, makes the delivery, and comes back to the droneways, becoming free to collect the next package or to find the closest recharging point.

The droneways operation can make use of many available technologies and tools for the system to reach its goals. The use of human crowd detection (TZELEPI; TEFAS, 2021), drone localization in a 3D space (SHARMA *et al.*, 2018), electronic sensors, implementation of a scheduling scheme, conflict avoidance methods, an emergency system, GPS usage and cell phone data are some of the technologies already being discussed for the use of autonomous delivery drones (DEVASIA; LEE, 2016; GHARIBI *et al.*, 2016). Additionally, signs and warning lights could be installed to help people know about drones operation, and a security team could be available to help with unpredictable setbacks.

One of the challenges to the implementation of delivery drones are the restriction rules. As already mentioned, these rules are still under development in most countries, and most of them do not allow the use of drones in populated areas. Despite this, as can be observed in the last 3 years since this research has started, these rules are evolving and being widely discussed by aviation agencies around the world, and in the next years drones will probably be flying in urban areas. The droneways can help to push the law enforcement, as it can help prevent several safety and privacy issues. As the droneways are expected to be an organized structure, they can also be used to speed up the weakening of restrictions.

To create the droneways samples, street maps were extracted as graphs from some selected locations around the world. Then, using two original developed graph coverage heuristics to find droneways resembling fishbone and spiderweb shapes, several configurations were obtained, covering different portions of these graphs. Finally, these droneways were compared by calculating their complex network efficiency, average path length and diameter. The main goal was to find the most efficient droneways, i.e., the ones having the shortest travelling paths for a given map coverage.

Although this work is focusing on a structure for delivery drones, other applications of this technology can take benefits from the droneways. It could be used for medical, traffic monitoring, ambulance and smart police drones. All these applications are already being tested (KHAN, 2018).

The proposed heuristics are based on two graph structures known for its high efficiency: the Fishbone, which resembles a backbone, and the Spiderweb, with a spider web like shape. The developed algorithms tries to find topologies similar to its heuristic shape, starting with few paths, increasing the coverage in each step.

As the drones will need to fly outside the droneways to finish the delivery, the distance and time that they will have to travel were also compared.

In summary, this work primarily seeks to find a balance. At one side, is the convenience for the drones, i.e., efficient paths, low cost flights and environmental benefits for them; at the other side, are the people involved, which needs to be kept safe during the operation and must not have their privacy violated. In second, given two heuristics to find droneways topologies, evaluate them to investigate which one provides the most balanced droneways.

The outer ways were shorter in the Fishbone resulting droneways, unlike the efficiency. However, considering the surplus average traveling distance that the drones would fly in these droneways and the metrics evaluated, the Spiderweb ones are suggested as the best choice in the selected case scenarios.

The droneways can cover up to 98% of the entire drones operation by using just 30% of the streets in Manhattan, one of the evaluated maps. This leads to reduced costs to build an infrastructure to inspect and control the drones operations. Therefore, stricter measures can be taken to ensure safety and privacy of the people involved

The droneways are the main contribution of this work, which provides an unprecedent concept to make efficient deliveries using drones while also considers personal safety and privacy. In addition to this, it proposes two heuristics, used to find efficient subgraphs on geographical complex networks, contributing to the fields of Graph and Complex Networks Theory. It provides new knowledge in urban topology and smart cities planning. Finally, it draws attention to the concerns regarding personal privacy and safety in face of emerging technologies.

This document is organized as follows: the Chapter 2 presents the Literature Review, in which works in the following matters are addressed: delivery drones prediction; personal privacy and safety concerns related to drones; incipient national rules from FAA, EASA and ANAC; and some references about Complex Networks. In the Chapter 3, Methodology, methods and procedures to extract and process the data are presented. Chapter 4 have the resulting droneways and their properties, together with the discussion of this work results. In Chapter 5 are the conclusions together with the recommendations for future works. At the end, the References can be found, followed by the Appendix, which presents data used to convert the maps into graphs and the resulting graphs pictures from all resulting droneways.

2 Literature Review

An examination of the literature to find related works was made and separated in the following four categories: drones in the near future, drones privacy and safety, drones regulations, and complex networks. For this literature scan, a search over the main scientific databases was done, restricting the publication date from 2015 until today, since the recent changes in regulations have guided the discussion in this issue. In the complex networks category, works about the concepts necessary to represent and find the droneways paths were reviewed.

2.1 Delivery Drones in the Near Future

The technical barriers which avoids package delivery by drones are getting more and more fragile (SCHNEIDER, 2020). Since January 1, 2020, airplanes and helicopters must broadcast their positions by radio. Although drones are not required to do this, they are being equipped with the ability to receive those radio signals, aiming to avoid collision with manned aircraft, i.e., drones are already being built keeping in mind that eventually they are going to share the airspace.

Khan (2018) has made a review on the emerging opportunities for drones in smart cities. For example, drones for real time traffic monitoring and analysis, in which they collect information about traffic and road accidents, being able to fly over the streets, avoiding collisions with other drones and tall buildings; self-flying autonomous taxi, able to carry a passenger weighting up to 100kg, a load very much higher than the expected for delivery drones at the start; ambulance drones, which can carry medications and medical equipment, reaching the scene of the accident sooner than a ground vehicle, being equipped with a defibrillator, camera, microphone and speaker, remotely operated by a paramedic, will probably need to fly beyond line of sight; at last, drones for package delivery, which have potential to carry a heavy payload, doing it autonomously and quickly.

Devasia and Lee (2016) propose the uNet, an UAV operation paradigm created to allow drones to fly beyond line-of-sight and without substantial human intervention. Their model is basically a set of sNets, which are regions in the airspace with predefined paths and a control structure for the UAVs to fly inside it. In Figure 1 a uNet consisting of four sNets is shown. Unlike the free-flight approach, in which the drones can freely fly in a delimited area, the uNets favours conflict avoidance, since it is easier to map obstacles in a predefined path than map the entire airspace. Each sNet controls the conflict avoidance and scheduling only for the drones inside its limits, allowing them to fly and switch between different height levels with a decoupling scheme on each edge of the network.

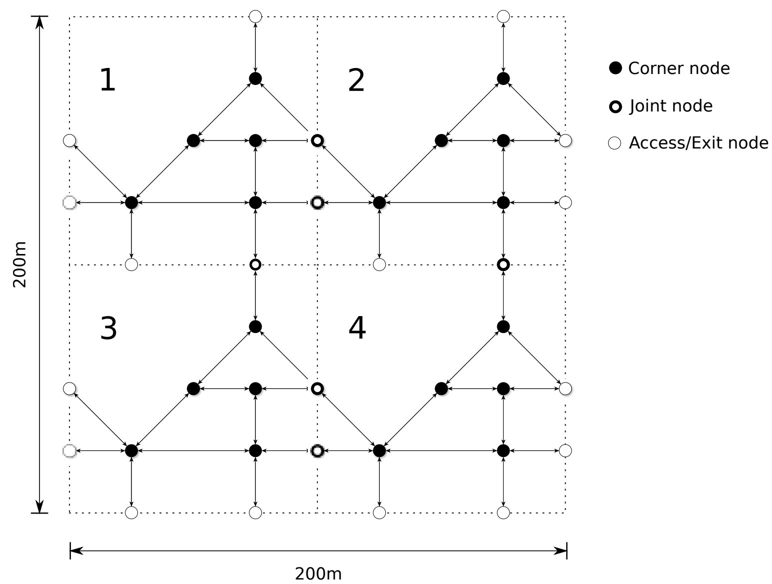


Figure 1 – Example uNet composed by 4 similar sNets (numbered sections). Source: Devasia and Lee (2016)

Another interesting idea highlighted by Devasia and Lee (2016) is that the routes can be dense and time-varying. In addition to optimize the flying against wind speed and precipitation, as pointed by the authors, the routes could change based on people density over the time of day. For example, during the night, in which usually there is less people in the streets, more paths can be used to optimize deliveries.

As both ideas are focused on city maps, the uNet can be used as the droneways underlying structure, bringing together all their advantages to this work's approach. The uNet paper is also an evidence that soon or later drones will be used for delivery in densely populated areas, emphasizing the importance of this research.

Gharibi *et al.* (2016) have proposed the Internet of Drones (IoD), a layered network control architecture designed to coordinate the access to airspace and to provide navigation services. This architecture is designed for free-flight, i.e., the drones are allowed to fly in an open area. The architecture is complex, and it is divided into four concepts: 1) structure, which describes the airspace using virtual routes, paths, intersections, zones and gates between the zones; 2) components, which includes the Zone Service Providers (ZSP), and the drones, both connected to the cloud to allow communication between them; 3) the layers, divided into application, service, end-to-end, node-to-node and airspace layer; 4) and cross-cutting features, in witch any feature needs to be implemented in several layers. The concept of zones, in witch locations, intersections and paths are defined, resembles a street map. Merging the IoD concept and the droneways seems to be a promising approach, where both could use the benefits of each other.

Choudhury *et al.* (2021) have proposed an algorithm for drones to use transit networks (buses and/or trams), allowing the UAV to conserve energy by landing at the vehicles roof until the closest stop from the delivery destination. The idea seems to be very promising. However, it limits the number of drones by the area available to land over the vehicles. Nevertheless, the goal of their work was the algorithm and logistics to use the vehicles ceilings as drone land stations, without worrying with the path outside the vehicles. Maybe merging the two ideas could be interesting, with the droneways defining a street topology for the drones to use them, and the transit network being used as landing stations when available.

2.2 Privacy and Safety Concerns

There are many concerns about personal privacy and safety that need to be addressed when thinking about drones in populated areas. Would people feel uncomfortable? Would a drone equipped with cameras and microphones violate someone's privacy? Is there a chance that a drone malfunction lead it to fall and hurt someone? Researches, authorities, and agencies around the world are already discussing these issues.

In his work, Aydin (2019) has evaluated the public acceptance, perception and knowledge of drones by regular people. With a sample of 153 participants, he made a survey to understand people awareness of applications, knowledge and perception of drones. He found that drones are constantly criticized, since the main source of knowledge from the people are mainstream news media and movie or television series, which emphasizes malicious uses of drones. Public is worried about government agencies monitoring the society with drones, package delivery to the wrong address, and about noise pollution with a large number of drones flying close to them. However, the people supports the use of drones for public safety and scientific research applications. In 2019, drones were seen as risky machines to kill, interrupt privacy or as toys for hobbyists, suggesting that actions are needed to show people the benefits of drones and what is being done to mitigate their problems.

Also evaluating people perception about drones, Zhu *et al.* (2020) have interviewed 1465 people, who have answered 13 questions addressing public risk beliefs about delivery drones. The results have shown again that people are worried about privacy and safety, as questions involving the drones malfunction damaging property or people worries more than 50% of the respondents, privacy violation worries around 30%, and only 7.6% responded that have no worries at all.

Uchidiuno *et al.* (2018) have made a survey on how people fear about their privacy related to drones and if the use of technologies to preserve the privacy would make them change their minds. Most of them think that the owner should provide information about the operation, the drone, and its purpose; the operator must be careful to where the drone is going to fly and how it would impact someone else's life; and the person himself / herself must be able to supervise the operation, guaranteeing their rights and their privacy. When asked about what type of technology would help them to feel more comfortable, most of the subjects have chosen a way to query a drone for its owner, purpose, and data being collected, using a smartphone, for example.

In their work, Hristozov and Shishkov (2020) discuss about Unmanned Traffic Management (UTM). The main problem highlighted by the authors is how to integrate it with manned aircraft. The solution perspectives they suggest are: 1) prioritize human safety in the sky; 2) an integrated air traffic system for UTM and manned aircraft; 3) an aircraft taxonomy for all flying objects; 4) explicit regulations; and 5) investigation and traceability mechanisms to enforce accountability for manned and unmanned aircraft. The droneways proposal may help on achieving all these solutions, as it is intended to be a controlled environment.

Agencies from several countries started to create rules to prevent safety and privacy issues (more detailed in the Section 2.3), but these rules are still being discussed, since there are divergent opinions on the subject. For example, Park and Lee (2017) have pointed that the regulations are mostly focused on defining technical aspects for drone operation, but it's not clear about invasion of privacy. The authors suggest a formula to define when privacy is invaded by a drone equipped with a camera by using the UK CCTV guidelines, which defines image resolution levels that allows the human eye to identify faces. They were able to calculate the minimum distance that a drone must be to not violate a personal privacy, depending on which camera it is using. A drone using a high definition camera (1080p), for example, should stay at least 30m away from people to guarantee their privacy.

The camera attached to the drone is only one of many available devices and sensors that raises concerns. There are other ways to use drones for malicious tasks, as discussed by Vattapparamban *et al.* (2016). The communication between the drone and its owner is an issue being studied, as most drone supplier companies are not focusing on safety yet. Techniques like de-authentication attacks and GPS spoofing can be used for attacker to gain control of a drone, which could contain private data. A malicious owner could use his drone to collect images, sound, and intercept wireless communications using the proper devices attached to the drone. The authors have reviewed some techniques to bring down unauthorized drones, such as other drones using net traps, trained eagles and net-launcher weapons. There is still a lot of work to be done to guarantee the safety, security and privacy, from both the citizens and the drones.

In order to improve drones flight safety, Tzelepi and Tefas (2021) have used deep learning to detect human crowds in pictures taken by drones. In a drone equipped with the right hardware for it, they could successfully detect human crowds at an average of 9 frames per second. As delivery drones in near future shall be flying over people, it is important to create mechanisms for human detection for drones to avoid flying over or go towards people in emergency cases.

As it is also expected that a large number of delivery drones would be flying at the same time, mechanisms to avoid collision between them an with other objects are important for the flight safety. Dentler *et al.* (2016) propose a real time obstacle avoidance with a model predictive control. Sharma *et al.* (2018) present a context-aware localization for drones, by placing sensors in buildings and providing communication among the drones, which builds their own Petri net model to share their coordinates with all others. Kumar *et al.* (2021) evaluate an avoidance collision system based on a Software-Defined Drone Network (SDDN) to help on traffic monitoring, connected to the Internet of Vehicles, making use of sensors across the road network and defining drone movement zones.

In the droneways, mechanisms could be installed to solve several issues. For example, proximity sensors combined with GPS could identify the drones in the droneways, and a smartphone app could be used for someone to query information about the drone and its owner. Detailed description about the droneways, as the paths they use, the companies using them, what they collect and how they use it, and the authorities responsible for the personal privacy and safety of the droneways could be provided online. As the droneways are going to partially overlap the map, it will be easier to identify unauthorized drones in the droneways paths. The drones are expected to be out of the droneways for a few seconds only to finish the delivery, as discussed in the Chapter 4, allowing someone to suspect of a drone flying at randomly over the streets.

2.3 Incipient national rules

In this subsection are presented the regulations for drones operation from three different agencies: The FAA - Federal Aviation Administration (2021), from United States of America, the EASA - European Union Aviation Safety Agency (2021), from Europe, and the ANAC - *Agência Nacional de Aviação Civil* (2021), from Brazil.

For easy explanation, the main directives that the three regulations have in common are summarized in the following list, divided in two categories: the complied ones, which does not affect the implementation of the droneways, and the challenging ones, which this work could help to achieve or could encourage changes and adaptations in the regulations so the droneways can become reality:

- Complied regulations:
  1. Do not fly over private properties;
  2. Fly at or below 400 feet (approximately 122 meters);
  3. Do not fly next to airports, helipads, areas affecting public safety or next to ongoing emergency effort;
  4. Do not fly over sensitive or protected sites;
  5. Yield the right of way to manned aircraft;
  6. Do not control the UAV from moving vehicles;
  7. Do not use the drone to carry dangerous goods.
- Challenging regulations:
  1. Keep the unmanned aircraft within visual line-of-sight (VLOS);
  2. Keep a safe distance from people, animals and other aircraft;
  3. Do not fly directly over people.

Starting by the complied regulations, as the droneways are planned to be implemented over a location street map, the drones will be allowed to fly only over the streets, not violating the 1st complied regulation. Even rivers or open areas are not included in the droneways proposal. Considering that a drone is working properly, it will not fly over private properties, protected sites or close to critical areas. The only possible issue is to fly over the private property of the delivery location (and nearby vicinity), which might be solved, for example, by asking the addressee to accept the drone to fly over there.

The droneways are expected to be created with landing areas and technology to guide and monitor the drones allowed to fly over it. If a drone start to gain altitude, the system could inform it to come down, or notify the rule violation to the system management team. This way precautions can be taken and, in the worst case scenario, the drone can be taken down to prevent it to be above 400 feet or to get in the way of manned aircraft. It is expected that only autonomous drones will fly in the droneways, so it will not be necessary to control the drones from moving vehicles.

Back to 2018, when these rules were first evaluated to write the first version of this text, there was no way to get an authorization to bypass the three challenging regulations for commercial use, created by the selected agencies. As the drones are a recent technology, they could not be trusted to fly without concerning about safety and privacy, which should be kept by following these rules.

At this time (October, 2021), looking again at the regulations, changes can be found. ANAC is allowing beyond VLOS (BVLOS) and extended VLOS (EVLOS) if the drone and the applicant fulfil certain security requirements. The EVLOS means that the operator can control the drone using auxiliary observers. Both BVLOS and EVLOS was not even mentioned in the ANAC regulations in 2016.

Although FAA is still not allowing BVLOS operations, there's a new section in the regulation called "Package Delivery by Drone (Part 135)" [1]. The agency mentions the Integration Pilot Program, focusing on testing and integrating civil and public drone operations into the national air space. The program was finished in 2020, but the work continues in a new program called BEYOND [2], which is focusing on the remaining challenges, including BVLOS operations.

EASA has recently approved the Regulations 2019/947 and 2019/945, which clarify conditions to operate drones BVLOS over populated areas or assembly of people. Therefore, in Europe, the droneways implementation could already be possible.

Floreano and Wood (2015) have evaluated the U.S.A. and European UAV regulations back in 2015, looking to discuss what can be expected in the near future, and their predictions are already becoming a reality. According to the authors, if a considerable progress in drones reliability and safety were achieved, it would be possible to get a change in legal requirements next to 2030, allowing the use of autonomous drones. Evaluating the regulations today, it can be seen that it could be achieved sooner, as at least the three regulations evaluated in this work are going towards the autonomous drones operation.

2.4 Complex Networks

When a network is represented as a graph, assuming that its elements are nodes (or vertices) and their connections are edges, it can be evaluated using the Complex Network Theory. This is a quite recent area of study, which had a boost when the increase in computational power allowed the evaluation of great magnitude networks, as the Internet, social networks, biological networks and more. Examples and basic concepts of the theory are explained by Barabasi (2003). The author explains the difference between Random, Small-World and Scale-Free networks. In the first one, a given number of nodes is created and a probability is defined for any pair of nodes to have and edge linking them. In Small-World Networks, hubs

[1] ⟨https://www.faa.gov/uas/advanced_operations/package_delivery_drone/⟩
[2] ⟨https://www.faa.gov/uas/programs_partnerships/beyond/⟩

are commonly found, which makes the diameter to be very small (units or rarely tens) and, consequently, travelling through its paths is fast. The Scale-Free Network follows a rule that makes a node having many connections to have a higher chance to get even more, while low degree nodes remains unchanged. At the end, the degree sequence of a Scale-Free network follows a power law.

The street network does not fit any of these three mentioned types. It is not a random network, as humans tends to be together, and this makes the cities to grow from a central starting point. It can not be a Small-World network, as it is not physically easy to directly link any two streets from anywhere in a map. The physical limitation of a crossing to have a high number of adjacent streets prevents the highway network to become a Scale-Free. So, this is a specific case, and this network is known as Geographical, where physical limitations dictates its shape, and the position of the nodes and their distance are important (COSTA *et al.*, 2007).

Newman (2003) has made a complex network extensive review, explaining in details several network topologies, the main metrics calculations, complex network models and processes, as epidemics, percolation and search. Following the same direction, Boccaletti *et al.* (2006) goes beyond, discussing complex network robustness, network synchronization and some real applications in the Internet network, in social, biological and brain networks. Both references are the basis of complex networks, and were used in this work to build the glossary.

Costa *et al.* (2007) have presented a review focusing on how to use metrics to describe, classify, and evaluate different types of complex networks. Worth emphasizing the description of geographical or spatial network, in which the nodes position is important, as it influences the network's evolution. As examples, they cite Internet, power grids, airport networks, subway, neural networks, and, of particular interest, highway networks, that despite not being exactly like the street network used by the droneways, serve for the same purpose and have most of the features and limitations of them.

Mello *et al.* (2010) have applied this theory to assess how information spreads across adjacent cities using three different networks: the intercity roadway network, the telephone network, and the radio stations network. To classify the cities, two centrality metrics were used: the page-rank property and the network efficiency. They have also defined a new metric, called diffusion power, to measure how a node can influence its neighbours and how it affect the network. Correlating the three metrics, they defined cities with greater power to disseminate information, showing that this is proportional to population density and the cities GDP.

The Dijkstra algorithm (DIJKSTRA, 1959), an effective algorithm to find the shortest path between two given points in a graph, was used by Chow *et al.* (2019) to find the best route for surveillance drones. With an aerial picture of the environment, their algorithm divides the figure in squares, turning them into nodes. They classify these nodes into an obstacle or free of obstacles areas. After that, adjacent free of obstacle nodes, in eight directions, are linked to each other, creating a graph. Using this graph, the Dijkstra algorithm returns, if exists, the shortest path between a source and destination area. Although the work has proven that Dijkstra algorithm can be used for drones to find the shortest path, the work could be improved, as it only works with a 2D image and may not find a path between two given points.

The network efficiency cited before is the most important metric for this work, since it was used to guide the droneways comparison. It was first proposed by Latora and Marchiori (2001) and defines how efficient is the information exchange between all the network nodes. This metric is affected by the number of nodes and edges that the network has and thus: adding more nodes reduce the efficiency and adding more edges increases it. Worth notice that different edges may induce different increases in the metric, making the topology an important attribute to be considered.

The diameter and average length of the shortest paths (NEWMAN, 2003; BOCCALETTI *et al.*, 2006) should give an idea of the resulting droneways extension. When paths are removed from a given network, it can affect the routing process, making the resulting droneways to have its diameter higher than the initial one, especially when nodes with higher centrality are not included in the droneways set. These metrics are used to make a correlation with the final efficiency.

The outer path length also has to be considered, as it will show if the drones will have longer paths to travel outside the droneways. The ideal droneways should have the highest possible efficiency and the shorter outer path length, meaning the drones will always have the lowest flying distance to travel between any source and target locations. However, the droneways efficiency have priority over this metric, since the drone must fly over the droneways for the most of the time, leaving it only to finish a delivery.

Finally, the map coverage ratio will help understand the extension of the droneways. This metric is the ratio between the complete length of the droneways and the complete length of the streets in the map.

In short, the perfect combination of the defined metrics for the droneways is: lower coverage, high efficiency, and small outer paths.

In this subsection it was presented a background in Complex Networks Theory, focusing on the metrics that have been used in this work. The next chapter presents the methodology of this work.

3 Methodology

Droneways are air routes drawn over a subset of streets in an urban area that are designed for the drones displacement, seeking efficiency, safety and personal privacy. The drones are intended to be inside the droneways most of the time. However, they may fly outside the droneways to collect or delivery a package at its destination.

Maps from three existing locations were used as case study of this work: the Manhattan borough, in U.S.A; the Paris city, in France; and the Uruapan city, in Mexico. It was assumed that the selected regions were *not* planned to support droneways. If an entirely new city would be designed from scratch, the droneways system could be projected since the beginning according to this work's guidelines or could be devised in a whole new fashion, bringing a new face to the urban landscape.

The delivery model defined for the drones is that they can depart from any place, arriving in any other place in the city. So, there is not a distribution center nor any centralized port for them. Due to their small size, they can take-off or landing at any point, without the need of special facilities. This means that even small companies or individuals could launch drones flying to all possible destinations. Conversely, the delivery *must* be done in the sidewalk in front of the target address. Certainly the later statement is somewhat restrictive, but it was not included in this work's model the possible presence of ports or drone-exclusive landing areas in favor of the simplicity.

The drones *must have* an automatic collision avoidance system (ACAS) (DENTLER *et al.*, 2016; KUMAR *et al.*, 2021), as it is expected that they will fly at different speeds, in both directions, and will need to maneuver to enter or exit the droneways or to change direction in the intersection points. ACAS needs to prevent collisions against fixed and mobile obstacles and against other drones flying around. The format of the ACAS is not relevant for this research, assuming only that it works properly. Centralized, decentralized, or combined control mechanisms can be employed successfully to supply ACAS services.

To measure the time that a drone will fly over the droneways and outside it, in this work it was considered that a drone can fly at a speed of 11m/s, which is half of the speed that Amazon was expecting its delivery drones to fly in 2015 experiments (LAVARS, 2015). This value is low to be conservative, and will not affect the goal of this work, as it will only be used to compare flying times over the droneways and over the outer paths. Considering that recent drones can fly faster than this, the actual delivery times would be even shorter than those calculated in this work, but the ratio of time in and out of droneways would be the same.

Rivers, lakes, sidewalks, bike paths, pathways, and open water are disallowed for the droneways, but they can also be considered in specific cases, which is not the focus of this work. Albeit the water presents important advantages, easing the navigation, the fall of a drone would leads to the lost of the device and its load.

A system to guide the drones through the streets, to make scheduling, to control the drones at different altitudes and speeds, is also necessary and is already being discussed by other authors (GHARIBI *et al.*, 2016; DEVASIA; LEE, 2016). It is assumed that this system will work out of the box, regardless of the droneways shape.

Then, the droneways are allowed to overlap only the city streets, being forbidden to fly over private properties, houses, buildings, an so on. In the same way, drones cannot fly over open public areas such as parks and squares, avoiding chaos, hits against flagpoles, falls over trees, and other undesired situations.

The droneways are the main routes for drones, but it is not expected to cover all the city. For instance, a drone must depart from an arbitrary point, fly to the nearest point from the target in the droneways, and, finally, leave the droneways near the delivery point to carry out its mission. In this sense, the droneways is the distribution network, concentrating all traffic, and the streets that are not covered by it, henceforth called *outer ways*, are used only for local delivery. In Figure 2 it is shown an example of a delivery situation using a droneways. The drone gets the load in the starting point and goes over the droneways until it reaches the closest droneways point. Then, it goes over the final delivery path, an outer way, until it finds the delivery address. After finishing the delivery, it comes back to the droneways, using the same outer way, and becomes free to collect another package to deliver.

The droneways may be composed from one single street up to the complete streets set of a map, as long as all selected streets result in a connected component, i.e., all of them are interconnected. Although that, these two extreme cases are unfeasible. With a low coverage, the drones would have to fly for too many time outside the droneways. The opposite, a complete map coverage, would dismiss the use of the droneways proposal. Thus, droneways with different coverage ratios are going to be created and tested for efficiency.

A parallel between this configuration and the *last mile problem* in the computer networks or cable TV can be made, because in the traditional scenario, optical fibers are not deployed to the people's houses, but they arrive to a local hub that distributes the signal over copper wires or wirelessly. In this analogy, the droneways make the role of the optical fibers and the outer ways make the role of the copper wires/wireless signal.

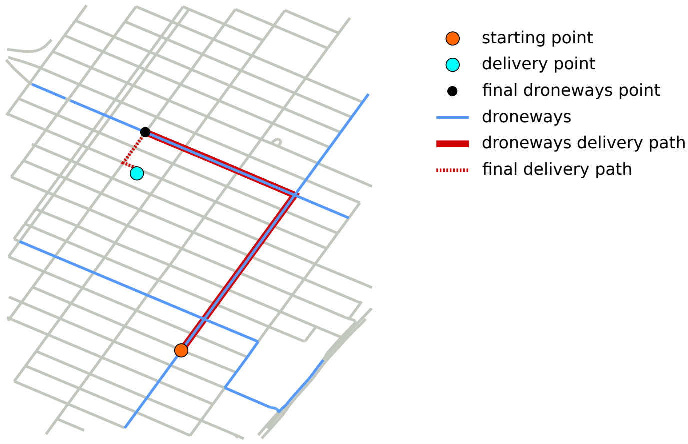


Figure 2 – Example of a delivery in an arbitrary droneways system.

.

City authorities can do adjustments accordingly to certain profiles, as for example, forcing middle- or large-scale traffic sources or destinations to stay along the droneways. This restriction will not be covered in this work, but could be considered as an optimization.

In this work, to model the droneways, street maps were extracted as graphs from some selected locations around the world. Several droneways were obtained, covering different portions of these graphs, using two original developed heuristics programmed in Python language. Finally, these droneways were compared by calculating a set of complex networks properties. The main goal was to find the most efficient droneways, i.e., the ones having the shortest travelling paths for a given map coverage.

The heuristics are based on two graph structures known for their high efficiency: the Fishbone, which resembles a backbone, and the Spiderweb, which looks like a circular spider web. The developed algorithms tries to find topologies similar to their heuristic shapes, starting with few paths, increasing the coverage in each step.

In the following sections, the resources needed to implement this work are described. Next, the procedures to extract the droneways from the selected maps are presented, which are divided into the scenario selection steps, the heuristics implementation, and the droneways assessment metrics.

3.1 Resources

In this section are listed the resources for the manipulation of digital maps, graphs, and also computational languages and environments, necessary to draw the droneways. The used resources are:

- Digital maps or other information source from the selected locations, from which the street network can be extracted;
- The extracted graph from the street network;
- Software development environment:
  - Arch Linux - Operational System;
  - VIM IDE;
  - Overpass Turbo[1] - map filtering tool,
  - Python 3.6 - Programming Language;
  - JOSM - map editor[2].
- General use microcomputers compatible with the pieces of software;
- Internet connection.

The algorithms to find and process the metrics of this work were programmed using the Python language. The main libraries that have been used are Snap[3] for geometric operations and Graph-tool[4] for graph manipulation. To speed up the algorithms, parallel programming techniques were used when it was suitable.

3.2 Procedures

The procedures taken in this research are presented in this section, divided in the following 3 subsections: Scenario Selection, in which the reasons why the selected locations were chosen are described; Heuristics, where the two proposed heuristics are described in details; and Networks assessment, where the methods, tools and algorithms to evaluate and compare the droneways are detailed.

3.2.1 Scenario selection

Although there are always restrictions to generalize local studies, it is intended to make this research applicable to the wide possible range of locations. Therefore, the places were chosen considering the following requirements:

[1] ⟨http://overpass-turbo.eu⟩
[2] JSOM software is open source OSM file editor and can be downloaded at ⟨https://josm.openstreetmap.de⟩
[3] http://snap.stanford.edu/snappy/index.html
[4] https://graph-tool.skewed.de

- the popularity of the place;
- the population density;
- the city delimitation;
- the map shape;
- regions density, which may reinforce the private buildings overflight forbiddance by means of the simple impossibility of crossing tall buildings.

Following them, the first choice was *New York City*, focusing in the *Manhattan* borough, a well delimited area, highly populated, created using an urban plan and one of the most popular cities in the world. The second choice was the city of *Paris*, delimited by the Boulevard Périphérique, having a different shape from the Manhattan one, it is not filled with tall buildings and it is an old city that has grown over centuries. The last choice was the city of *Uruapan*, a small and well delimited city in the *Mexican state of Michoacán*, a less popular, less populated and architecturally sparse city. The maps from the three locations are shown in the Figure 3.

The maps were extracted using the Overpass Turbo, a web-based data filtering tool for OpenStreetMap[5] maps. The tool have allowed the maps filtering by using a XML query. The final query used to filter the Manhattan, Paris and Uruapan maps can be found in the Appendix A. The graph extraction involved the following steps:

- Creation of the filtering query for the Overpass Turbo, as shown in the Appendix A;
- Manual selection of the desired map using the Overpass Turbo filtering tool;
- Application of the query to extract the OSM[6] file for download;
- Manual extraction of the region of interest (Manhattan, limited by the rivers; Paris, limited by the Boulevard Périphérique; and Uruapan, limited by the green area around the city), using the JOSM Software and the OSM downloaded file;
- Conversion of the resulting JOSM files to GT[7] (graph-tool) format, to use them with the custom python scripts.

[5] ⟨https://www.openstreetmap.org/⟩

[6] The OSM file format is the XML-based file provided by the OpenStreetMap API to represent a map region. Basically it is a list of instances of the OpenStreetMap data primitives (nodes, ways, and relations).

[7] The GT file format is a binary format designed to store graph-tool Graph instances, properly for reading and storing graphs using the tool. Source: ⟨https://graph-tool.skewed.de/static/doc/gt_format.html⟩.

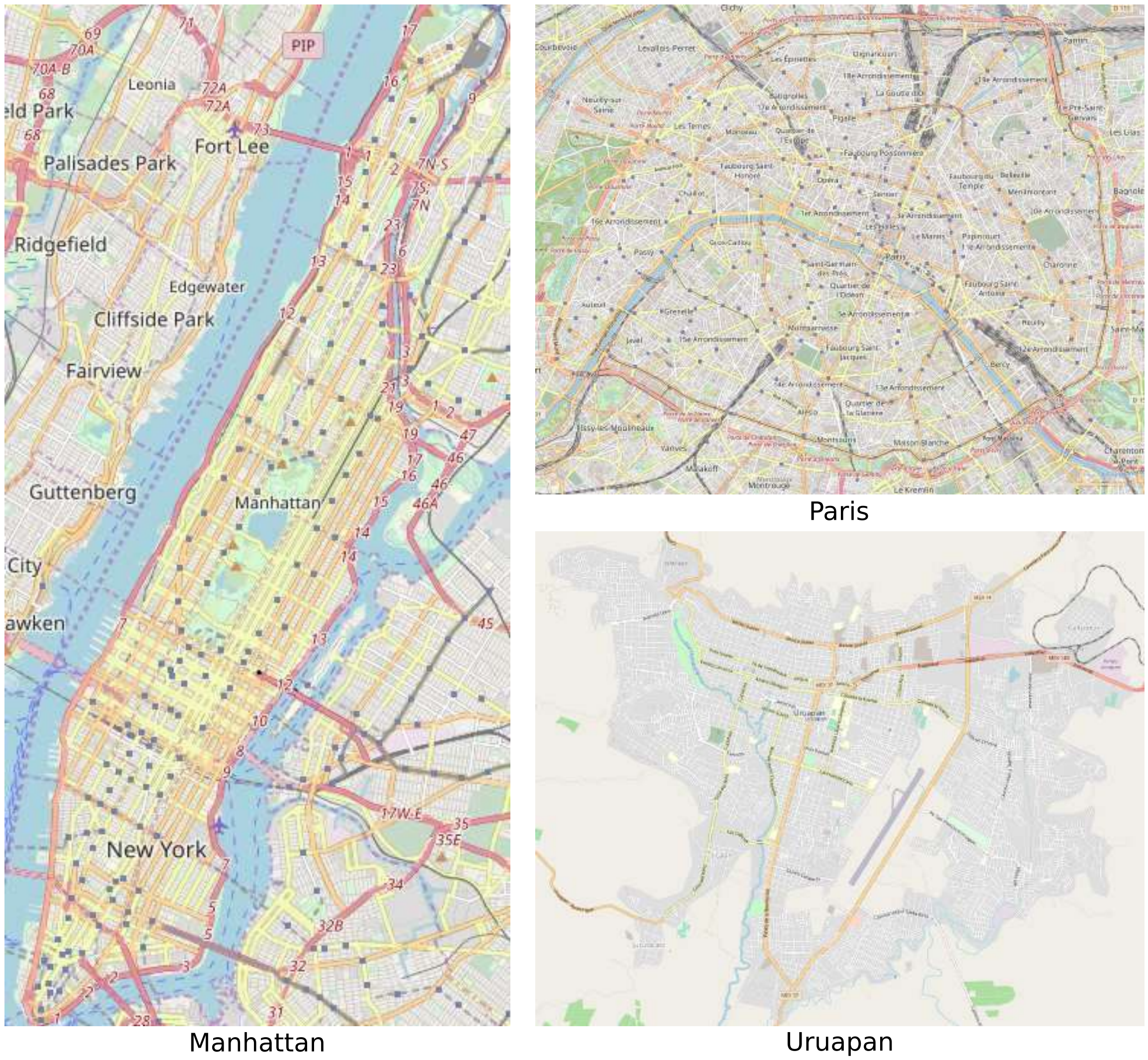


Figure 3 – Manhattan, Paris and Uruapan maps. Source:⟨http://www.openstreetmap.org⟩

At this point, it is important to remember that the resulting networks are *geographic* (also known as *spatial* or *geometric*) networks, whose definition consider the position of the nodes. So, there is no way to move the nodes or ignore their spatial location. Particularly, the edges cannot be changed to make, for instance, a star-like structure, which would be a very efficient one.

3.2.2 Heuristics

The graph coverage heuristics used in this thesis are based on the idea that a star-like network has high efficiency, and when its surrounding nodes are linked to each other, resembling a spider web, the efficiency is even higher. The other option, a fishbone-like topology also has a good efficiency, and cities are usually organized as rectangular blocks, then maybe its shape would fit better over the maps, what could possibly find more efficient droneways. Figure 4 shows examples of the three network structures.

To cope with the requirements two heuristic rules were created to find droneways:

- To incorporate a radial shape in the droneways, resembling a spider web with more density in the geographical center;

- To incorporate a fishbone shape in the droneways, with one or few main routes along the major axis.

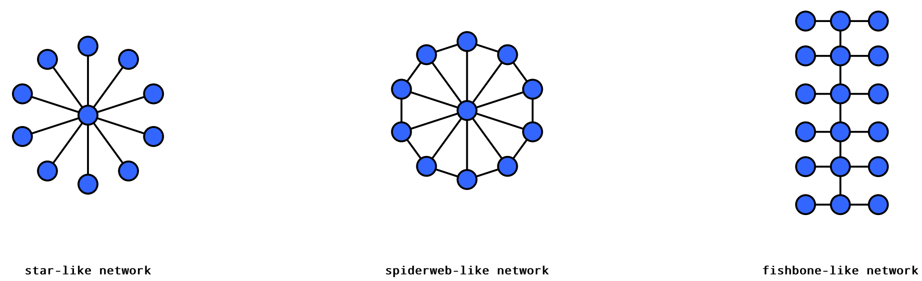


Figure 4 – Star-, Spiderweb- and Fishbone-like networks.

Every resulting graph must be a connected component, i.e., it is essential that there is a path between any two points of the droneways without leaving it. It is important that drones are able to reach the entire droneways without using the outer paths.

To create the droneways resembling a specific geometric shape (fishbone or spider web) it is necessary to find paths in the map trying to overlap that shape. Firstly, the shape must be placed over the map in a scale that fits or exceeds the map size. As the geometric shape will not exactly overlap the streets, it is necessary to find the path inside the street map which is closer to the shape lines. To do this, the shape must be separated in line segments, finding the closest nodes to the ends of the line, and then find the nearest path to the line between these two nodes. Worth mention that this path is not the same as the shortest path.

The A* algorithm is a graph search algorithm (HART *et al.*, 1968), guided by a heuristic function. This function was modified in the context of this work to find a path as near as possible to a straight line. The algorithm finds the path between the nodes s and t which has the minimum area of the geometric figure projected between the path edges and the straight line between s and t (grey area in Figure 5).

Figures 6 and 7 presents respectively the examples of each step of the Fishbone and Spiderweb heuristics. In the following paragraphs, the figures are complemented with the algorithms description for each proposed droneways heuristic. They are described for better understanding, relating the enumerated steps to the figures sequences.

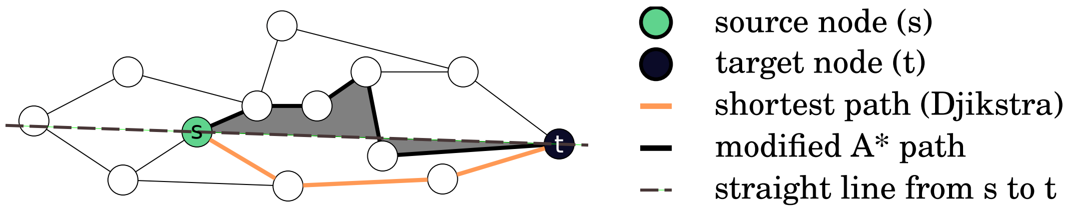


Figure 5 – Modified A* algorithm example path

Fishbone Heuristic

1. Calculate the betweenness centrality for all the nodes in the graph;

2. Find the node c, which has the highest betweenness centrality on the graph;

3. Find the most distant nodes in the map, using Euclidean distance, named v_1 and v_2. Using these two nodes:

   a) Find the shortest path between v_1 and v_2 using Dijkstra algorithm(DIJKSTRA, 1959), passing through the node c and add it to the *droneways*;

   b) Find the direct line between v_1 and v_2, named l_0;

   c) Find P equally distributed number of points along l_0. For each point named p_i:

      i. Find the perpendicular line to lp_i, crossing p_i;

      ii. Find the two most distant edges of the graph crossing lp_i, named $ep_{i,1}$ and $ep_{i,2}$;

      iii. Get one vertex from $ep_{i,1}$ and one from $ep_{i,2}$, each one closer to lp_i, respectively named $vp_{i,1}$ and $vp_{i,2}$;

      iv. Find the path between $vp_{i,1}$ and $vp_{i,2}$ using the custom A* algorithm and add this path to the *droneways*.

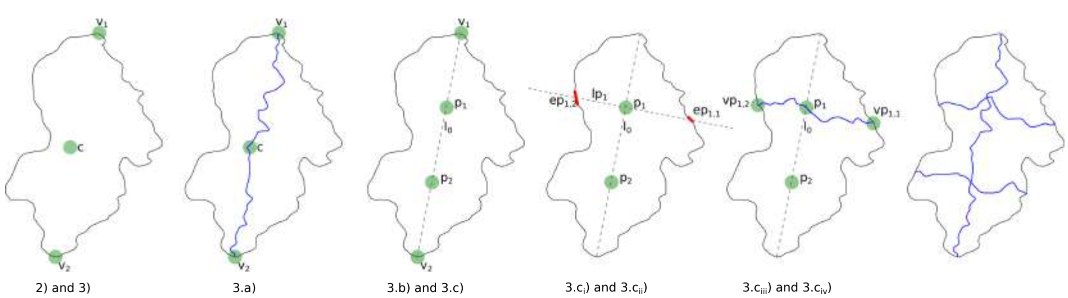


Figure 6 – Simplified illustration of the Fishbone heuristic to find a droneways with $P = 2$. The droneways are colored blue.

Spiderweb Heuristic

1. Calculate the betweenness centrality for all the nodes in the graph;
2. Find the node c, which has the highest betweenness centrality on the graph;
3. Find the Euclidean distance between c and the most distant node from it to find the radius r;
4. Calculate the graph convex hull[8] and add all its edges to the *droneways*;
5. Divide a circle in P slices and get the angle θ from one slice;
6. Get the angle ϕ_i, starting from degree 0 until 360, in step θ:
   a) Using the modified A* algorithm, find the path between c and the most distant vertex from it, located in the direction of the angle ϕ_i, and add this path to the *droneways*;
   b) Divide the radius r in Q parts, named r_j:
      i. Let $v_{i,j}$ be the vertex closer to the point $p_{i,j} = (r_j \cos(\phi_i), r_j \sin(\phi_i))$;
      ii. If $v_{i-1,j}$ is already defined, get the path between $v_{i-1,j}$ and $v_{i,j}$ using the modified A* algorithm, and add this path to the *droneways*;
      iii. If $v_{i+1,j}$ is the same as $v_{0,j}$, get the path between them using the modified A* algorithm and add it to the *droneways*.

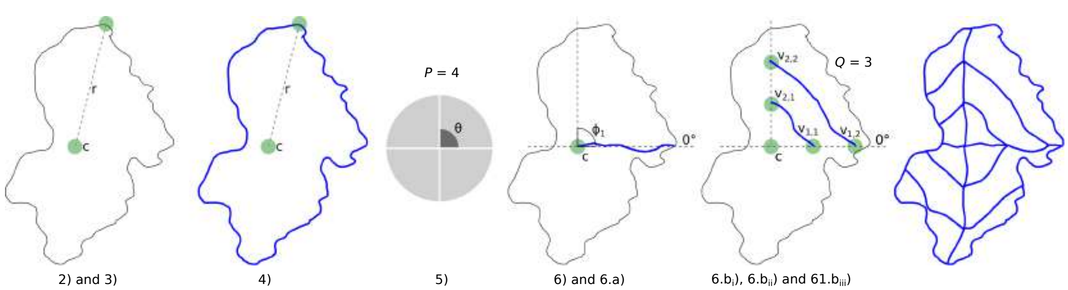


Figure 7 – Simplified illustration of the Spiderweb heuristic to find a droneways with $P = 4$ and $Q = 2$. The droneways are colored blue.

[8] A convex hull of a planar set is the minimum-area convex polygon containing the planar set (EDDY, 1977).

3.2.3 Networks assessment

The following metrics were used to evaluate the droneways:

1. relative efficiency of the resulting droneways graph;
2. network diameter and average length of the shortest path between each pair of nodes in the droneways;
3. maximum and average length of the outer ways (the paths not belonging to the droneways);
4. droneways street map coverage ratio, in terms of space overlapping.

The network efficiency is defined as

$$E(G) = \frac{1}{N\left(N-1\right)} \sum_{i \neq j \in G} \frac{1}{\sigma_{i,j}}, \tag{3.1}$$

where G is the graph, N is the number of nodes from this graph and $\sigma_{i,j}$ is the shortest path length from the node i to the node j, considering the width of each street segment as the edge weight. As it is normalized by the number of all possible edges ($N(N-1)$), it makes easy to compare two different network efficiencies, as the value will be between 0 and 1.

The initial number of nodes from the map to calculate this metric must always be considered, even if they are not included in the chosen droneways resulting set of nodes. This way the efficiency from a chosen heuristic will be relative to the initial map network. The Equation 3.2 was used to find the relative efficiency.

$$E(G_d) = \frac{1}{N_0\left(N_0-1\right)} \sum_{i \neq j \in G_d} \frac{1}{\sigma_{i,j}}, \tag{3.2}$$

where G_d is the resulting graph for the droneways d and N_0 is the map initial number of nodes.

To know the extension of the droneways, the map coverage ratio was used. The Equation 3.3 is the formula of this metric:

$$Cov_d = \frac{\sum_{e \in G_d} w\left(e\right)}{\sum_{e \in G_0} w\left(e\right)}, \tag{3.3}$$

where Cov_d is the coverage ratio of the droneways d, G_0 is the complete starting graph, and $w(e)$ is the weight of the edge e, i.e., the width of the street segment represented by the edge e.

The methods to collect and process the data to create and assess the droneways were presented in this chapter. The resulting droneways comparison and discussion is shown in the next chapter.

3.3 Chapter Summary

In this chapter it was presented the methodology of this work. It started by describing general aspects, requirements, and assumptions for the droneways to work properly. Then, in Section 3.1 were presented the needed resources to make this work.

In Section 3.2, the procedures were shown, divided into three subsections. In the first one, 3.2.1, are listed the requirements and reasons to select the map locations, as well as the three selected locations: Manhattan borough, and the cities of Paris and Uruapan. In the 3.2.2 the heuristics used to find two types of droneways, the Fishbone and Spiderweb, are detailed in a step-by-step enumerated description. Finally, the last subsection, 3.2.3 itemizes and describes the metrics used to evaluate and compare the resulting droneways.

In the next chapter are presented the results obtained in this research.

4 Results and Discussion

In this chapter are exposed and discussed work results. We first present and discuss the results and properties that Manhattan, Paris and Uruapan have in common. Then, in three separate sections, we present and discuss the specific results for each location. In the Section 4.5, are exposed the limitations of this work. Finally, in the last session, a summary of this chapter is presented

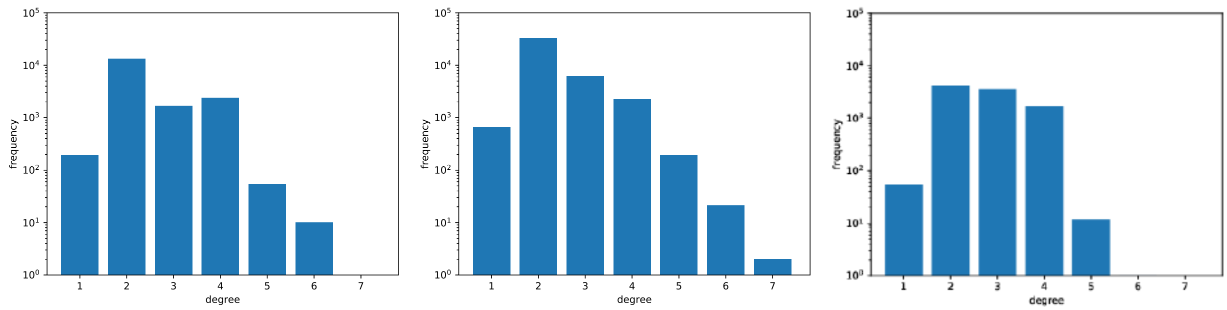
4.1 Results and Discussion

The proposed methodology was applied considering the three study cases. The first step was to extract the graphs from each location, which resulted in different sized graphs, both in number of nodes and edges, as shown in Table 1. The Uruapan graph is the tiniest one, being close to 10 thousand nodes and edges. Then comes Manhattan graph, being twice as bigger when compared to the Uruapan one. Finally, Paris graph is the bigger one, being twice as bigger of Manhattan graph. Although their sizes, the graphs have similar properties, as a close average degree and a very low average degree standard deviation. To evaluate this similarities in more details, in the Figure 8 is shown the degree histogram for the three resulting graphs. Worth notice that the frequency axis is in logarithmic scale.

At first, the desired portions of Manhattan, Paris and Uruapan maps were extracted and filtered, to keep only streets and roads. After processing them, three graphs of different sizes were obtained. Table 1 shows general data about the size and degree of these graphs.

	Manhattan	Paris	Uruapan
Nodes	17760	42196	9425
Edges	21006	47560	12866
Average Degree	2.3655	2.2542	2.7302
Avg. Deg. St. Dev.	0.0056	0.0029	0.0033

Table 1 – Manhattan, Paris and Uruapan graphs properties



(a) Manhattan (b) Paris (c) Uruapan

Figure 8 – Degree Histogram from Manhattan, Paris and Uruapan

It can be seen that is very uncommon for all the locations to have vertices with degree 5 or more, which is expected, as the most common type of crossroads is the two streets intersection, resulting in a 4 degree node.

Another expected peculiarity of these graphs is that they are sparse, i.e., they have few well distributed edges. Although, for Paris graph for example, seems to be a large number of 47560 edges, when comparing it to the maximum amount of possible edges it could have, which is 42196^2 (the number of nodes squared), it represents less than $0,003\%$ of the total number of edges. This is an expected behaviour from geographic graphs, where is impractical to cross edges or link directly two physically distant nodes.

The graphs ended up having a lot of nodes with only 2 edges, because the graph extraction tool uses line segments to represent curved roads. However, this will not have a negative effect in the results for two reasons: 1) the edges uses the road length as weight (values in meters), which are considered by the shortest path algorithm. It makes two segments of 10 meters worth the same as one 20m-segment, for example; 2) comparisons between two resulting droneways graphs employs the relative efficiency formula (Equation 3.2), in which the first part of the calculation ($\frac{1}{N_0(N_0-1)}$) works like a normalizer, as it always remains unchanged by using the initial graph number of nodes. The second part is a sum of the inverse of all shortest paths, and when a path between two vertices do not exists, the distance between them is considered infinite, which makes its inverse value tends to zero and be ignored in the summation.

These graphs were loaded into custom scripts made specifically to find the droneways using the heuristics algorithms as shown in the Section 3.2.3. The scripts have generated 114 droneways (38 for each map, each one with a different coverage). Only the first and last droneways maps, calculated using the number of paths in the Table 2 and Table 3 are shown in this section (Figures 9, 10, 12, 13, 15, and 16) to better understand the initial and final coverage of an heuristic. The remaining droneways maps can be found in the Appendix

B. The complete droneways map set, in vector images, together with the algorithms and resulting raw data from the calculations which have been made over the droneways, are available online at the URL:⟨http://github.com/willunicamp/droneways⟩, and physically in this thesis CD-ROM which can be requested from the University of Campinas (UNICAMP).

10	20	30	40	50	60	70	80	90	100	150	200	250	300	350	450	600

Table 2 – Values of P used in the fishbone droneways (see Fishbone Heuristic in section 3.2.2)

5	10	15	20	25	30	35	40	45	50	75
100	125	150	175	200	225	250	300	450	600	

Table 3 – Values of Q used in the spiderweb droneways (see Spiderweb Heuristic in section 3.2.2)

Using the fishbone heuristic, 17 droneways were created for each map, each one containing the main path and a number of perpendicular paths as listed in the Table 2. For the spiderweb heuristic, it were created 21 droneways for each map, each one having 8 angular paths, centered on the highest betweenness node (street intersection), and a number of circular paths as shown in Table 3, in which the radius increases equally for each circle, in a way that the larger circle has the diameter equals the length of the map.

For easy identification, from now on each droneways will be referenced by [**number of new paths**]-[**heuristic**]-[**location**]. For example, the Fishbone droneways with 50 new paths from Manhattan, will be called 50-Fishbone-Manhattan droneways. To refer to a group of droneways, any part can be omitted, like using 50-Fishbone droneways to refer to the droneways from all three selected cities.

In the next sections are presented and discussed the results obtained for the three locations: Manhattan, Paris and Uruapan.

4.2 Manhattan

It was generated 38 droneways over Manhattan map: 17 with Fishbone and 21 with Spiderweb. The Fishbone ones have covered from nearly 7% (when P = 10)to 68% (when P = 600) of the street map (Figure 9), and the Spiderweb droneways have covered from nearly 14% (when Q = 5) to 58% (when Q = 600) of the street map (Figure 10). The droneways were tested for efficiency, and in all cases the Spiderweb ones has shown a higher efficiency for a given map coverage, as can be seen in Figure 11a.

Both heuristics efficiency increase has saturated when more than 250 paths were included in the droneways, as shown in Figure 11b. The Spiderweb heuristics provided a higher slope angle below the 250-droneways, but after that the efficiency increase was negligible. The reason why this saturation occurs is that some paths start to overlap or even be the same as others previously included when the number of iterations is too high, although in different ways for each heuristics.

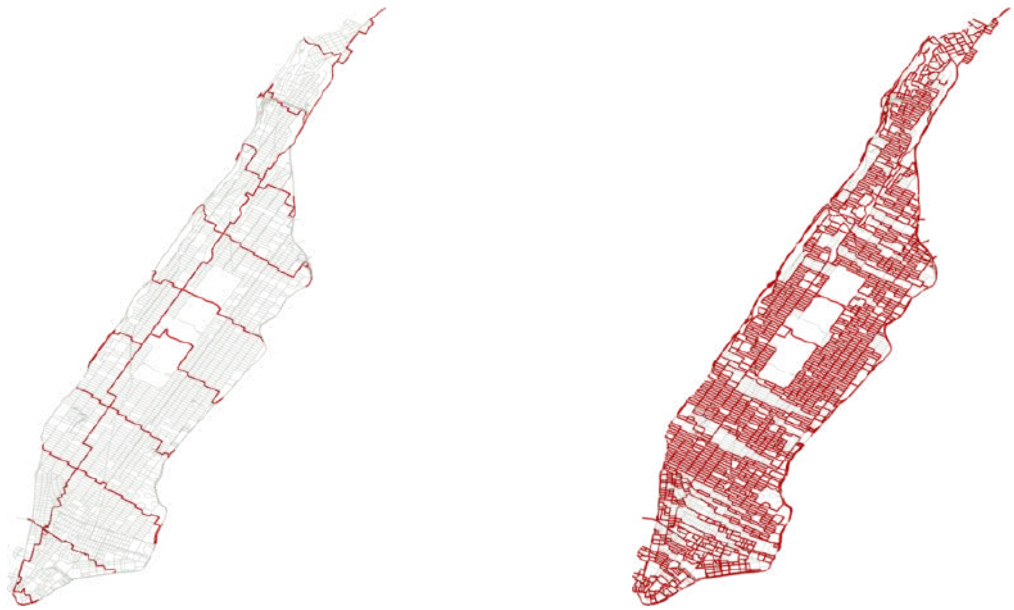
Including too many paths in the droneways to achieve a small gain in efficiency is not useful, as the goal of the droneways is to provide few paths with a high efficiency. For that reason, it was set a limit of 600 new paths to create droneways map, as the increase in its relative efficiency from the 450-droneways to the 600-droneways was low compared to the efficiency increas below the 450-droneways.

The average path length (Figure 11c) and network diameter (Figure 11d) are shorter for the Spiderweb resulting droneways in Manhattan. Consequently, it can be inferred that a drone will fly, in average, shorter paths in Spiderweb droneways, leading to lower drones energy (or fuel) consumption, lower delivery times and a higher amount of deliveries. For both metrics it can be noticed that there is an instability (alternated peaks and valleys in the charts) in the path lengths, as seen in Figures 11c and 11d. This occurs because when few paths are added to the droneways, some shortcuts have a low chance to be included in the droneways. It is possible that one iteration have a path without one shortcut, which can be included in the next iteration, and removed again in the following iteration. This causes a wide variation in the diameter and unbalance the average shortest paths between the iterations. When the number of new paths increases, the chance of those shortcuts be included also increases, and both metrics tend to vary less.

Figure 11e shows how the average length of the outer paths (ALOP) is reduced as the map coverage increases. The ALOP was always shorter for Fishbone heuristic, and the difference to the Spiderweb one is almost constant for any given droneways map coverage.

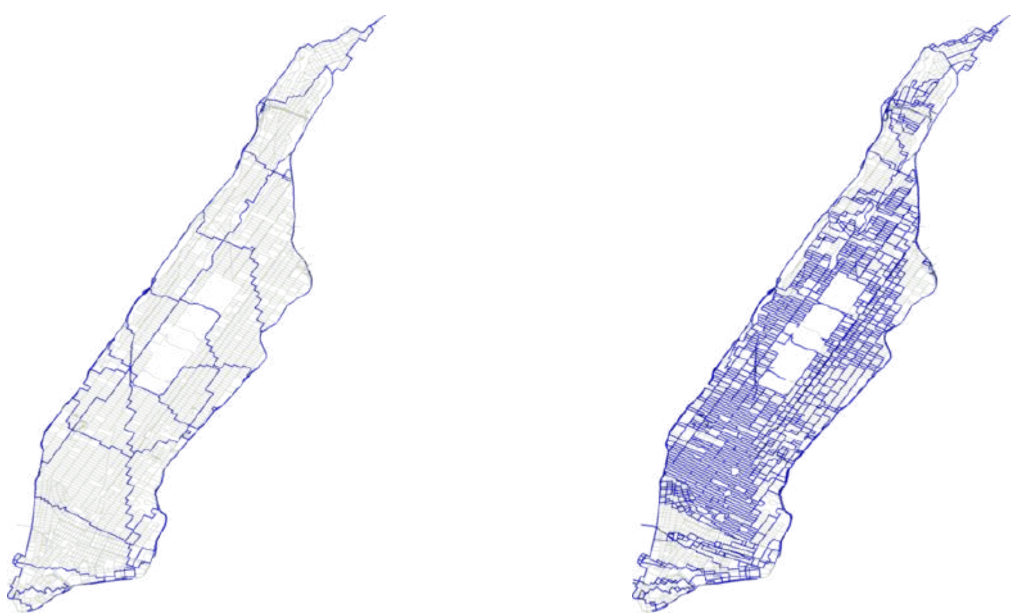
It can be noticed that the ALOP curves have different ranges between the heuristics. It is expected that ALOP will decrease as the map coverage increases, since the heuristics tries to spread the coverage evenly through the map. As seen in the Figure 11e, the map coverage range is different for each heuristic, and the ALOP is expected to follow the same behaviour.

The drones must come back to the droneways as soon as possible to finish the delivery in the outer paths, since these paths are not supposed to be prepared for drones to fly like droneways paths should be. In a closer analysis of the ALOP, it can be seen that, in average, the Fishbone ALOP is around 2m shorter than the Spiderweb ones. Considering that a drone will fly in the outer paths at a speed of 11 m/s (half of the speed mentioned by Lavars (2015)), the time outside the droneways will be almost the same in both cases. In contrast, the droneways shortest paths are, on average, about 1790 m shorter for the Spiderweb droneways, resulting in a delivery time reduction of 162 seconds.



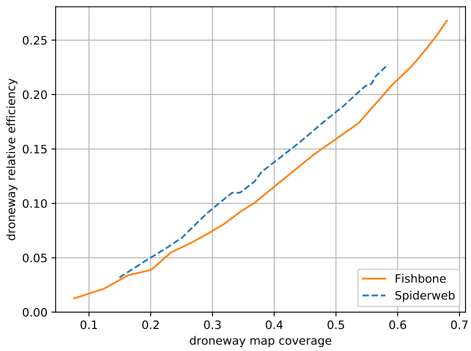
(a) $P = 10$. (b) $P = 600$.

Figure 9 – Manhattan Fishbone resulting droneways for $P = 10$ and $P = 600$.

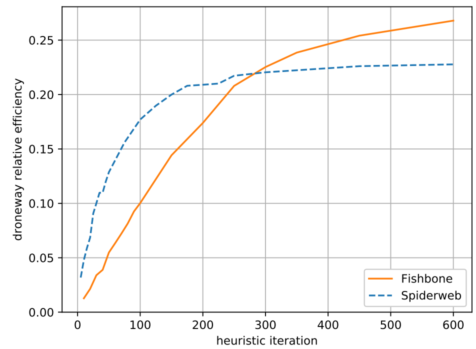


(a) $Q = 5$ and $P = 8$. (b) $Q = 600$ and $P = 8$.

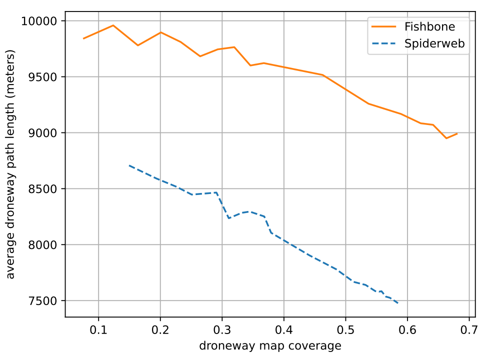
Figure 10 – Manhattan Spiderweb resulting droneways for $Q = 5$ and $Q = 600$. $P = 8$ for both droneways.



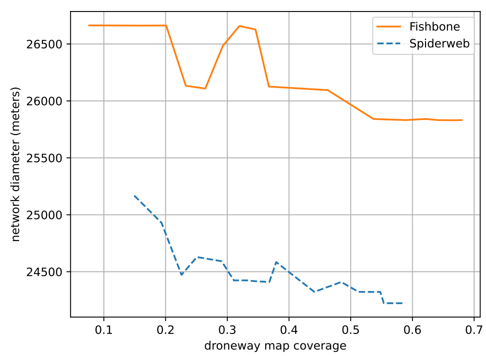
(a) Efficiency increase by coverage ratio



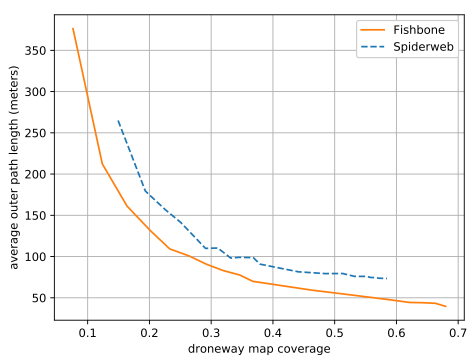
(b) Efficiency increase by iteration



(c) Average path length by coverage ratio



(d) Network diameter by coverage ratio



(e) Average outer ways path length by coverage ratio

Figure 11 – Fishbone and Spiderweb heuristics results comparison for Manhattan.

4.3 Paris

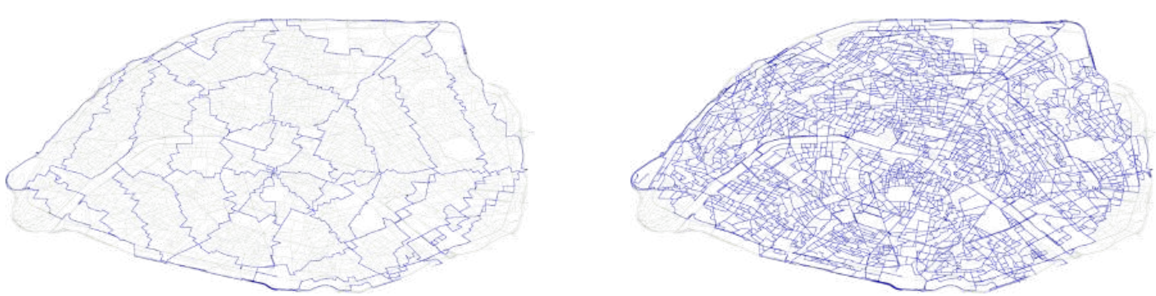
Over Paris map, the 17 Fishbone droneways have covered from approximately 9% (when P = 10) to 59% (when P = 600) of the street map (Figure 12), and the Spiderweb droneways have covered from nearly 14% (when Q = 5) to 65% (when Q = 600) of the street map (Figure 13).

Like in Manhattan, the Spiderweb heuristic has provided droneways with higher relative efficiency (Figure 14a). An identical behaviour can be seen on the average path length and droneways diameter (Figures 14b, 14c and 14d, respectively). The main difference can be seen in the efficiency saturation, in which the Fishbone results were always below the Spiderweb's one.

The Fishbone ALOP is around 19 m shorter than the Spiderweb ones. At the average, a drone would fly 4 seconds more outside the droneways. In contrast, the average droneways shortest path are, in average, close to 1170 m shorter for the Spiderweb resulting droneways.

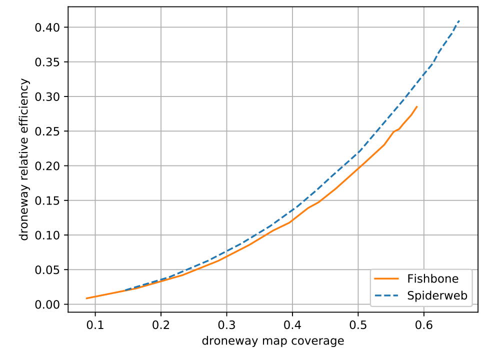
(a) $P = 10$ (b) $P = 600$

Figure 12 – Paris Fishbone resulting droneways for $P = 10$ and $P = 600$.

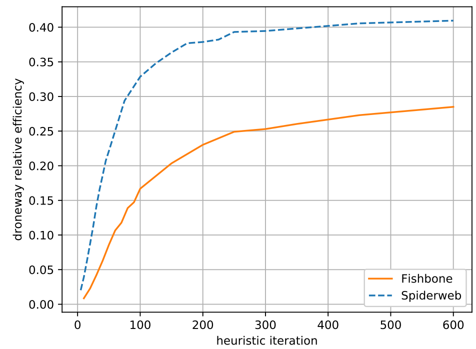


(a) $Q = 5$ and $P = 8$. (b) $Q = 600$ and $P = 8$

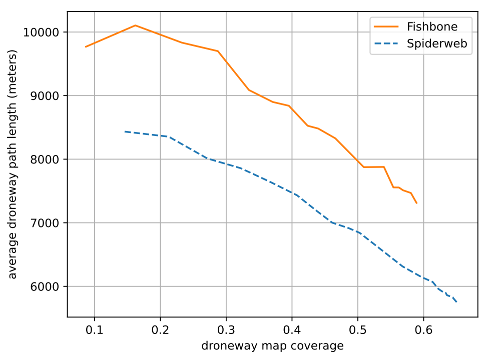
Figure 13 – Paris Spiderweb resulting droneways for $Q = 5$ and $Q = 600$.$P = 8$ for both droneways.



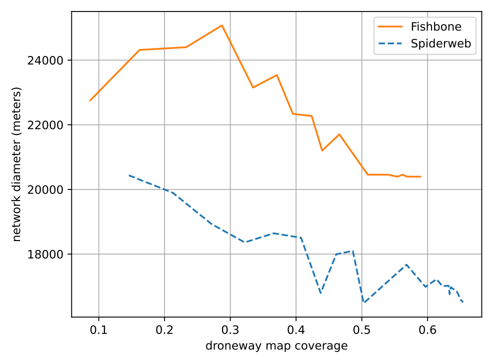
(a) Efficiency increase by coverage ratio



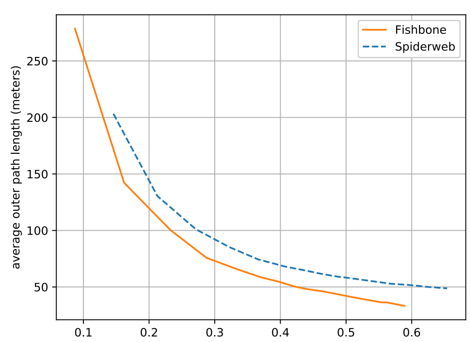
(b) Efficiency increase by iteration



(c) Average path length by coverage ratio



(d) Network diameter by coverage ratio



(e) Average outer ways path length by coverage ratio

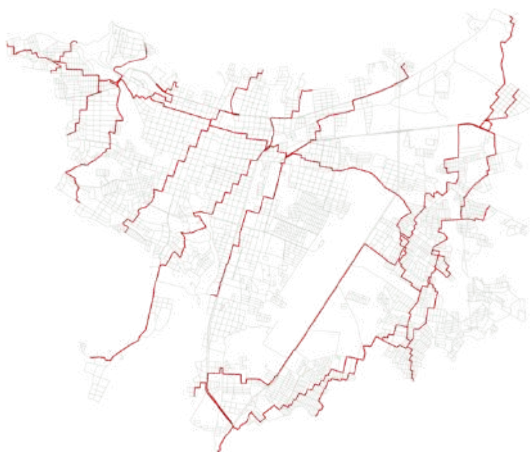
Figure 14 – Paris Fishbone and Spiderweb heuristics results comparison.

4.4 Uruapan

Over Uruapan map, the Fishbone droneways have covered from nearly 11% (when P = 10) to 47% (when P = 600) of the street map (Figure 15). The coverage of the Spiderweb droneways was nearly 19% (when Q = 5) up to 58% (when Q = 600) of the street map (Figure 16). The droneways were tested for efficiency, and in all cases the Spiderweb ones has shown a higher efficiency for a given map coverage, as can be seen in the Figure 17a.

Both heuristics have saturated fast when adding more paths to the droneways, as shown in Figure 17b. This is the same behaviour from Manhattan and Paris droneways.

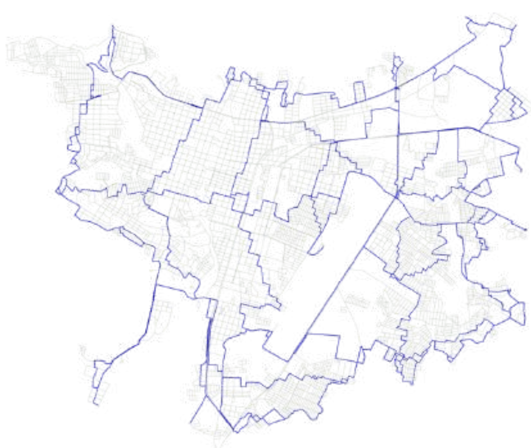
In Uruapan it can be noticed that the Fishbone droneways relative efficiency has saturated earlier than the Spiderweb's one.



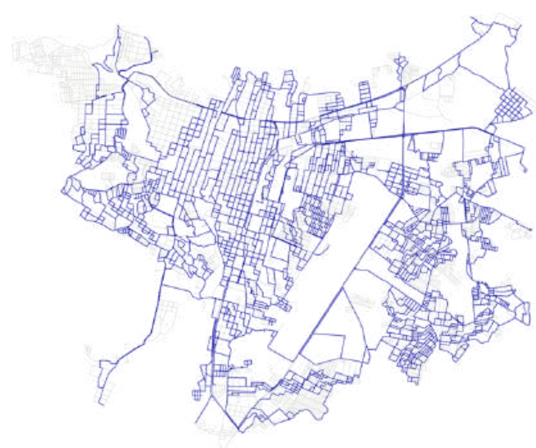
(a) $P = 10$

(b) $P = 600$

Figure 15 – Uruapan Fishbone resulting droneways P=10 and P=600.

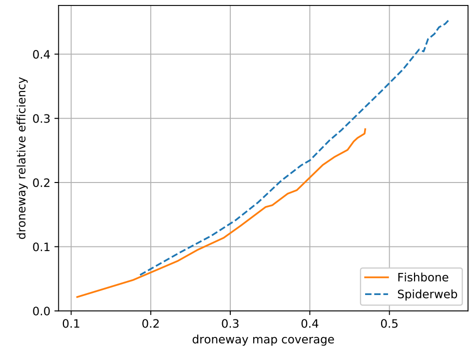


(a) $P = 8, Q = 5$

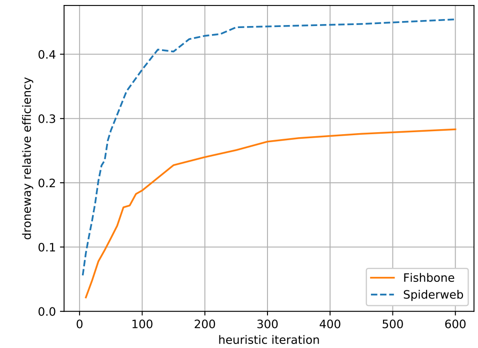


(b) $P = 8, Q = 600$

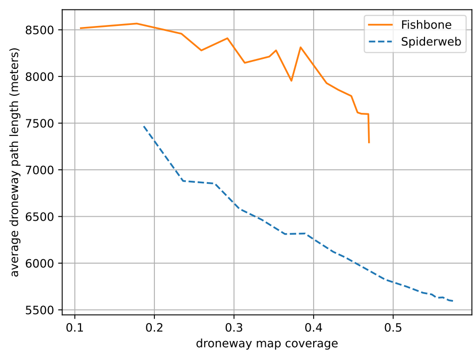
Figure 16 – Uruapan Spiderweb resulting droneways for Q=5 and Q=600. P=8 for both droneways.



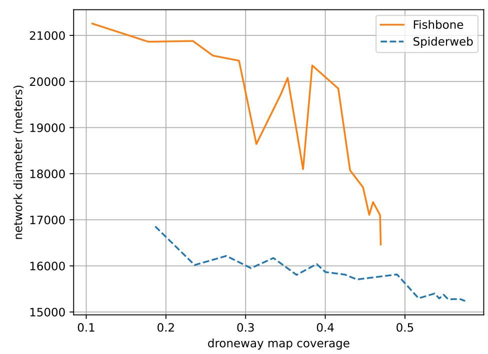
(a) Efficiency increase by coverage ratio



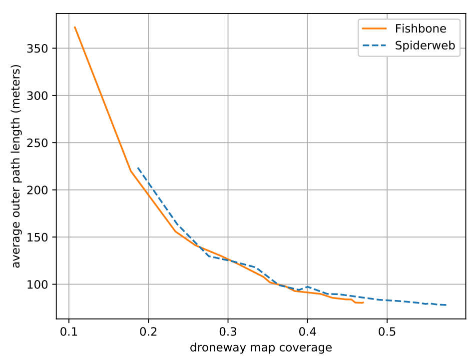
(b) Efficiency increase by iteration



(c) Average path length by coverage ratio



(d) Network diameter by coverage ratio



(e) Average outer ways path length by coverage ratio

Figure 17 – Fishbone and Spiderweb heuristics results comparison for Uruapan.

The average path length (Figure 17c) and network diameter (Figure 17d) are also shorter for the Spiderweb resulting droneways in Uruapan. So, it can be inferred that a drone have shorter delivery times in Spiderweb droneways.

The Figures 17e shows how the ALOP is reduced as the map coverage increases. The coverage is similar for Fishbone and Spiderweb in the range around 0.18 to 0.48. For this reason, the ALOP can not be used as criteria to choose between the heuristics in Uruapan.

In this section, we have presented the obtained results, discussing them throughout the text. In the next section, we present and justify some limitations of this work.

4.5 Limitations

The droneways are intended to be a balance proposal. On the one hand we have convenience, low cost and environmental benefits for the drones, and on the other, personal privacy and safety precautions to be taken. To achieve this balance, we suggest reducing the street map coverage, suggesting an efficient topological structure. This is not going to completely solve the personal privacy and safety issues, but it should help in applying the restriction rules imposed by the agencies, which mostly seeks to protect people involved in the operation, while also considering that drones must fulfil their tasks quickly, using the shortest possible paths for their deliveries.

We have proposed two heuristics based on shapes known for their efficiency in Complex Networks. These two could probably be applied to any street map over the planet. However, other heuristics could be employed and, in certain circumstances, they could surpass the results from the ones proposed here. It is, indeed, not feasible to test every possible heuristics, as there is not a known definite set of them to be used for this task, and the ones proposed in this work were sufficient to achieve the objectives of this work.

Our work has the premise that a drone can depart from anywhere and arrive at anywhere else. This makes this work quite generic, allowing it to be applied on different locations, but on the other hand, requires higher map coverage. If data about departure and arriving places and distribution centers become available, this could be considered to help reduce map coverage.

We do not go into drones operational, chemical, mechanical or electrical details, nor discuss drones mechanisms for: collision avoidance, routing, conversion, altitude control, emergency landing, obstacle detection, or any other features that are needed for the drones to fulfill their tasks. The droneways proposal does not depend on drones speed, their load, routing, or any drones operations, but on the droneways configuration to provide efficiency, safety and privacy.

In this proposal, droneways have a fixed configuration and are exclusively related to the city street map topology. An approach not addressed in this work would be the real-time dynamical reconfiguration of the droneways. This could be useful, for example, to avoid momentarily inappropriate paths, to allow a drone-free time in a specific area, or to attend to safety issues. Nonetheless, this dynamical reconfiguration would be tied to the needs of a specific location, and we are seeking to offer a generic proposal to be the foundation for the droneways.

With the work's limitations established, we can move on to the summary of this chapter.

4.6 Summary of Results

To better understand and compare the droneways behaviour in the three selected locations, Table 4 presents a summary of the metrics results. It can be noted that the resulting droneways from the Spiderweb heuristic surpassed the Fishbone heuristic ones in almost all attributes. Spiderweb heuristic provided droneways with higher efficiency and shorter average path length and diameter than the Fishbone ones for any given map coverage. In the three evaluated maps, the Spiderweb droneways presented smaller average shortest path length and diameter.

The only attribute that was better for Fishbone resulting droneways is the ALOP. After its evaluation, it was observed that the difference betweeen the ALOP from both heuristics is negligible, making a drone to fly, in average, no more than 25 m outside the droneways to finish the delivery. When compared to the droneways average shortest path, the additional distance from one heuristic to another can be more than 1000 m, favouring the Spiderweb droneways.

It is worth notice that, for all the droneways, the relative efficiency do not have a linear relation to the map coverage. For the three cities the maximum coverage is near 60%, but the relative efficiency is around 40% of the full map for Paris and Uruapan, and around 25% for Manhattan. This happens because the droneways are intended to be evenly distributed through the maps. The efficiency of the droneways tends to increase as it become closer to be the complete streets set of the selected maps. If droneways were implemented on a map, covering 60% of its paths, but all of them condensed around the higher betweeness node, letting the other 40% aside, it would probably have a higher relative efficiency, but the outer paths would be very high, maybe even higher than average path length. In the proposed solution, the outer paths are very short in comparison with the average path length of the droneways.

Sacrificing the relative efficiency in favour of the outer paths length is necessary for the droneways to be safer for people. The droneways are intended to bring a balance to the drones operation on populated areas, providing efficient paths for the drones to fly while also takes into account the safety and privacy of the citizens.

As the Spiderweb droneways shown better results, for easily understand their advantages and why planning it carefully is important, consider the 35-Spiderweb-Manhattan droneways. It covers 33% of the map, has a relative efficiency of 11%, the average outer path length is around 98 m, and the droneways average shortest path is around 8284 m. Based on these distances, it can be inferred that the drones would fly 98.83% of their delivery path over the droneways and only 1.17% of their path outside them.

The operational costs would be smaller to implement the droneways over 33% of the map,

	Fishbone	**Spiderweb**	**Map**
Coverage	11% to 47%	19 to 58%	Uruapan
	9% to 59%	14% to 65%	Paris
	7% to 68%	14% to 58%	Manhattan
Relative Efficiency Saturation	Earlier	Later	Uruapan
	Earlier	Later	Paris
	Earlier	Earlier	Manhattan
Droneway Average Shortest Path Length	Larger	Shorter	Uruapan
	Larger	Shorter	Paris
	Larger	Shorter	Manhattan
Droneway Diameter	Larger	Shorter	Uruapan
	Larger	Shorter	Paris
	Larger	Shorter	Manhattan
Average Outer Path Length	Equals	Equals	Uruapan
	Shorter	Larger	Paris
	Shorter	Larger	Manhattan

Table 4 – Summary of the results

and it would cover 98.83% of the drones operation. The other 1.17% must not be ignored, but different precautions can be taken for the area, involving reduced cost actions, as public awareness and rescue team training for emergency cases.

To meet the privacy and safety requirements, it will be necessary to settle an operation to constantly monitor the drones delivering process. In the example above, it would be easier and cheaper to install cameras and sensors in 33% of the streets than to the entire set. If only the droneways were monitored, on average 98.83% of the time the drones would be inside the monitored area, granting more safety for the operation.

Privacy concerns would be reduced by using the droneways. In this specific case, 67% of the streets would be used for a little short time, avoiding dwellers of the area to be bothered by the drones most of the time. If the droneways could be prepared to inform people of the droneways purpose, owners and data collected, people involved in the operation could feel more comfortable about their privacy, as pointed by Uchidiuno *et al.* (2018). This way, not only personal privacy would be increased, but also unauthorized drones could be identified by people, increasing the safety and security of the droneways.

Looking back to the Hristozov and Shishkov (2020) work, the droneways could help on achieve the solutions proposed by the authors in their conclusions: 1) human safety must be the top priority in the sky, and as drones are intended to fly only over streets, people should be safer on sidewalks and pathways. People walking in streets outside the droneways should also be more safety; 2) the droneways can be implemented integrating other IoT related technologies and manned aircraft systems; 3) the droneways could help on following a defined aircraft taxonomy for any objects in the sky; 4) it could help on follow the recent regulations; and 5) investigation and traceability mechanisms could be integrated with the droneways to enforce accountability.

If the operation needs to keep the drone under EVLOS, to meet regulations restrictions for example, the droneways could also be of help. Cameras installed along the routes could keep the drones under EVLOS most of the time, being remotely monitored and controlled when necessary.

Now, to compare the differences between two droneways, consider the 600-Spiderweb-Manhattan: it has 58% map coverage and 23% relative efficiency, both approximately twice the value if compared to the 35-Spiderweb-Manhattan droneways. The greater efficiency comes with a high price, as the investments to build that droneways could also be two times compared to the previous example.

The 600-Spiderweb-Manhattan has the ALOP of 73 m and an average shortest path length of 7477m, both representing a reduction of respectively 25% and 9% compared to the 35-Spiderweb-Manhattan. In this droneways, on average the drones would fly 99% of the time inside the droneways and 1% outside of it.

At first look, judging by the investments necessary to establish the operation, the 600-Spiderweb-Manhattan droneways do not seems to be advantageous, but it is worth noting that a closer analysis should be made to take this decision. In the long run, a large number of deliveries in a large period of time could justify the initial investment, reducing the energy or fuel consumption, improving the security by having bigger droneways, reducing delivery time and allowing more deliveries.

The examples brought to discussion shown that droneways can bring many advantages against drones freely flying above all the streets. The heuristics used in this work are based on known structures considered efficient. However, to find the most efficient droneways for a given coverage ratio, it would be necessary to test all possible droneways sets, calculating the coverage and efficiency, which has a high computational cost, takes time and demand computation resources. Nevertheless, it should be considered in the case of implementing a real droneways operation, which would certainly have a high economical cost.

In the previous section we have exposed the limitations of this work. It basically seeks to find a balance between convenience for the drones operation and personal privacy and safety, inevitably weakening one side when favoring the other. Other heuristics to solve this problem may exist, but it is not feasible nor necessary to seek and use them all, as the ones proposed here were enough to make our conclusions. As this work aims to be the foundation of the droneways, it was chosen to keep it generic to be applied on any street map, to use any type of delivery drones, with no restriction from departing and arriving places, and not considering any type of environmental issues to dynamically reconfigure the droneways.

In this chapter, we first established and discussed this work limitations. After that, it were presented and discussed the results of this work, discussing each location results in different sections. The limitations of this work were then explained. Finally, a summary of this chapter were presented and in the next one the conclusions and recommendations for future works are exposed.

5 Conclusion and Future Works

When it comes to deliveries using drones, we have two extreme situations: one would be the optimal condition for the drones to fly, without any restrictions, going in a straight line from source to the target destination to make the delivery. The other one is from the people involved in the operation, that wants the guarantee to live in a safe environment, without having to worry about their privacy being violated, whether inside or outside their homes. In the middle of this, are the regulatory agencies, trying to make a balance between these extreme situations.

The droneways can help to reach this balance. By creating an organized infrastructure for the drones to fly, which can be supervised and assisted, safety precautions can be taken. As suggested by evaluating this work's results, drones may fly up to 98% of the time within the drowneways delimitations, avoiding to fly over private properties, yards and sidewalks. Drones could be kept under EVLOS inside it and inform sensors and devices along the droneways about their route and status. Different precautions could be taken on the remaining routes outside the droneways, where drones should fly 2% of the time, to avoid putting people in danger, as for example, mapping safer areas to land in emergency cases, or maybe an agreement with people to create landing stations in yards or roofs.

Droneways can also help to avoid privacy issues, as only authorized aircraft would be allowed to fly over it. Mechanisms could be installed along the droneways to assure that no intruder drones are flying over it, also granting more personal safety. Visual identification on the drones can help people to query the drone for its purpose and owner, also helping to identify outsiders.

To provide this balance, two heuristics were proposed and evaluated to find efficient droneways: the *Fishbone*, which has a main longitudinal path with several perpendicular paths crossing it; and the *Spiderweb*, which has its center on the most central intersection, surrounded by centered circular paths and several straight paths starting from it until the edge of the map, following equally distributed angles.

Using complex network metrics, droneways were investigated using maps of three selected locations: Manhattan, Paris and Uruapan. Evaluating the results, it was clear that the Spiderweb heuristic was better suited to find efficient droneways using the same map coverage as the Fishbone heuristic. The drones flying distance outside the droneways were generally longer in the Spiderweb, but as the results suggest, the time outside the droneways would be no more than 4 to 5 seconds longer, considering a drone flying at a low speed. The efficiency achieved in determining the droneways is not outweighed by this short additional time, leading us to the conclusion that the Spiderweb heuristic is the best choice.

This work has provided an unprecedented solution to the use of drones for delivery in populated areas, a problem actually being faced by delivery companies. It has contributed to the smart cities planning, suggesting a structure to manage and control drones, which can be used mainly for delivery, but has potential to be used for other important activities, such as security surveillance and real time traffic planning through footage by drones. It has increased the knowledge in urban topology, which can help to change existing cities and design new ones. It has provided a method for evaluation over existing city maps, planned or not, small or big ones. It has contributed to the Complex Networks, modelling cities as graphs and evaluating them using quantitative metrics. Thus, we consider that this work objectives were fully achieved.

Future Works

This work proposed the creation of the droneways. By modelling the street maps as complex networks, it was possible to propose a balance solution between convenience for the drones and personal privacy and safety. This was made suggesting a structure over a portion of a street map. With that in mind and thinking ahead, in this section are listed some future works suggestions.

Both heuristics proposed in this work, Fishbone and Spiderweb, are based on structures known as efficient. However, it is possible to find the most efficient structure by testing all combinations of streets for a given coverage. This would have a high computational cost, as the efficiency algorithm is greedy, but considering the magnitude of a real droneways and its economical costs, using a computer cluster with high processing power and high RAM memory, combined with an optimized algorithm, could provide the most efficient droneways. The proposed droneways are a starting point, which could be used to drive the droneways development to a most efficient structure.

Observed data from real operation could be evaluated together with the topology to create more suitable structures, as historical deliver data and demographic density. This could increase or decrease the droneways coverage on specific areas depending on the delivery demand. The same data can be used to reinforce safety on areas where drones could fly more often.

Finally, virtual simulations can be made on the droneways and using the complete streets set to gave an idea on how the structure would behave. Testing for random deliveries, tuning the amount of drones, droneways coverage, different drones speed based on different models, and testing strategic deliveries, based on previously mentioned population density or historical delivery data, if available, could gave an insight on how the system would work before building it.

References

AGÊNCIA NACIONAL DE AVIAÇÃO CIVIL. *Drones*. 2021. Available at: ⟨https://www.gov.br/anac/pt-br/assuntos/drones⟩.

AYDIN, B. Public acceptance of drones: Knowledge, attitudes, and practice. *Technology in Society*, Elsevier Ltd, v. 59, n. July, p. 101180, nov 2019. ISSN 0160791X. Available at: ⟨https://doi.org/10.1016/j.techsoc.2019.101180⟩.

BARABASI, A.-L. *Linked: How Everything Is Connected to Everything Else and What It Means*. [S.l.: s.n.], 2003. ISSN 1098-6596. ISBN 0452284392.

BOCCALETTI, S.; LATORA, V.; MORENO, Y.; CHAVEZ, M.; HWANG, D.-U. Complex networks: Structure and dynamics. *Physics Reports*, v. 424, p. 175–308, 2006.

CHOUDHURY, S.; SOLOVEY, K.; KOCHENDERFER, M. J.; PAVONE, M. Efficient large-scale multi-drone delivery using transit networks. *Journal of Artificial Intelligence Research*, v. 70, p. 757–788, 2021. ISSN 10769757. Available at: ⟨https://arxiv.org/abs/1909.11840⟩.

CHOW, N.; GUGAN, G.; HAQUE, A. RADR: Routing for Autonomous Drones. In: *2019 15th International Wireless Communications & Mobile Computing Conference (IWCMC)*. IEEE, 2019. p. 1445–1450. ISBN 978-1-5386-7747-6. Available at: ⟨https://ieeexplore.ieee.org/document/8766530/⟩.

COSTA, L. d. F.; RODRIGUES, F. A.; TRAVIESO, G.; Villas Boas, P. R. Characterization of complex networks: A survey of measurements. *Advances in Physics*, v. 56, n. 1, p. 167–242, jan. 2007. ISSN 0001-8732. Available at: ⟨http://www.tandfonline.com/doi/abs/10.1080/00018730601170527⟩.

DENTLER, J.; KANNAN, S.; MENDEZ, M. A. O.; VOOS, H. A real-time model predictive position control with collision avoidance for commercial low-cost quadrotors. In: *2016 IEEE Conference on Control Applications (CCA)*. IEEE, 2016. p. 519–525. ISBN 978-1-5090-0755-4. Available at: ⟨http://ieeexplore.ieee.org/document/7587882/⟩.

DEVASIA, S.; LEE, A. Scalable Low-Cost Unmanned-Aerial-Vehicle Traffic Network. *Journal of Air Transportation*, v. 24, n. 3, p. 74–83, jul 2016. ISSN 2380-9450. Available at: ⟨http://arc.aiaa.org/doi/10.2514/1.D0022⟩.

DIJKSTRA, E. W. A note on two problems in connexion with graphs. *Numerische Mathematik*, 1959. ISSN 0029599X.

EDDY, W. F. A New Convex Hull Algorithm for Planar Sets. *ACM Transactions on Mathematical Software*, v. 3, n. 4, p. 398–403, dec 1977. ISSN 00983500. Available at: ⟨http://portal.acm.org/citation.cfm?doid=355759.355766⟩.

European Union Aviation Safety Agency. *Civil drones (Unmanned aircraft)*. 2021. Available at: ⟨https://www.easa.europa.eu/domains/civil-drones-rpas⟩.

Federal Aviation Administration. *Unmanned Aircraft Systems (UAS)*. 2021. Available at: ⟨https://www.faa.gov/uas/⟩.

FLOREANO, D.; WOOD, R. J. Science, technology and the future of small autonomous drones. *Nature*, v. 521, n. 7553, p. 460–466, may 2015. ISSN 0028-0836. Available at: ⟨http://www.nature.com/articles/nature14542⟩.

GHARIBI, M.; BOUTABA, R.; WASLANDER, S. L. Internet of Drones. *IEEE Access*, v. 4, p. 1148–1162, 2016. ISSN 21693536. Available at: ⟨https://arxiv.org/abs/1601.01289⟩.

HART, P.; NILSSON, N.; RAPHAEL, B. A Formal Basis for the Heuristic Determination of Minimum Cost Paths. *IEEE Transactions on Systems Science and Cybernetics*, v. 4, n. 2, p. 100–107, 1968. ISSN 0536-1567. Available at: ⟨http://ieeexplore.ieee.org/document/4082128/⟩.

HRISTOZOV, S.; SHISHKOV, B. Unmanned Traffic Management - Motivation and Future Perspectives. In: *Proceedings of the 9th International Conference on Telecommunications and Remote Sensing*. New York, NY, USA: ACM, 2020. p. 33–37. ISBN 9781450377300. Available at: ⟨https://dl.acm.org/doi/10.1145/3430116.3430122⟩.

KHAN, M. A. Drones for Good in Smart Cities : A Review. n. January, 2018. Available at: ⟨https://www.researchgate.net/publication/316846331_Drones_for_Good_in_Smart_CitiesA_Review⟩.

KUMAR, A.; KRISHNAMURTHI, R.; NAYYAR, A.; LUHACH, A. K.; KHAN, M. S.; SINGH, A. A novel Software-Defined Drone Network (SDDN)-based collision avoidance strategies for on-road traffic monitoring and management. *Vehicular Communications*, Elsevier Inc., v. 28, p. 100313, apr 2021. ISSN 22142096. Available at: ⟨https://doi.org/10.1016/j.vehcom.2020.100313https://linkinghub.elsevier.com/retrieve/pii/S221420962030084X⟩.

LATORA, V.; MARCHIORI, M. Efficient behavior of small-world networks. *Physical Review Letters*, v. 87, n. 19, p. 198701–1–198701–4, jan 2001. ISSN 10797114. Available at: ⟨http://arxiv.org/abs/cond-mat/0101396⟩.

LAVARS, N. *Amazon to begin testing new delivery drones in the US*. 2015. Available at: ⟨https://newatlas.com/amazon-new-delivery-drones-us-faa-approval/36957/⟩.

MELLO, B. A.; CAJUEIRO, D. O.; GOMIDE, L. H. B.; VIEIRA, R.; BOUERI, R. *Teoria de Redes Complexas e o Poder de Difusão dos Municípios*. Instituto de Pesquisa Econômica Aplicada, Brasília, Brasil, 2010.

NEWMAN, M. E. J. The Structure and Function of Complex Networks. *SIAM Review*, v. 45, n. 2, p. 167–256, jan 2003. ISSN 0036-1445. Available at: ⟨http://epubs.siam.org/doi/10.1137/S003614450342480⟩.

PARK, S. H.; LEE, K. H. Developing Criteria for Invasion of Privacy by Personal Drone. *2017 International Conference on Platform Technology and Service, PlatCon 2017 - Proceedings*, p. 1–7, 2017. Available at: ⟨https://ieeexplore.ieee.org/document/7883702⟩.

SCHNEIDER, D. The delivery drones are coming. *IEEE Spectrum*, v. 57, n. 1, p. 28–29, jan 2020. ISSN 0018-9235. Available at: ⟨https://ieeexplore.ieee.org/document/8946304/⟩.

SHARMA, V.; JAYAKODY, D. N. K.; YOU, I.; KUMAR, R.; LI, J. Secure and Efficient Context-Aware Localization of Drones in Urban Scenarios. *IEEE Communications Magazine*, IEEE, v. 56, n. 4, p. 120–128, apr 2018. ISSN 0163-6804. Available at: ⟨https://ieeexplore.ieee.org/document/8337908/⟩.

TZELEPI, M.; TEFAS, A. Graph Embedded Convolutional Neural Networks in Human Crowd Detection for Drone Flight Safety. *IEEE Transactions on Emerging Topics in Computational Intelligence*, IEEE, v. 5, n. 2, p. 191–204, apr 2021. ISSN 2471-285X. Available at: ⟨https://ieeexplore.ieee.org/document/8657776/⟩.

UCHIDIUNO, J. O.; MANWEILER, J.; WEISZ, J. D. Privacy and Fear in the Drone Era. In: *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. New York, New York, USA: ACM Press, 2018. p. 1–6. ISBN 9781450356213. Available at: ⟨http://dl.acm.org/citation.cfm?doid=3170427.3188457⟩.

VATTAPPARAMBAN, E.; GÜVENÇ, I.; YUREKLI, A. I.; AKKAYA, K.; ULUAGAÇ, S. Drones for smart cities: Issues in cybersecurity, privacy, and public safety. *2016 International Wireless Communications and Mobile Computing Conference, IWCMC 2016*, p. 216–221, 2016. ISSN 2376-6492. Available at: ⟨https://ieeexplore.ieee.org/document/7577060⟩.

ZHU, X.; PASCH, T. J.; BERGSTROM, A. Understanding the structure of risk belief systems concerning drone delivery: A network analysis. *Technology in Society*, v. 62, p. 101262, aug 2020. ISSN 0160791X. Available at: ⟨https://www.sciencedirect.com/science/article/pii/S0160791X1930613X⟩.

Appendix

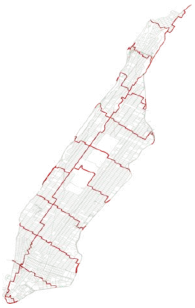
A Overpass Turbo filtering query

```
<osm-script output="xml" timeout="100">
    <union>
        <query type="node">
            <has-kv k="highway"/>
            <has-kv k="highway" modv="not" v="footway"/>
            <has-kv k="highway" modv="not" v="bridleway"/>
            <has-kv k="highway" modv="not" v="path"/>
            <has-kv k="highway" modv="not" v="traffic_signals"/>
            <has-kv k="highway" modv="not" v="cycleway"/>
            <has-kv k="motor_vehicle" modv="not" v="no"/>
            <has-kv k="highway" modv="not" v="steps"/>
            <has-kv k="highway" modv="not" v="service"/>
            <has-kv k="highway" modv="not" v="pedestrian"/>
            <has-kv k="-highway" modv="not" v="path"/>
            <bbox-query {{bbox}}/>
        </query>
        <query type="way">
            <has-kv k="highway"/>
            <has-kv k="highway" modv="not" v="footway"/>
            <has-kv k="highway" modv="not" v="bridleway"/>
            <has-kv k="highway" modv="not" v="path"/>
            <has-kv k="highway" modv="not" v="traffic_signals"/>
            <has-kv k="highway" modv="not" v="cycleway"/>
            <has-kv k="motor_vehicle" modv="not" v="no"/>
            <has-kv k="highway" modv="not" v="steps"/>
            <has-kv k="highway" modv="not" v="service"/>
            <has-kv k="highway" modv="not" v="pedestrian"/>
            <has-kv k="-highway" modv="not" v="path"/>
            <bbox-query {{bbox}}/>
        </query>
        <query type="relation">
            <has-kv k="highway"/>
            <has-kv k="highway" modv="not" v="footway"/>
            <has-kv k="highway" modv="not" v="bridleway"/>
            <has-kv k="highway" modv="not" v="path"/>
            <has-kv k="highway" modv="not" v="traffic_signals"/>
            <has-kv k="highway" modv="not" v="cycleway"/>
            <has-kv k="motor_vehicle" modv="not" v="no"/>
            <has-kv k="highway" modv="not" v="steps"/>
            <has-kv k="highway" modv="not" v="service"/>
            <has-kv k="highway" modv="not" v="pedestrian"/>
            <has-kv k="-highway" modv="not" v="path"/>
            <bbox-query {{bbox}}/>
```

```
        </query>
    </union>
    <print mode="meta"/>
    <recurse type="down"/>
    <print mode="meta" order="quadtile"/>
</osm-script>
```

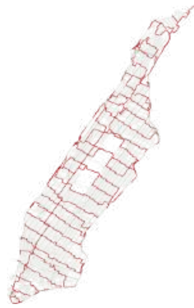
B Resulting Droneways

In this appendix are shown all the resulting droneways from this work. The images are grouped by location: Manhattan first, then Paris, and Uruapan last. For each location, are presented first the Fishbone heuristics droneways, painted in red, and then the Spiderweb ones, painted in blue. More detailed figures can be found in the thesis repository ⟨http://github.com/willunicamp/droneways⟩ or may be requested to the University of Campinas.

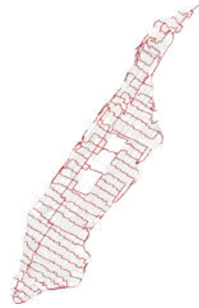


(a) $P = 10$.

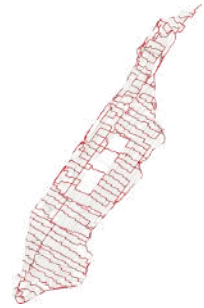
(b) $P = 20$.



(c) $P = 30$.



(d) $P = 40$.



(e) $P = 50$.

(f) $P = 60$.

(g) $P = 70$.

(h) $P = 80$.

(i) $P = 90$.

(j) $P = 100$.

(k) $P = 150$.

(l) $P = 200$.

(m) $P = 250$.

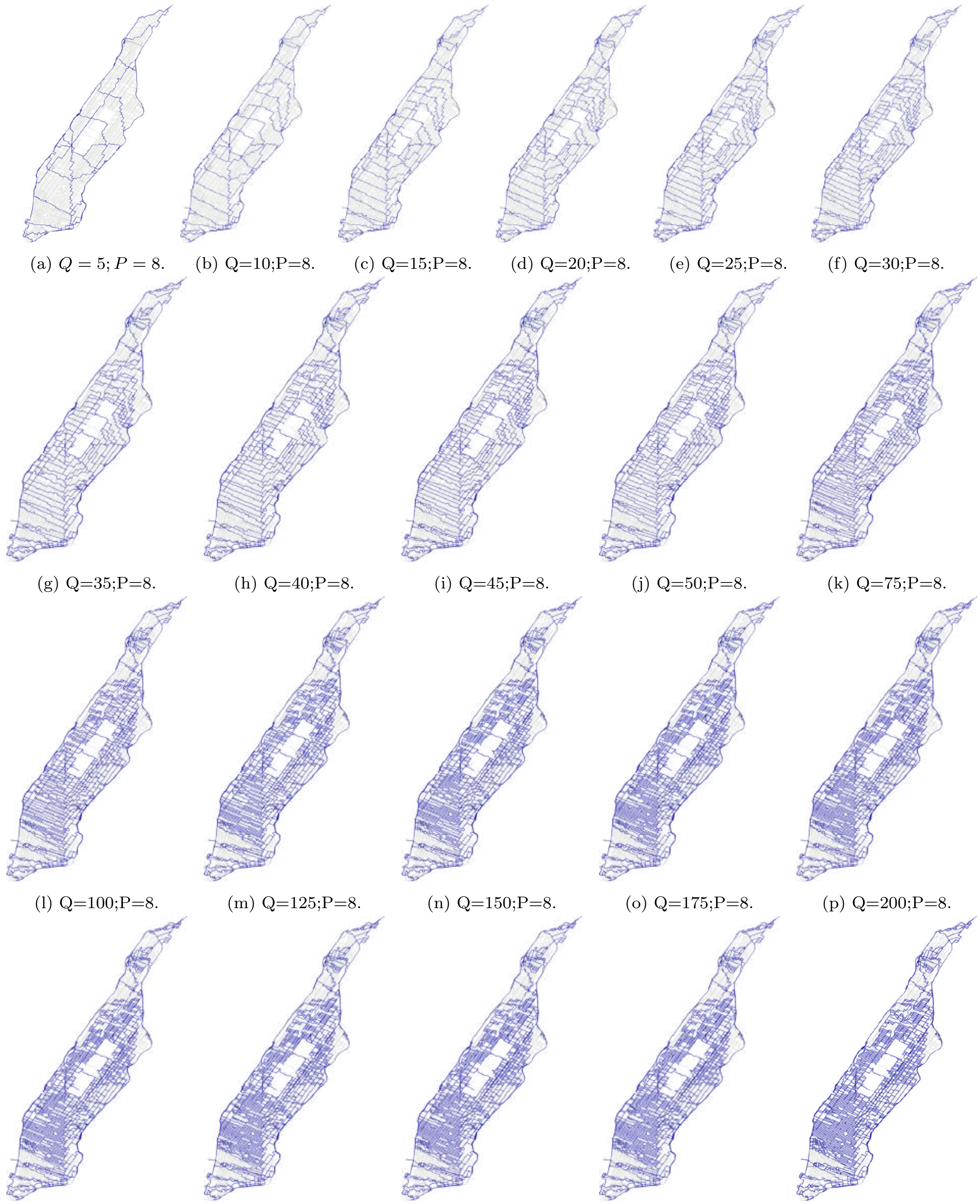
(n) $P = 300$.

(o) $P = 350$.

(p) $P = 450$.

(q) $P = 600$.

Figure 18 – Manhattan Fishbone resulting droneways.



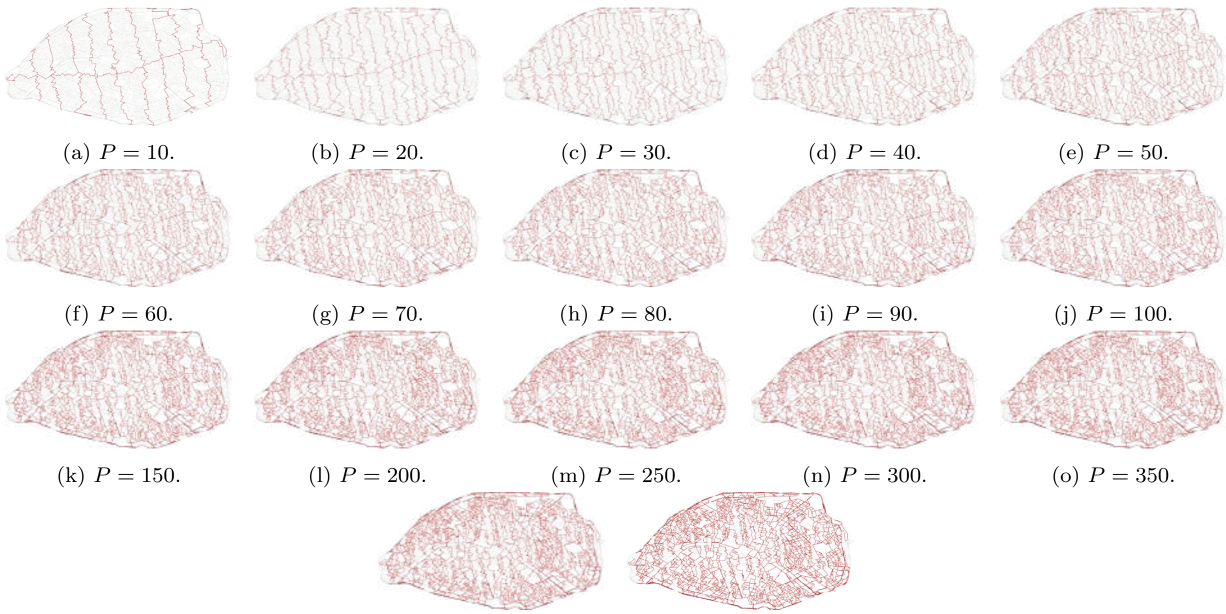
(a) $Q = 5$; $P = 8$. (b) Q=10;P=8. (c) Q=15;P=8. (d) Q=20;P=8. (e) Q=25;P=8. (f) Q=30;P=8.

(g) Q=35;P=8. (h) Q=40;P=8. (i) Q=45;P=8. (j) Q=50;P=8. (k) Q=75;P=8.

(l) Q=100;P=8. (m) Q=125;P=8. (n) Q=150;P=8. (o) Q=175;P=8. (p) Q=200;P=8.

(q) Q=225;P=8. (r) Q=250;P=8. (s) Q=300;P=8. (t) Q=450;P=8. (u) Q=600;P=8.

Figure 19 – Manhattan Spiderweb resulting droneways.



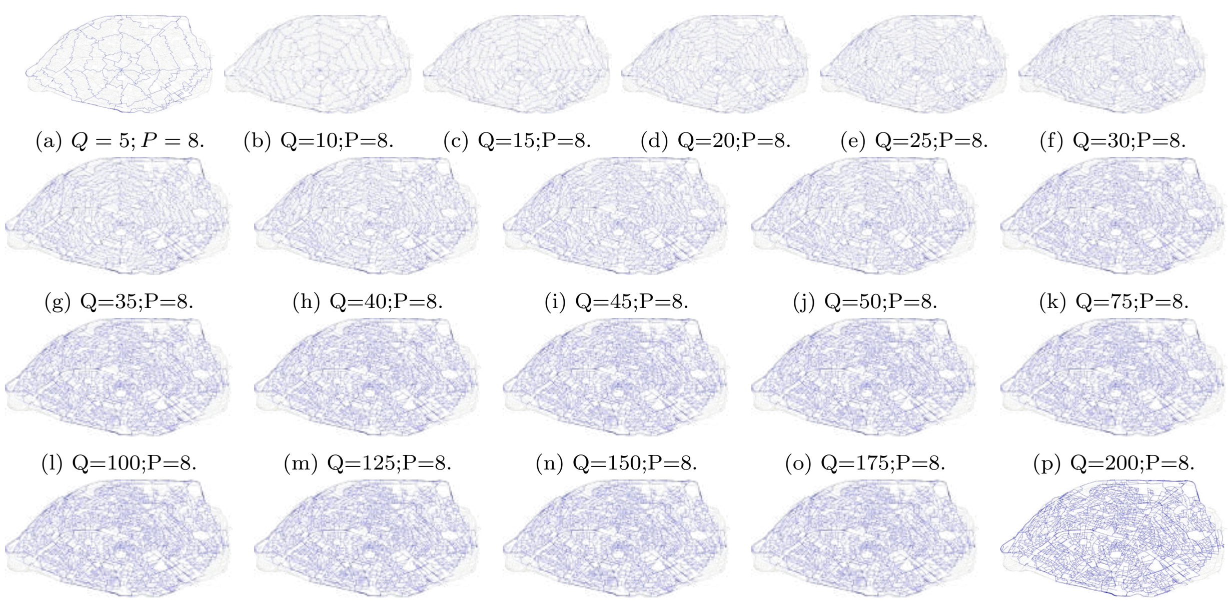
(a) $P = 10$. (b) $P = 20$. (c) $P = 30$. (d) $P = 40$. (e) $P = 50$.

(f) $P = 60$. (g) $P = 70$. (h) $P = 80$. (i) $P = 90$. (j) $P = 100$.

(k) $P = 150$. (l) $P = 200$. (m) $P = 250$. (n) $P = 300$. (o) $P = 350$.

(p) $P = 450$. (q) $P = 600$.

Figure 20 – Paris Fishbone resulting droneways.



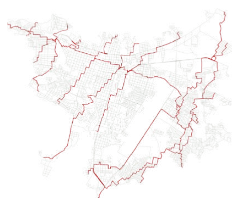
(a) $Q = 5; P = 8$. (b) Q=10;P=8. (c) Q=15;P=8. (d) Q=20;P=8. (e) Q=25;P=8. (f) Q=30;P=8.

(g) Q=35;P=8. (h) Q=40;P=8. (i) Q=45;P=8. (j) Q=50;P=8. (k) Q=75;P=8.

(l) Q=100;P=8. (m) Q=125;P=8. (n) Q=150;P=8. (o) Q=175;P=8. (p) Q=200;P=8.

(q) Q=225;P=8. (r) Q=250;P=8. (s) Q=300;P=8. (t) Q=450;P=8. (u) Q=600;P=8.

Figure 21 – Paris Spiderweb resulting droneways.

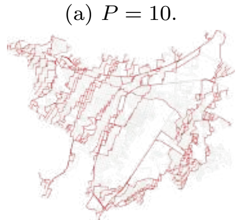

(a) $P = 10$.

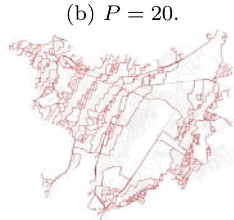

(b) $P = 20$.

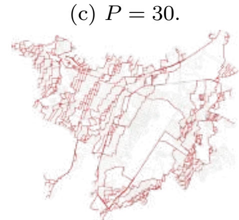

(c) $P = 30$.

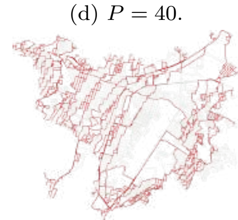

(d) $P = 40$.

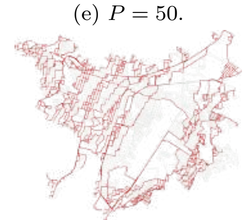

(e) $P = 50$.

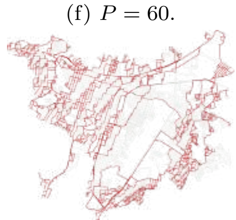

(f) $P = 60$.

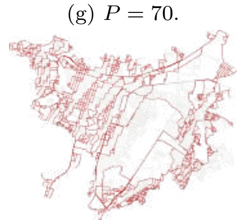

(g) $P = 70$.

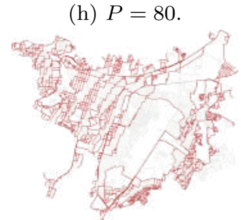

(h) $P = 80$.

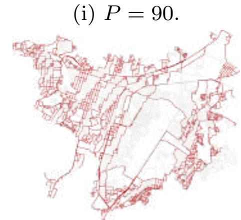

(i) $P = 90$.

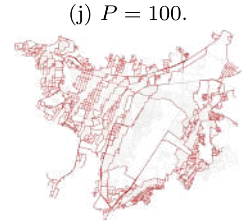

(j) $P = 100$.

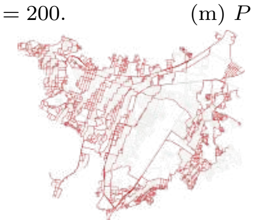

(k) $P = 150$.


(l) $P = 200$.


(m) $P = 250$.


(n) $P = 300$.


(o) $P = 350$.


(p) $P = 450$.

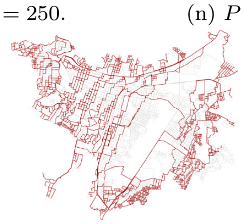
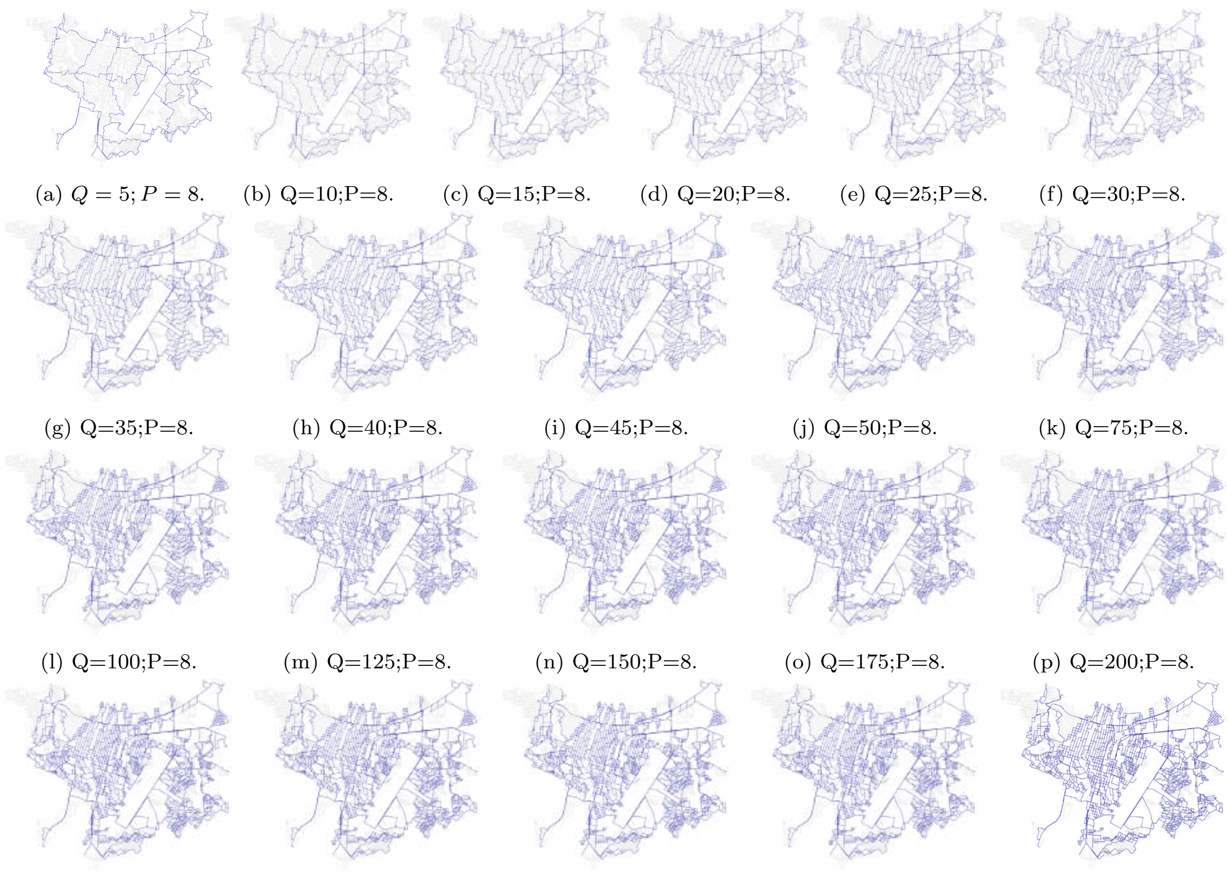

(q) $P = 600$.

Figure 22 – Uruapan Fishbone resulting droneways.



(a) $Q = 5; P = 8$. (b) Q=10;P=8. (c) Q=15;P=8. (d) Q=20;P=8. (e) Q=25;P=8. (f) Q=30;P=8.

(g) Q=35;P=8. (h) Q=40;P=8. (i) Q=45;P=8. (j) Q=50;P=8. (k) Q=75;P=8.

(l) Q=100;P=8. (m) Q=125;P=8. (n) Q=150;P=8. (o) Q=175;P=8. (p) Q=200;P=8.

(q) Q=225;P=8. (r) Q=250;P=8. (s) Q=300;P=8. (t) Q=450;P=8. (u) Q=600;P=8.

Figure 23 – Uruapan Spiderweb resulting droneways.