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Towards an automatic UAS-based mapping tool for first responders:
Defibrillator Missions
in Alpine Regions

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Dedicatory

“To my parents, Danny and Heidys, my sister Daniela
and my grandparents, Rosario, Eleazar, Elcida (†) and Pablo (†)”.
Eliezer Jesús, Fajardo Figueroa

“Usa el amor como un puente”.
Gustavo Cerati (1999), “Puente”.

Statement of Authorship

Herewith I declare that I am the sole author of the submitted Master's thesis entitled:

**"Towards an automatic UAS-based mapping tool for first responders:
Defibrillator Missions in Alpine Regions".**

I have fully referenced the ideas and work of others, whether published or unpublished. Literal or analogous citations are clearly marked as such.

Munich, 07.09.2023 Eliezer Jesús, Fajardo Figueroa

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Abstract

This research aims to design a map-driven distributed emergency drone service network, enable to localize suitable areas and propose time-effective strategies for delivering Automatic External Defibrillators (AED) in Alpine Regions. As a contribution to the development of a solution for first responders to plan automatic Unmanned Aircraft System (UAS) missions in mountainous environments.

The first phase of the study concentrates on designing a map-driven distributed emergency drone service network tailored to deploy UAS-AED missions within the Province of South Tyrol, Italy. The research begins by identifying suitable areas in South Tyrol for positioning drone stations, based on the unique spatial characteristics of the region. Potential locations to place the UAS stations are selected as the base of the proposed network, considering the spatial distribution of existing facilities in the studied area. Furthermore, the study estimates the spatial coverage that the proposed network could reach considering current UAS regulations.

The second phase focuses on defining a workflow for programming automatic flight missions to facilitate the efficient delivery of defibrillators using drones in Alpine environments, taking South Tyrol as a model for its implementation and testing. After a comprehensive analysis of the spatial variables critical for navigating demanding mountain scenarios. The study introduces the Low-Altitude-Flight Elevation Model (LAFEM) as a modified surface model for creating flight routes using least-cost path methods. Subsequently, a semi-automatic workflow, based on geographic information management and geoprocessing techniques, is developed to generate optimal flight paths for AED delivery using drones. To assess the effectiveness of the proposed workflow, field tests are conducted to compare its performance against other routing approaches considered by first responders in rescue missions.

The outcomes of this project show the extent that would have an emergency drone service network in the studied region, and the promising improvements of considering a routing workflow to plan automatic UAS-AED missions in mountain environments based on cartographic methods.

Key Words: Emergency Drone Service Network, Alpine Regions, Automatic External Defibrillators (AED), Unmanned Aircraft Systems (UAS), Low-Altitude-Flight Elevation Model (LAFEM), Cartographic Workflow, Optimal Flight Paths, UAS-AED Missions

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List of Abbreviations

2D	Two Dimensions
3D	Three Dimensions
AED	Automatic External Defibrillator
AIP	Aeronautical Information Publication
DEM	Digital Elevation Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
EMS	Emergency Medical Services
FR	First Responders
GIS	Geographic Information Systems
GPS	Global Positioning System
LAFEM	Low-Altitude-Flight Elevation Model
MEM	Mountain Emergency Medicine
NOTAM	Notice to Airmen
OHCA	Out-of-Hospital Cardiac Arrest
RO	Research Objective
RQ	Research Question
SAR	Search and Rescue
SDG	Sustainable Development Goal
UAS	Unmanned Aircraft System

1. Introduction

1.1. Motivation and Problem Statement

Cardiovascular disorders are the main cause of emergencies with fatal outcomes related to mountain activities in Alpine Regions (23% average) (Mitterer, 2023). Time is crucial to respond effectively to these urgencies, which drives local rescue teams to consider novel strategies to aid the affected and increase their odds of survival (P. Fischer et al., 2023). Adopting methods such as drones to deliver Automatic External Defibrillators (AED) to assist Out-of-Hospital Cardiac Arrests (OHCA) in remote scenarios (Lim et al., 2022a).

The technological development of Unmanned Aircraft Systems (UAS), also known as drones, has extended the applications of these aircrafts in the civil sector, being relevant tools in fields such as environmental management, land mapping, commercial delivery and healthcare services (Sabino et al., 2022). Recent studies have demonstrated their efficiency to carry supplies flying over long distances, making them feasible to transport AED to assist OHCA with chances of improving the response time of Emergency Medical Services (EMS) (Baumgarten et al., 2022). Although this solution has shown promising time savings, especially in rural areas (Lim et al., 2022a). Its procedures still need further development and testing to be implemented extensively in mountain environments (Wankmüller et al., 2020).

Some factors that require to be optimized to deliver AED using drones effectively, are the placement of the stations to deploy the drones and routing systems to flight avoiding obstacles (Lim et al., 2022a). Implementing this in Alpine Regions, would need to identify suitable locations within limited facilities to perform the missions, as well as a routing workflow capable of identifying efficient pathways in a 3D environment, considering detailed elevation models to assure safe flights in the shortest time (Wankmüller et al., 2020).

These requirements have an intrinsic spatial component, which can be addressed through the use of cartographic and geostatistic methods based on suitability models and least-cost paths (Bennett & Calkins, 2013; Hildemann & de Campolide, 2019). Generating optimal routes for drones to flight at low-altitude, compatible with the on-going design of a secure airspace for UAS operations as the U-Space (Xu et al., 2020), keeping a safe altitude across topographic variations while avoiding obstacles, to support the joint efforts of emergency teams (Wankmüller et al., 2021). Aiming to integrate these automated drone routes into a UAS-based mapping application for first responders to plan defibrillator missions in Alpine Regions.

1.2. Research Objectives and Questions

According to the presented statements, the overarching objective of this research is:

To design a map-driven distributed emergency drone service network enabled to localize suitable areas and suggest time-effective strategies to deliver AED in Alpine Regions.

The main objective of this work, is tackled by pursuing the following Research Objectives (RO) according to the Research Questions (RQ), taking the Autonomous Province of South Tyrol in Italy, as the model study region to implement the proposed solutions.

RO1 To propose a map-driven distributed emergency drone service network to deploy UAS-AED missions in South Tyrol, Italy.

RQ1 Where are the suitable areas in South Tyrol to provide emergency drone services according to its general geographic conditions and local spatial flight restrictions?

RQ2 What is the optimal spatial configuration of an emergency drone service network to time-effectively cover South Tyrol?

RQ3 How much is the spatial coverage of the proposed emergency drone service network according to UAS capabilities and constraints in South Tyrol?

RO2 To define a workflow to program automatic low-altitude-flight missions for drones to deliver medical supplies adapted to the topographic variations of South Tyrol, Italy.

RQ4 What spatial variables should be considered to program automatic low-altitude-flight missions for emergency drone services adapted to the topographic variations of South Tyrol?

RQ5 How can be developed a map-based workflow to program optimal automatic missions for emergency drones to deliver medical supplies in South Tyrol?

RQ6 How effective are the missions generated with the proposed workflow against other routing approaches implemented in mountain rescue operations in South Tyrol?

1.3. Research Scope

This research aims to propose locations for an emergency drone service network based on existing facilities of South Tyrol, Italy, and a map-based routing workflow capable to find optimal paths to deliver AED following the terrain variations of the province. As a model to foster the implementation of UAS-AED missions in Alpine Regions, supporting the labour of local first responders to assist life-threatening emergency calls in mountain environments.

The emergency drone service network is proposed according to a tailored suitability model based on spatial raster weighted overlay and nearest neighbour cluster point analysis (By & Huisman, 2009; M. M. Fischer & Getis, 2010). For this is used the most recent spatial information available in the geoportal of South Tyrol, regarding digital elevation models, land use, protected areas, line service infrastructure and service facilities (Südtiroler Bürgernetz, 2023). In relation to the spatial restrictions regarding drone operations, are used UAS Geographical Zones based on areas defined by the Italian Civil Aviation Authority (ENAC) (d-flight, 2023). The location of the facilities and complementary cartographic information of the studied region is based on open data provided by OpenStreetMap contributors (OpenStreetMap, 2023).

The routing workflow proposed is based on least-cost path analysis over an adapted elevation model that integrates vertical and horizontal modifications to assure safe flights on a highly restricted 3D environment (de Smith et al., 2021; Hildemann & de Campolide, 2019; Lifeng Liu & Shuqing Zhang, 2009). This workflow is designed using the Model Builder application in ArcGIS Pro 3.1, creating a semi-automatic geoprocessing model that runs a set of GIS-based processes using a visual programming language. As the outputs of this workflow can be obtained a 3D vector line, which vertex are transformed into a table of waypoints to define the pathway of the drone towards an emergency point. Which require to be adapted to the data format required by the UAS provider to perform the mission.

The outcomes of this research aim to be integrated into the DRONE-AED project coordinated by Eurac Research in South Tyrol. Supporting their endeavour to develop a UAS meant to deliver medical supplies under extreme circumstances. The estimations related to drone-based services, spatial coverage and mission routing in this research, were be done considering the parameters of the aircraft in developed the frame of the DRONE-AED project. Furthermore, the examples and tests presented in this research took place in the Autonomous Province of South Tyrol in Italy, looking forward to its potential application in other areas of the Alpine Regions (Van Veelen, Mendicino, et al., 2023).

1.4. Innovation Intended

The distribution of the emergency drone service network in this research, and the routing workflow to deliver defibrillators in mountain environments using these devices, are proposed from a cartographic approach. Using methods that rely mainly on spatial analysis and geostatistics, such as suitability models to filter the locations of the potential UAS-AED facilities, least-cost paths to define the optimal aerial routes through challenging terrain, and spatial raster filtering and modifications to generate a tailored surface model to calculate the mentioned routes. Exploring unconventional fields for cartographic studies such as drone automation and mountain emergency medicine, aiming to solve underlying problems with a spatial component and propose solutions based on geographic information, thus making the maps an essential part of the decision-making process.

The routing workflow and coverage estimation of the proposed drone network are inspired on recent efforts that aimed to defined UAS routes in a highly restricted 3D urban airspace (He et al., 2022; Hildemann & Verstegen, 2023) Aiming to extent this potential to mountain environments, supporting the efforts of first responders in Alpine Regions by delivering medical supplies (Van Veelen, Roveri, et al., 2023). The routes generated with the proposed workflow are based on a Low-Altitude-Flight Elevation Model (LAFEM), which is presented in this research as a solution to route drone pathways according to a predefined altitude threshold following topographic variations, while avoiding obstacles.

These capabilities can be implemented to support the development of the U-Space project, initiated by the European Commission, which is defining the framework to deploy drones in low-level airspace, ensuring safe interactions with manned aviation operations (Bauranov & Rakas, 2021). To allow automatic drone operations beyond visual line of sight (BVLOS), relying on highly automated services to deliver medical supplies in a dense traffic airspace as in remote scenarios (Xu et al., 2020).

Since the results of this research aim to contribute with the improvement of the capabilities of Emergency Medical Services (EMS) in Alpine Regions, providing a workflow based on cartographic methods that can be integrated in an automatic application to determine optimal routes to deliver AED using drones. This project is aligned with the Sustainable Development Goals (SDG) 3.8 and 9.3 respectively, expecting to extended the coverage of health services for life-threatening emergencies, as sudden cardiac arrests, in sparsely populated areas or zones with limited access in the Apls (UN, 2023). As well as supporting the development of

UAS technologies in local companies of South Tyrol (Italy), such as Eurac Research and Mav Tech, to incorporate these solutions as a suitable option to provide medical supplies timely as a contribution to the DRONE-AED project (Van Veelen, Mendicino, et al., 2023).

1.5. Thesis Outline

This project is organized in six chapters that elaborate every aspect of the presented research. The introduction gives a general background of the project, including motivation and objectives. The literature review describes the development and methods related to UAS delivery for medical purposes, as well as cartographic solutions used by first responders. The methodology describes the detailed process implemented to determine the proposed drone emergency drone network and its coverage, and the routing workflow based on a Low-Altitude-Flight Elevation Model (LAFEM). The experimental setup describes the areas of interest and explains how was applied the stated methodology, including the practical tests. The results and discussion describe the findings and considerations of the experiments. Finalizing with a summarized conclusion.

2. Literature Review

This chapter summarizes the findings of the review of related works to the study (Table 1), aiming to understand the current developments regarding the use of defibrillators in mountain regions, AED-UAS delivery and routing process and map-based tools used by first responders.

2.1. Automatic External Defibrillators in the Mountains

The Automated External Defibrillators (AED) are portable medical heart monitors and defibrillators capable of recognizing certain cardiac affections and performing defibrillation shocks whether a victim needs it (Elsensohn et al., 2006). Improving the accessibility of these devices might increase the positive outcomes of Out-of-Hospital Cardiac Arrests (OHCA) (Liu et al., 2021). Especially facing life-threatening conditions such as cardiac arrhythmias, ventricular fibrillation or pulseless ventricular tachycardia, that could be treated in an early stage using AED with chances of increasing the survival rate with good neurological results for the patients (Paal & Elsensohn, 2021).

According to the International Commission for Mountain Emergency Medicine (ICAR-MEDCOM), it is crucial to introduce defibrillators for public access in popular areas, especially those which are easily accessible by persons with high risks for sudden cardiac death (Elsensohn et al., 2006). In urban environments over 75% of the affected by cardiac arrests do not receive adequate care, which may be lower in mountain scenarios due to logistic reasons and their geographical context (Elsensohn et al., 2006). Therefore, it is important to define strategically the placement of AED aiming to extend the coverage of cardiac arrests, which can be done based on cartographic methods (Ball et al., 2022).

In the systematic review made by Liu, were highlighted three different approaches to estimate the optimal number of AED and their location in an area of interest (Liu et al., 2021). The first strategy is the “guidelines-based”, where the devices are placed according to a radius to the location of documented OHCA incidents (Liu et al., 2021). The second one refers to a “grid-based” approach, that determine the location of the defibrillators considering regular and mixed distances (Liu et al., 2021). The third one is the “landmark-based”, where the location of the devices rely on the specific characteristics of the considered places, such as subway stations, recreational areas and educational institutes, offering bystanders the chance to access quickly to them in case of an emergency (Liu et al., 2021).

This last approach is currently been used in many countries to determine the distribution of their public access defibrillators network (Liu et al., 2021). As well as can be applied to compare different candidate locations, in relation to their position and services, ranking them according to their potential to supplement the existing OHCA coverage by placing AED strategically (Ball et al., 2022).

Public networks of defibrillators have had excellent results in assisting primary cardiac arrests in urban areas, however this is not a suitable solution to assure a timely response in mountains and remote areas due to the sparce population and the conditions of the terrain (Vögele et al., 2020). These devices should be placed in areas with high probabilities of use, such as ski slopes, huts and restaurants in the mountains and highly visited locations (Elsensohn et al., 2006). Even though the chain of survival in OHCA in these environments can still be strengthened by establishing drone services to deliver the AED, to reach the population in need and reduce the time to first defibrillation in such places (Vögele et al., 2020).

To extend the health service coverage in remote scenarios, there have been efforts to design optimized networks to deliver AED using Unmanned Aerial Systems (UAS). In Canada, was estimated a theoretical drone network using a mathematical model, focused in reducing the AED arrival in comparison to historical data (Boutilier et al., 2017). With this approach was possible to define the zones where is more likely to occur OHCA and define the placement of drone bases where the delivery could be done in urban and rural areas, to improve the median response time from local Emergency Medicine Services (EMS) in an integrated space unit (Boutilier et al., 2017).

Specially for mountain environments, a similar approach was adapted considering the geographic conditions and infrastructure available in Alpine Regions (Wankmüller et al., 2020). Using an Integer Linear Program (ILP) to analyse candidate places such as alpine huts and fire stations to allocate drone bases for the region South Tyrol (Italy), was possible to estimate response times around 5 minutes in distant areas, which enter in a suitable threshold to assist sudden cardiac arrests (Wankmüller et al., 2020).

These studies provide decision makers with powerful insight to use local infrastructure and emerging technologies to extend the coverage of OHCA to the farthest regions (Wankmüller et al., 2020). Even though, there are still important technical and logistic challenges to overcome in order to exploit this potential (Boutilier et al., 2017).

2.2. Unmanned Aircraft Systems and Automatic External Defibrillators

On 2021 in Sweden, a 71-year-old man suffered a cardiac arrest, for which the local EMS sent an ambulance and an AED-equipped drone to the scene (Schierbeck, Svensson, et al., 2022).

The drone flew autonomously and delivered the AED safely near the victim, who received the first shock shortly after the call and survived with a full neurologic recovery (Schierbeck, Svensson, et al., 2022).

Success cases like this, prove that it is feasible to deliver defibrillators using Unmanned Aerial Systems and their capability to provide early defibrillation to patients that need it with extreme urgency (Schierbeck, Svensson, et al., 2022).

The promise of improving the response times of Emergency Medical Services during the most time-critical medical emergencies using these devices, have been pushing the development of this emerging technology worldwide (Lim et al., 2022b). Nowadays there is evidence that it is safe and feasible to use them for delivering an AED to assist OHCA, starting from Geographic Information System (GIS) models as a spatial reference to identify the deployment areas (Ayamga et al., 2021).

UAS are small aircrafts that can be piloted remotely, what gives them a bast range of uses in application areas such as military, humanitarian relief and healthcare (Lim et al., 2022b). Specially for medical purposes drones have been implemented successfully to deliver supplies to remote health facilities, in countries like Rwanda and Ghana, providing faster response times and reducing transportation costs (Ayamga et al., 2021). As well as played an important role in distributing medicines and food during the Covid-19 pandemic, showing a potential that could be exploited in the delivery market (Ayamga et al., 2021).

Besides its commercial applications, drones can be considered a disruptive technology that is changing Search and Rescue (SAR) and disaster management logistics (Wankmüller et al., 2021). Providing rescue organizations with powerful tools to locate victims rapidly in the most adverse scenarios and generating situational awareness to the plan effective strategies to reach the accident sites (Wankmüller et al., 2021). Which have driven fire brigades, telemedicine teams, mountain rescuers and police departments, to integrate them into their operations (Wankmüller et al., 2021).

The last decade these teams have growing interest in the capacity that drones have to support their efforts for saving life by delivering AED (Lim et al., 2022b). Using these devices is possible to provide bystanders with a defibrillator and heart monitor before the first responders arrive to the emergency site, extending the chances of reducing the time to assist OHCA victims (Lim et al., 2022b). Even though there is still room for further development and research in this field (Lim et al., 2022b).

In the scoping review made by Lim, is mentioned that recent research related to UAS-AED have been dedicated to study the limitations that implementing this technology would have in the real world, considering the legal framework, technical constraints, terrain variability, the effect of weather conditions and the cost to implement this solution (Lim et al., 2022b).

Regarding the direct benefit of reducing the response time of Emergency Medical Services using UAS to deliver AED, studies have shown that is possible to accomplish the shipment to the emergency sites in around 5 minutes (Roberts et al., 2023). Which could also be achieved in mountain scenarios (Wankmüller et al., 2020). Making feasible the ideal scenario of an effective coverage for OHCA in urban areas, as in the mountains (Elsensohn et al., 2006).

The potential of the drones to support integrated efforts of local rescue and telemedicine teams, have also been recognized by the general population (Sabino et al., 2022). Multiple studies agreed in the large public acceptance that share these devices for rescue purposes, where the general population perceive them as useful, instead of risky or harmful (Sabino et al., 2022). Beside their concern for the possibility of improper recording, the general public considers that recording or flyovers would not be a bother to them in drone rescue operations (Sabino et al., 2022).

Beside the possibilities and acceptance of the drones in the field of medicine and rescue, it is important to address their main limitations and considerations (Mermiri et al., 2020). The legal framework of every country where these solutions are planned to be deployed has to be studied separately (Mermiri et al., 2020). Because each State establishes their local UAS operation procedures and geographical zones (EASA, 2022). Therefore special arrangements are required to allow fly over restricted flight zones, as protected areas or near high building (Boutilier et al., 2017).

Another factor to consider is the cost of these platforms, which is a major obstacle for their actual implementation and a main reason to optimize effectively the distribution in the proposed networks (Bereg et al., 2022). Based on spatial analysis methods that permit to estimate its coverage for cardiac arrests assistance in dense and sparce population (Ball et al., 2022). Using the existing infrastructure as a starting point (Wankmüller et al., 2020).

A final consideration would be the optimization of the AED delivery logistics in real-life scenarios. (Mermiri et al., 2020). Implementing automated drone routing workflows that consider obstacles and elevation differences, as well as weather variations (Bereg et al., 2022). Identifying barriers that are not present in mathematical models and simulations (Mermiri et al., 2020). Aiming to achieve a full integration with the emergency services procedures, aiming to reduce their response time towards life-threatening emergencies (Boutilier et al., 2017).

2.3. Drone Routing for Defibrillator Missions

In recent years the distribution of supplies via drones has been a primary interest topic in research and business development, due to their potential to reduce traffic congestion, connect remote areas, decrease logistic cost and optimize response time during emergencies (He et al., 2022). Being acknowledged by governments and private firms as an alternative to cover sparsely populated areas (Jung & Kim, 2022).

In this endeavour, research teams worldwide have developed ways to optimize delivering procedures assisted by drones, using methods as cost-efficient drone networks or strategies as the flying sidekick for hybrid truck-drone operations (Roca-Riu & Menendez, 2019). Even though most of these methods has been developed with a commercial approach, it could be possible to contemplate some of the principles they use to benefit SAR and telemedicine logistics. However, it is important to consider for their implementation the local regulations and safety measures, select appropriated technology to plan the operation routes, and share experiences and evidences to support further research (Robakowska et al., 2022).

Important factors to consider routing drones are the constraints imposed by obstacles and the distances these devices are capable to cover (Hong et al., 2018). On a recent model proposed to configure recharging stations for commercial drone delivery services, were included in the coverage estimations range variations depending on the interaction of the drone with the environment, according to technological factors, weather conditions and payload size (Hong et al., 2018). Making possible to define the shortest paths from a drone station to the delivery points based on detailed cartography, avoiding obstacles along the flight plan and taking into account its successful return from a round trip (Hong et al., 2018).

The use of drones to assist in urgent daily operations, opens the possibility of planning aerial route networks (Robakowska et al., 2022). Defining low-altitude air routes have been consider as a solution to perform UAS flights safely, ensuring their separation from manned aircraft and land obstacles (Xu et al., 2020). This can be achieved by combining detailed geographic data sets at different scales to model precisely the environment in which the drones will navigate (Xu et al., 2020). This kind of networks could consider not only the path of the drone, but the entire volume of the operation, making tube-based routes on a 3D space to flight across constrained environments in a reasonable time, minimizing the energy consumption, potential risk to ground and airspace occupancy (He et al., 2022).

This approach has been studied for its implementation in Manhattan (USA), where a dense urban environment would require to plan precise routes avoiding restricted airspace and cause minimal negative impact on the citizens (Hildemann & de Campolide, 2019). An optimized method based geoprocessing models and detailed cartographic information was used in this case to identify the least cost distance connections between the bases and delivery points (Hildemann & de Campolide, 2019). Showing GIS workflows as valuable tools for the decision makers to manage the airspace.

However in remote scenarios drones might not be able to use effectively these pre-defined networks, facing the problem of finding the shortest path across the land while avoiding obstacles (Hong et al., 2018). In such cases could be considered methods that implement spatial raster information to decompose the planning environment into a grid, to generate optimal routes connecting the origin and destination points avoiding cells occupied by obstacles (Xu et al., 2020). However, this would require to have a highly detailed and updated cartography, along with UAS equipped with sensors to comply with precision regulations (Xu et al., 2020).

Although there has been extended efforts to refine aerial routing automation, there is still further development required, specially avoiding obstacles in a 3D environment (Hildemann & Verstegen, 2023). UAS are currently unable to make use full geographic information at flight time, requiring pre-constructed environments to plan optimal paths (Xu et al., 2020, p. 74184). Therefore, is important to generate highly detailed geographic models considering the obstacles, to ensure accurate navigation following precise plans that rely mainly in the cartography (Mangiameli et al., 2013).

In reference to drone routing for defibrillator missions, there are relevant studies that can be addressed. In Sweden, was tested an automatic dispatch system to deploy drones, where the aircraft followed route plans focused on minimizing the proportion of flight time over populated areas (Schierbeck, Hollenberg, et al., 2022). During these flights air-traffic control granted the remote pilot permission to fly up to 150 meters in a defined airspace, accomplishing flights of 3.1 kilometres distance as median (Schierbeck, Hollenberg, et al., 2022). Their results showed that after 86% effective take-offs (12/14), the drones were able to deliver the AED successfully in 92% of the cases (11/12), arriving in 64% (7/11) of them prior to the ambulance in an urban environment (Schierbeck, Hollenberg, et al., 2022).

This technology has also been tested on mountain environments, such as the Alpine Regions. Between Austria and Slovenia, were run 30 scenarios aiming to test the feasibility of the drones to deliver defibrillators in rough terrain (P. Fischer et al., 2023).

That case was supported by the Austrian Red Cross, who responded to the OHCA test scenarios as it would be done for real emergencies (P. Fischer et al., 2023). The research used 4 emergency points, with different distances and elevation differences in relation to the drone base, flying in a straight line towards them while keeping an altitude above the ground of 100 meters to avoid collisions (P. Fischer et al., 2023). The results of these showed response times of 12 – 14 min, implying promising outcomes from shockable cardiac arrests, as well as a high acceptance rate from untrained bystanders and rescuers that were also involved in the tests (P. Fischer et al., 2023).

In the optimized drone allocation model proposed to the mountainous region of South Tyrol (Italy), was considered a way of routing the drone across the challenging terrain. During the design of this network, the theoretical coverage of the drone stations was calculated using a model that connects the base to the emergency with a direct line, taking into account 5 meters above the highest obstacle as a safety distance (Wankmüller et al., 2020). In which the optimal positioning of the stations would result into travel times around 5 minutes towards the patients in the district of Val Venosta. Even though, the authors mentioned that their approach would require identifying the shortest path through a 3D environment, considering detailed elevation models, obstacles and atmospheric conditions.

All these enhancements require further improvement be implemented in response to actual emergencies. Integrating a map-based tool that allows the victims of OHCA send their locations to the first responders, for them to easily route the drones to deliver AED, according to the aerial regulations and the aircraft capabilities (Schierbeck, Hollenberg, et al., 2022). Capable of selecting the optimally placed hangars and deploying the drones to provide a rapid assistance, even under adverse atmospheric conditions (Schierbeck, Hollenberg, et al., 2022). Even though, it has not been confirm an optimal strategy to deploy them and additional methods keep emerging (Liu et al., 2021)

2.4. Map-based Tools for First Responders

Regarding the tools used for first responder during emergencies and disasters, cartography plays an important role to optimize their operations. This is an invaluable source of information to predict risk and analyse damage (Zupan et al., 2022). Finding the shortest route towards a victim over rough terrain (Danser, 2018) Providing reliable spatial context for local officers to design strategies to manage the emergency situation and coordinate joint efforts to response timely to the citizens that require help (Hubbard & MacLaughlin, 2006)

Nowadays there are mobile applications that allow first responders assist OHCA, providing them with the accurate location of the patient and the closest AED, aiming to increase their chances of survival with good neurological outcomes before EMS arrive to the scene (Gamberini et al., 2023). These solutions collect continuously the information about the position of the responder, giving the dispatch centre the possibility to call for their intervention in a suitable action radius (Gamberini et al., 2023).

Recent studies have also proposed location-based solutions capable of requesting the assistance of ambulances nearby (Arunachalam et al., 2021). Giving to patients and bystanders the possibility of easily send their accurate GPS location with a smartphone, for the local EMS to process the request quickly (Arunachalam et al., 2021).

These kinds of solutions could be optimized in collaboration with UAS to support the coordinated efforts of first responders (Caballero et al., 2021). Taking advantage the agile performance of these devices to locate victims in large geographic areas or transporting supplies in emergency situations (Mohd Daud et al., 2022).

A map-based tool that combine those capabilities, could use the patients GPS location provided by a mobile phone to make a request (Yukun et al., 2023). This position would be processed for the dispatch centre as an emergency call, sending a nearby drone and a crew of first responders to the scene (Yukun et al., 2023). Then the route for the drone could be followed in real time by the operators and the patient using a map interface, showing the estimated time for the arrival of the supplies (Yukun et al., 2023). Meanwhile the patient and bystanders would have constant communication with the EMS, who will be directing the operation remotely (Yukun et al., 2023).

Most of these functionalities have already been implemented in mobile applications, such as GeoResQ in Italy, that sends the essential information required to local rescue teams in case of an emergency, especially in the mountains (Italian Alpine Club, 2023). Even though this would require to adapt its interface to include drone functionalities, after the placement of an optimal the drone network in the covered area, beside a cartographic interface for first responders to route them without further technical guidance (Caballero et al., 2021). Therefore, ensuring a full integration with the Emergency Medical Services operations workflows (Boutilier et al., 2017).

Table 1: Literature Review Findings Summary

Study Field	Main Findings	Authors and Date
Automatic External Defibrillators in the Mountains	• Businesses can be ranked according to their potential to improve coverage of OHCA by placing AED. • Spatial analysis methods are used to compare location according to their potential to held AED.	Ball et al., 2022
	• AED should be available wherever a cardiac arrest occurs, especially in areas of high probability of use. • Early defibrillation should be feasible in the mountains, as in urban areas. • Encouraging people with medical conditions to exercise in mountainous areas is increasing the number of persons at risk.	Elsensohn et al., 2006
	• In rural areas AED have shown significant optimization issues due to geographical challenges. • Three main strategies have been used to locate AED, which are: guidelines-based, grid-based and landmark-based.	Liu et al., 2021
	• Mountains and remote areas are not suitable for tight AED networks	Vögele et al., 2020
	• Mountain rescue services are interested in the implementation of drones. • Rescue organizations and EMS are integrating drones into their operations.	Wankmüller et al., 2021
Unmanned Aircraft Systems and Automatic External Defibrillators	• Drones aerial delivery of medical supplies have been used by remote communities in Rwanda and Ghana.	Ayamga et al., 2021
	• An integrated drone network can achieve the same overall performance as eight independent regional networks with few resources. • Theoretical benefits of AED drone delivery using a mathematical model are to optimizing drone base locations and fleet size.	Boutilier et al., 2017
	• Governments and public firms are considering to adopt drone delivery services to cover sparsely populated areas.	Jung and Kim, 2022
	• Multiple simulated studies concluded overall reduction in response times using UAS-AED in rural areas.	Lim et al., 2022
	• UAS-AED studies based on real-life scenarios are required to identify barriers that are not present in mathematical models.	Mermiri et al., 2020
	• Drone applications with the most acceptance are related to SAR operations and medicine.	Sabino et al., 2022
	• An autonomous drone was used to deliver an AED in a real emergency scenario before EMS arrived.	Schierbeck et al., 2022
	• Alpine shelters and fire rescue stations can be considered as potential drone base stations	Wankmüller et al., 2020
	• Drones over terrestrial and helicopter transportation are cheaper, faster and more effective to provide AED.	Wankmüller et al., 2021

Study Field	Main Findings	Authors and Date
Drone Routing for Defibrillator Missions	• Use of a sequential route network to plan tube-based operations of drone deliveries in large urban areas time.	He et al., 2022
	• Least-cost paths can be found using GIS models based on weighted spatial attributes. • No method currently exists to optimize flight routes under multiple conflicting objectives while avoiding 3D restricted areas.	Hildemann and Verstegen, 2023
	• The key to achieve the best obstacle-avoiding route with drones is finding the Euclidean Shortest Path.	Hong et al., 2018
	• An appropriate location model and cost breakdown must be determined to allow maximum utility of a UAS-AED network.	Lim et al., 2022
	• No optimal deployment strategy for drones has been confirmed and additional methods are emerging.	Liu et al., 2021
	• Model assumes drones flying in a straight line from the base station to the patient in mountains environments. • Sophisticated flight routes could potentially result in shorter flight times, requiring a full 3D model.	Wankmüller et al., 2020
	• Exclusive low-altitude flight path of UAS ensure the separation of civil aviation and safe drone navigation. • It is possible to create drone routes dividing the environment into a grid and connecting adjacent cells.	Xu et al., 2020
Map-based Tools for First Responders	• Mobile applications can be used to request for an ambulance sending the GPS location with one tap on a button. • Mobile applications for first responders will require a module for them to handle data and coordinate the operation.	Arunachalam et al., 2021
	• Drones will need to be integrated with the EMS response and this will determine the network scope.	Boutilier et al., 2017
	• Would be required an interface to enable the end users to perform drone routing without the guidance of technical staff.	Caballero et al., 2021
	• Mobile applications involve volunteer citizens based on their geo-localization and distance to the OHCA.	Gamberini et al., 2023
	• Drones are able to search and locate victims over large areas in less time than rescuers. • Studies that rely on simulations might overestimate the performance of the drone in comparison to real-world scenarios. • Using drones for SAR has important drawback like legal constraints, weather conditions and local community capacity.	Mohd Daud et al., 2022
	• An end-to-end location-based solution for delivering AED using drones is described conceptually.	Yukun et al., 2023
	• The use of cartography speeds up communication and provides indispensable information for predicting risk.	Zupan et al., 2022

3. Methodology

In order to deploy timely an AED using a drone, would be required that a bystander contacts the local Emergency Medical Services (EMS) addressing an Out-of-Hospital Cardiac Arrest (OHCA), calling the emergency number (112 in Europe) (Brugger et al., 2021). In a situation like this, the first responders initiate the operation getting the position of the emergency site, confirm the position within the covered area by this service, select the nearest station and generate the route (Schierbeck, Hollenberg, et al., 2022). The drone is deployed automatically to the patient location and the defibrillator is received on the emergency site, to initiate the resuscitation procedure prior the arrival of the first responders to the scene.

According to this, UAS-AED missions have an important spatial component that can be addressed using map-driven processes. Prior establishing the coverage area for these kind of emergency services, is required to analyse the optimal places to allocate the stations and define a reliable network (Wankmüller et al., 2020). Once the coverage is defined, is important to generate an optimal route to reach the emergency site in the least possible time to increase the odds of positive outcomes for a patient suffering an OHCA (Schierbeck, Hollenberg, et al., 2022). This chapter explains in detail the methods considered to tackled the stated processes (Figure 1), aiming to define the placement of the proposed network and its coverage area, as well as the optimal routing process to plan automatic UAS-AED missions in the mountain.

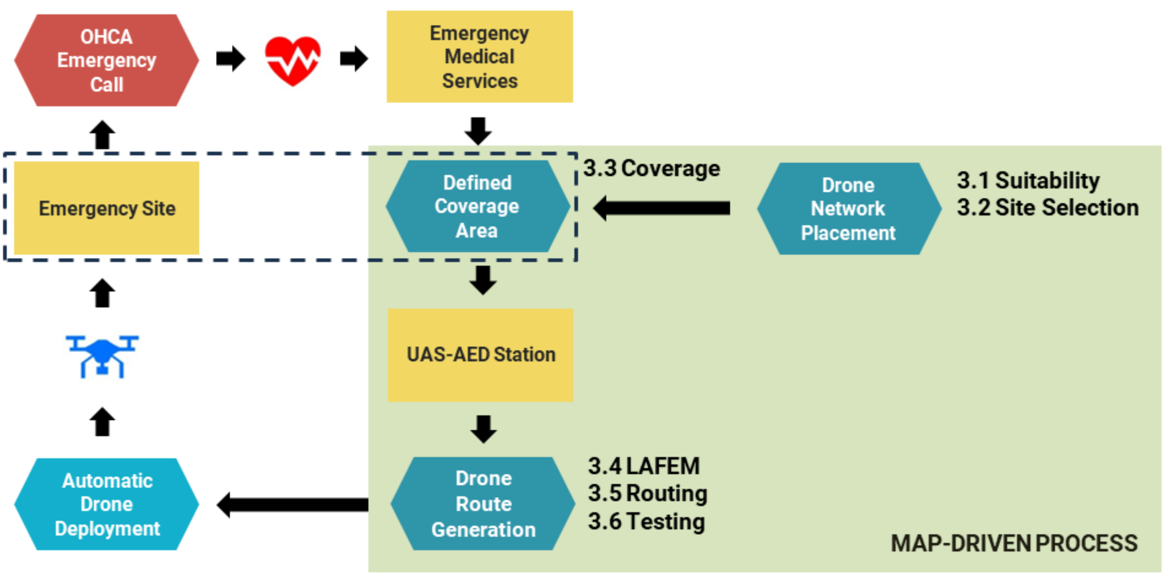

Figure 1: UAS-AED Mission Map-Driven Methodological Process

3.1. Emergency Drone Service Network Placement Suitability

In order to propose a map-driven distributed emergency drone service network, this research consider to study the spatial suitability as a starting point to site drone bases in the interest region. The suitability was defined as a result of the overlay of relevant spatial variables that would require to be considered to deploy automatic drone missions in mountain regions, as in any other scenario.

The suitability of a place is defined by its characteristics, in relation to a set of requirements regarding a certain objective, helping prioritize areas aiming to select the best locations (Bennett & Calkins, 2013). This is a cartographic method that displays simultaneously different inputs, overlaying spatial indexes as raster or vector datasets, showing their combined distribution and patterns (Ahlqvist, 2009). Using a deductive reasoning, the sum of the overlapped variables can be used as an inference matrix, that results into a suitability map where the highest values correspond to the most suitable locations (Ahlqvist, 2009).

Spatial suitability models have been considered as an insightful cartographic decision-making approach to optimize the location of limited resources strategically, according to the determined geographic characteristics of a region (Younes et al., 2022). This method has been used broadly as a site-selection tool for large areas, such as locating photovoltaic cells in Egypt (Habib et al., 2020). As well as in humanitarian logistics and disaster risk management, to define the sites for refugee camps in Kenya (Younes et al., 2022).

The selection of the variables used to study where to place an emergency drone service network, aimed to identify the areas in which would be feasible to deploy UAS-AED missions in the vast possible extent of the interest region. The suitability model only considered variables that would restraint the direct implementation of this technology in a real situation, extending the operation range of actual Emergency Medical Services (EMS) in their endeavour to assist emergency calls. Therefore, the variables considered are the UAS Geographical Zones that regulate drone operations and the detailed land use of the study area, classified according to their feasibility to stablish drone bases regarding the current legal framework (EASA, 2022)

The UAS geographical zones are portions of airspace defined by the competent authority of a State, which restrict or exclude operations of drones to reduce risk towards other aircraft, people or the environment, depending on the nature of the mission and the characteristics of the device (EASA, 2022).

For safety reasons, these prohibit certain or all UAS operations, and might require permissions to flight over populated or protected areas, such as national parks (EASA, 2022). These can be permanently stablished, as in the proximity zones to airports, or exclude the use of certain zones temporarily using AIP or NOTAM (EASA, 2022).

According to international conventions these areas have to be public, standardized, accessible and understandable to people that are non-professional to the aeronautical field. (EASA, 2022). Regarding to Italy, these can be found in the d-flight web application (Figure 2), where prohibited and dangerous zones are depicted in red, restricted areas in yellow and green and the areas without major restrictions blank to facilitate civilian UAS operations. (Südtiroler Bürgernetz, 2023). Considering these, drone missions could take place without an application for an authorization when flying up to 120 meters, with an aircraft up to 25 kg (EASA, 2022).

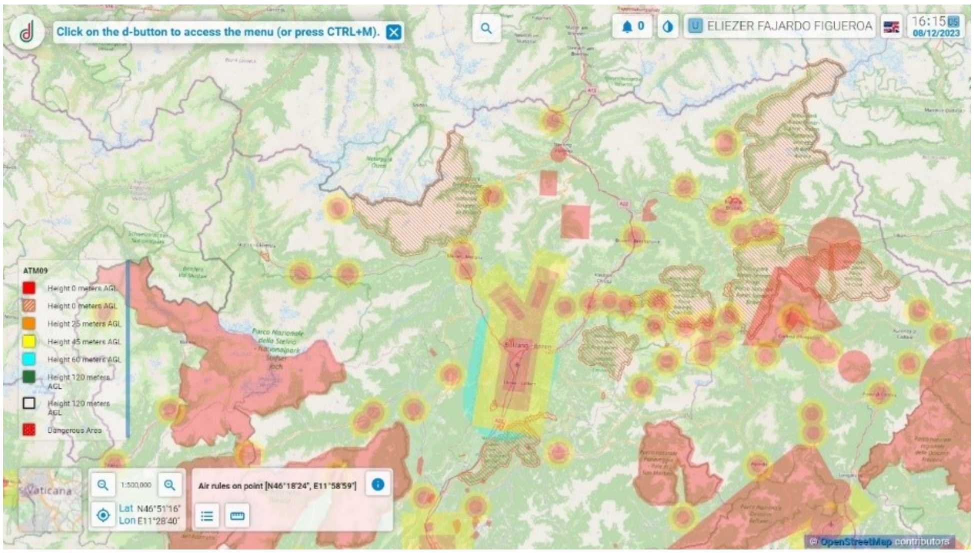

Figure 2: UAS Geographical Zones of Italy, d-Flight web application

Regarding the land use information, it is considered a spatial layer provided by the Office for Regional Planning and Cartography, in the geoportal of the province of South Tyrol (Südtiroler Bürgernetz, 2023). This input was published in 2005 and has the most detailed characterization available of the interest region real usage of the land at 1:10.000 scale (Figure 3).The land use of South Tyrol is described according to the national legislation of Italy using pre-defined categories (Südtiroler Bürgernetz, 2023).

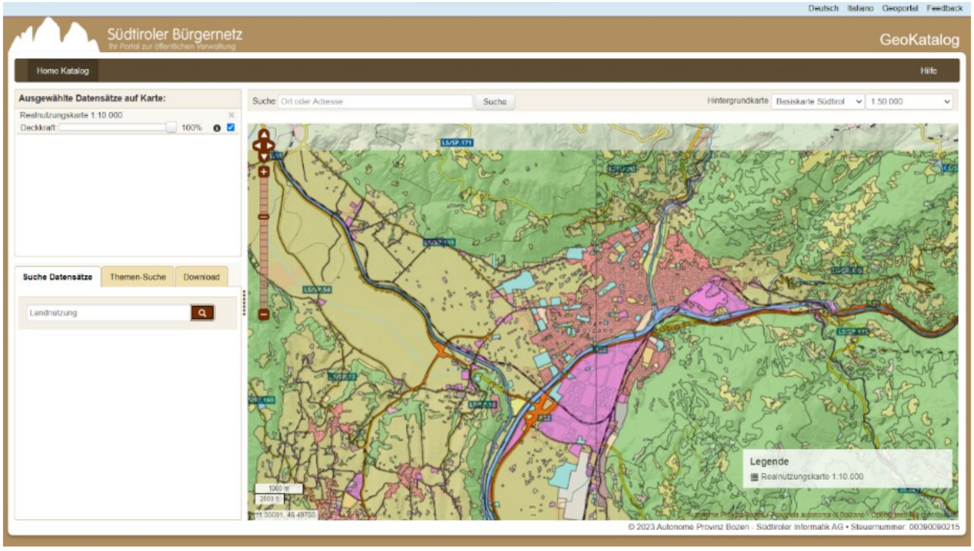

Figure 3: Real Land Use, geoportal of South Tyrol

Both geographic layers are classified and transformed from vector to raster format, according to ranks stablished to perform a macro selection of the suitable areas in South Tyrol to place drone bases for UAS-AED operations, using a Weighted Overlay spatial analysis tool in ArcGIS Pro 3.1 (Esri, 2023g). During this process, the variables were weighted equally with 50%, while the classes were assigned a value according to a 1 - 100 scale for the overlay (Table 2).

Table 2: UAS-AED Suitability Weighted Overlay Parameters

Variable	Weighted Value
UAS Geographical Zone	**50%**
120 meters	100
60 meters	75
45 meters	50
25 meters	1
0 meters	0 (Restricted)
Land Use	**50%**
Feasible	100
Restricted	50
Unfeasible	1
Prohibited / Dangerous	0 (Restricted)

The result of this summary depicts the combination of the spatial characteristics of the studied region (Figure 4), showing as highly suitable those areas that present fewer flight restrictions in contrast to those where drone operations are restricted or prohibited. The UAS Geographical Zones were classified according to the maximum altitude permitted for civil drone operations in the open category (EASA, 2022). Assuming areas where flights could be performed up to 120 meters as the less restrictive, in comparison to zones where the operation ceiling is 25 to 45 meters, or those that prohibit the operations of these aircraft for safety purposes in the proximity to hospitals, military facilities, power plants, etc (EASA, 2022).

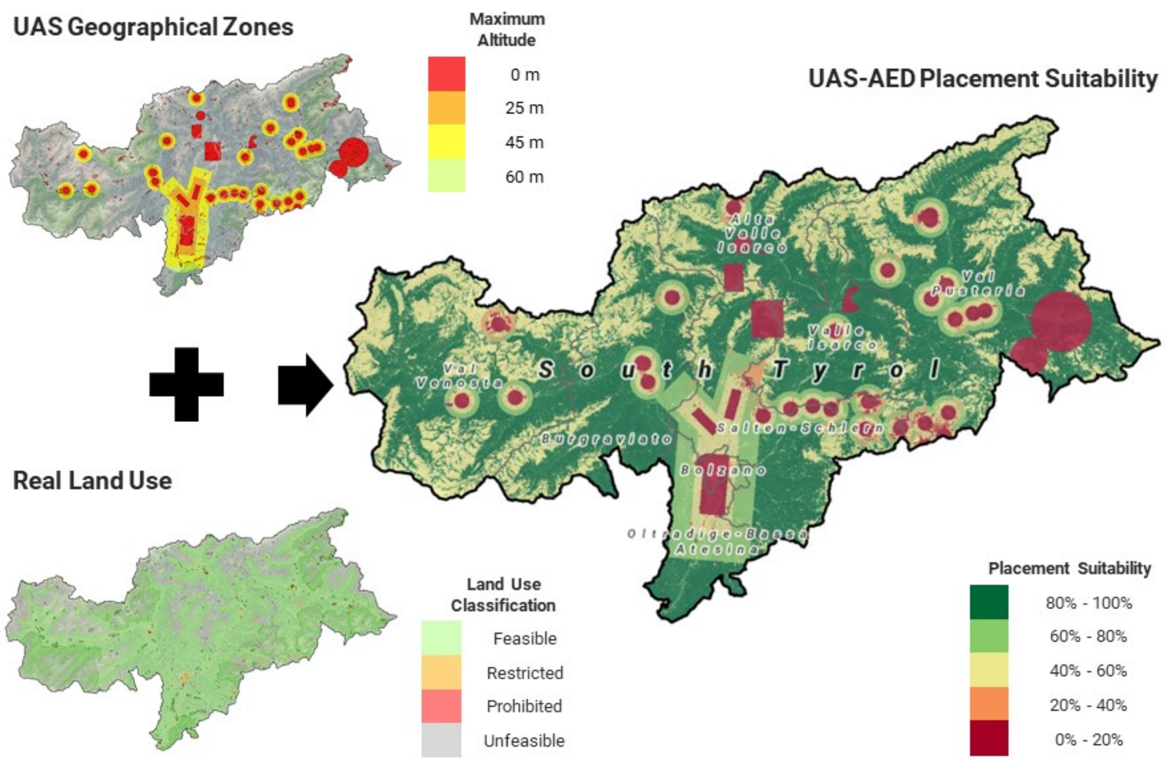

Figure 4: UAS-AED Placement Suitability Weighted Overlay (South Tyrol, Italy)

Regarding the land use, this was classified into four types, where the original categories could be considered as feasible if there are not stated restrictions to deploy drones, like in open areas in sparsely populated zones (EASA, 2022). Restricted if there are some limitations to be considered according to current UAS regulations, as in the proximity to dense urban fabrics, streets or sport facilities (EASA, 2022). Unfeasible if refer to areas that would present major obstacles to place the drone bases, such as water bodies, debris and glacier zones or near to cable car systems. Otherwise as prohibited, if the land use refer to military or aeronautical facilities, such as airdromes, heliports or airports (EASA, 2022).

3.2. Emergency Drone Service Network Spatial Configuration

Once the most suitable areas in the studied region were identified, these results were used to filter candidate locations to place the drone bases. The candidate locations in this research refer to places with potential to place a UAS station for defibrillator mission, according to facilities available in the studied region (Wankmüller et al., 2020).

Recent studies have analysed the optimal distribution for drone bases to deliver defibrillators based on cartographic information (Lim et al., 2022a). Mathematical simulations that use historical OHCA locations, are commonly implemented to identify occurrence hotspots and allocate UAS accordingly (Lim et al., 2022a). As well as have been considered stablished EMS bases in combination to other potential places, such as post offices, as alternative deployment sites to extend the coverage of life-threatening emergencies (Lim et al., 2022a).

During this research, it was not available detailed historical data regarding location and occurrence of OHCA for the area of interest in South Tyrol (Italy). Therefore, the potential UAS base locations proposed for the emergency drone service network is based on actual facilities of the region, such as stations of fire fighters and rescuers, considering also mountain facilities, such as huts or camp sites, which are specially relevant in Alpine regions due to the high number of visitors passing by each year (Wankmüller et al., 2020).

The site selection started with a query of all the plausible facilities in the region, according to geographic information provided by OpenStreetMap contributors (OpenStreetMap, 2023). Multiple places were located in the region, which were then filtered according to their suitability value for further analyses.

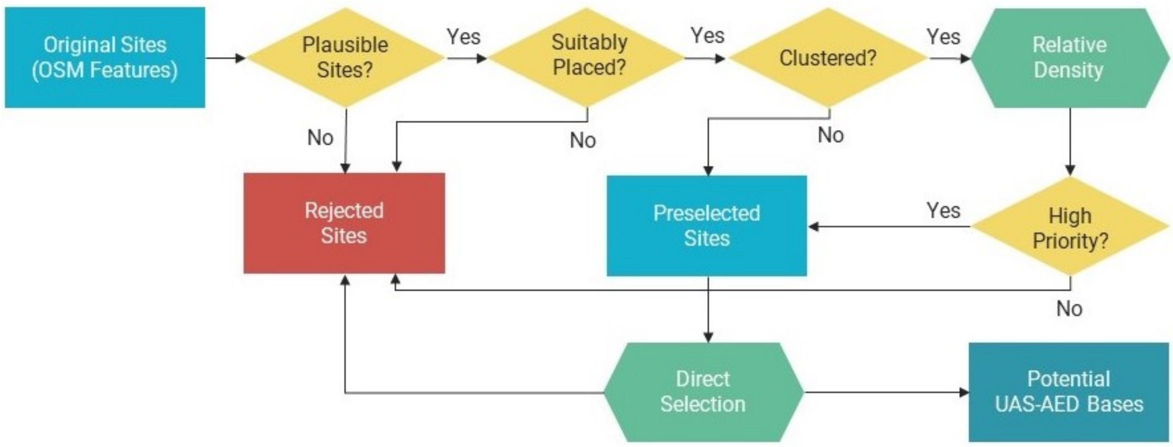

Figure 5: Potential UAS-AED Bases Selection Procedure

The filtered locations were then studied using spatial statistics, according to their relative density, to select the tentative places for the drone bases. During this process were calculated clusters between the points to determine spatial aggregations along them (M. M. Fischer & Getis, 2010). This method was implemented to identify areas in which the potential locations are bundled requiring a specific selection process to determine which of them would be part of the network regarding the type of facility, as well those locations disperse in the area of interest and distant from any other potential site (Figure 5).

This analysis was based on the result of the DBSCAN algorithm, implemented using the geo-analytics tool to find point clusters in ArcGIS Pro 3.1.3 (Esri, 2023c). This algorithm identifies groups of elements within a certain distance of a point, using a search distance parameter (Esri, 2023c). This parameter was defined according to the current UAS regulations, which state that unmanned aircraft operations could be held up to 1 kilometre without airspaces observers performing unaided visual scanning to avoid potential hazard in the air (EASA, 2022). Therefore, the analysis showed those sites closer than 1 kilometre into clusters, whether scattered locations were assigned to non (Cluster -1) (Figure 6).

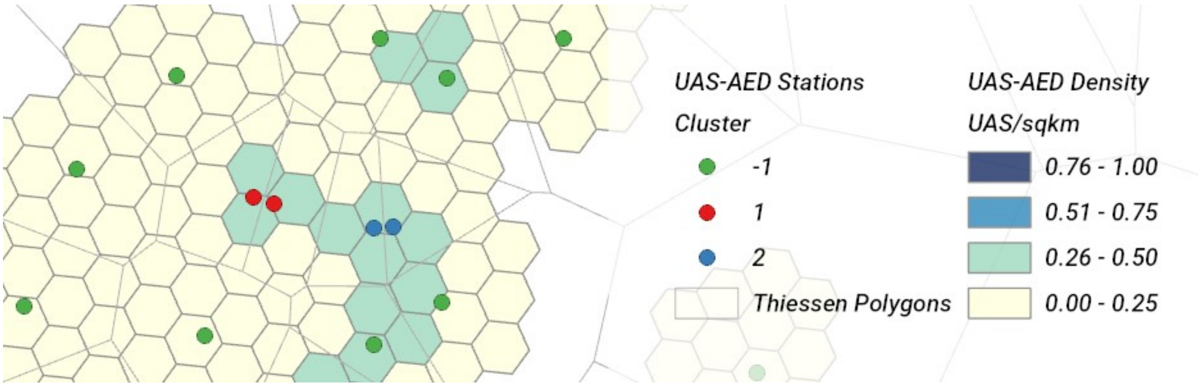

Figure 6: UAS-AED Stations Cluster Definition and Relative Density

The clustered points were then filtered according to the characteristics of the facilities, keeping from the selection first responder stations as high priority sites (Wankmüller et al., 2020). Finally, all the preselected candidate locations were validated and selected directly as part of the proposed emergency drone service network, considering the real distribution of the available facilities in the region of interest. Looking forward to generate the vast possible coverage to respond to emergencies time-effectively under the current scenario (Wankmüller et al., 2020).

3.3. Emergency Drone Service Network Coverage Area

The estimation of the coverage area for the proposed drone service network in the studied region, considered the optimal distance reachable in the shortest time according to the UAS capabilities, and the restrictions imposed by physical obstacles and the legal framework that regulates them (EASA, 2022). During the estimation of the theoretical coverage of optimized emergency drone networks, can be used radius as buffers that refers to the distance that drones can reach in their maximum flight time (Boutilier et al., 2017). Even though, these could be improved using methods that find the Euclidean Distance or shortest distance between origin and destination points, in a continuous space that includes barriers such as buildings or restricted areas to get an approximation closer to a real-world scenario (Hong et al., 2018).

Distance accumulation is a widely used in spatial analysis method for cost distance estimations, that allows to define reachable areas and shortest paths relying on network-based path planning algorithms (de Smith et al., 2021). In these workflows the cost not necessarily imply financial cost, but a composite measure considered to determine distances across a region (de Smith et al., 2021). This cost might refer to the distance itself or characteristics of the terrain, such as the land use, that increase linearly through the interest area making a path more or less expensive or time-consuming depending on local variations (de Smith et al., 2021).

The estimation of the lowest total distance to a target is based on accumulated cost surface methods, which commonly take the cells of a spatial grid as nodes to connect the origin and destination points over a surface (de Smith et al., 2021). This research takes the potential UAS-AED of the proposed emergency network as the source points to calculate the covered area across the studied region, using the Distance Accumulation algorithm integrated in the Distance toolset of ArcGIS Pro 3.1 (Esri, 2023a). This method was selected because it allows to build a continuous accumulative surface area to measure the cost distance from the initial points in any direction while considering the slopes, not being limited to perform path finding calculations through a network of 8 directions per node, achieving to define more effectively the Euclidean Distance towards the target locations (Esri, 2023a).

This procedure has also shown to be useful to calculate the shortest paths around obstacles (TenBrink, 2019). Generating a barrier-aware continuous surface from the initial points, avoiding distance distortions that are present in calculations based on prior algorithms that rely on 8-way connected graph to define the shortest paths, due to the use of a back direction raster with encoded floating point azimuth values in the range of 360 degrees (TenBrink, 2019). These characteristics are important to determine the services areas and routes for emergency drones over a highly restricted airspace (Hong et al., 2018).

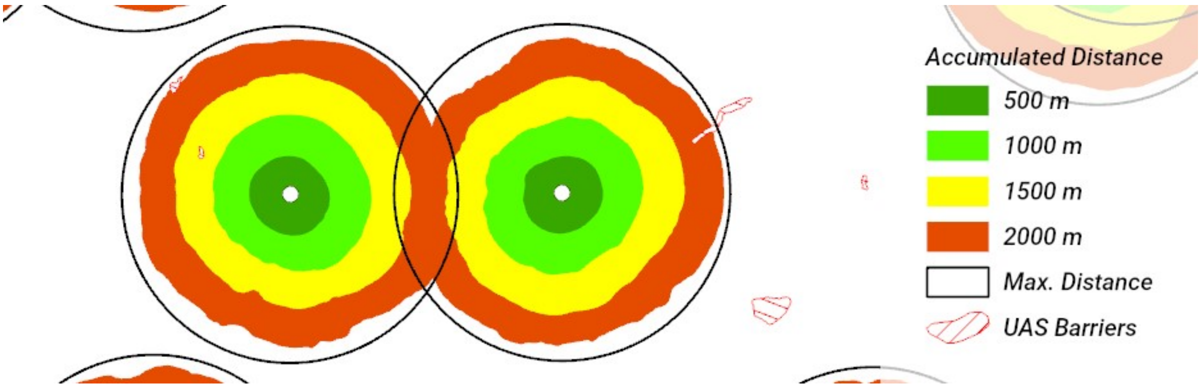

Figure 7: Coverage Area Estimation from UAS-AED Stations

Regarding this research, the spatial coverage of the proposed emergency drone service network was calculated from the selected UAS-AED stations (Figure 7). Considering that UAS missions could only be held up to 2 kilometres counting on airspace observers that support the operation, according to current regulations (EASA, 2022). Which can be reduced in certain areas due to the proximity of protected or dangerous zones. Therefore, further calculations refer to the surface that drones could reach effectively to deliver AED in the less possible time, using a Low-Altitude-Flight Elevation Model (LAFEM), looking forward to increase the odds of positive outcomes from an OHCA in the studied region (Lim et al., 2022b).

3.4. Low-Altitude-Flight Elevation Model (LAFEM)

The Low-Flight-Altitude Elevation Model (LAFEM) is a concept defined in this research, that refers to a modified surface elevation model to calculate effective service areas and generate optimal low-altitude-flight paths for drones, in terrains with important topographic variations (Figure 8). Thought to be used along with accumulated cost surface methods, as a barrier-aware surface that integrate spatial UAS restrictions, physical obstacles and a safety threshold to ensure drone missions avoiding collisions in a three-dimensional environment.

This model was inspired by recent efforts to standardize and manage UAS operations in low-altitude airspace, aiming to stablish levels for air traffic services based urban air mobility solutions, as in the U-Space project (Xu et al., 2020). Addressing the need of identifying the shortest path through a 3D space to deliver defibrillators successfully in Alpine Regions (Wankmüller et al., 2020). Considering methods that allow to define flight routes that follow the terrain variations and avoid obstacles, based on the estimating low-cost paths over modified Digital Elevation Models (DEM) (Lifeng Liu & Shuqing Zhang, 2009).

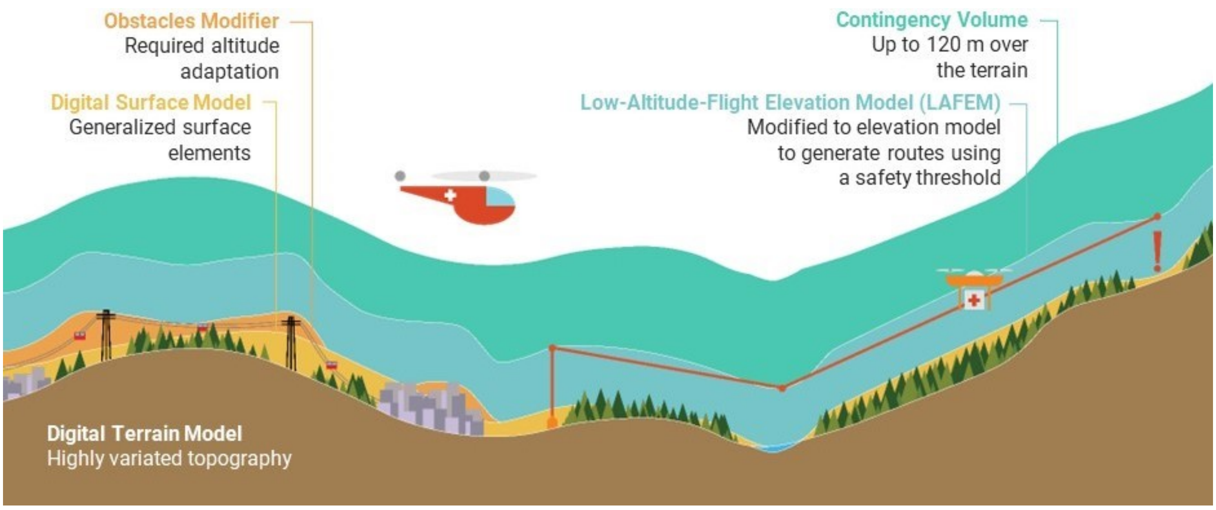

Figure 8: Low-Altitude-Flight Elevation Model (LAFEM) Conceptual Model

The starting point to generate a LAFEM surface, is modifying a detailed Digital Surface Model (DSM) by exaggerating its values, adding a safety threshold as minimum vertical clearance from the ground (Lifeng Liu & Shuqing Zhang, 2009). This is a simple sum to the spatial grid values, that cause an homogenous lift of the original surface model over the area of interest to assure a secure constant height for the operation (Lifeng Liu & Shuqing Zhang, 2009).This added value can be modified easily in raster calculation operations and should be defined considering the characteristics of the area that will be flown on automatic missions. In the following example, the DEM is modified summing 10 meters to the original elevation values (Figure 9).

Original DEM

10	10	10	20	30	50
20	20	30	20	40	40
40	30	40	30	30	30
50	40	50	20	10	20
60	70	50	30	10	20
50	60	50	40	20	10

+ 10 =

Modified DEM

20	20	20	30	40	60
30	30	40	30	50	50
50	40	50	40	40	40
60	50	60	30	20	30
70	80	60	40	20	30
60	70	60	50	30	20

Figure 9: DEM Exaggeration Using Safety Threshold

This modification ensures initially that the routes calculated over that surface maintain a safe altitude(Lifeng Liu & Shuqing Zhang, 2009). Even though would still require further vertical modifications to avoid high obstacles and flight in mountain environments, if the base surface to define the paths has low resolution (Xu et al., 2020). Therefore, this model also proposes to transform the resulting surface based on detailed vectorial information of the obstacles in the studied region (Mangiameli et al., 2013). Considering buffers around them to adapt route estimations over the surface grid (He et al., 2022). In the proximity to artificial obstacles, regulations recommend to operate further than 30 meters horizontally, flying up to 15 meters over them in a segregated area (EASA, 2022). Which allow to define raster buffers to make a progressive modification to the surface model elevation accordingly, to avoid collisions while approaching to the obstacles present in the studied region, such as cableways (Figure 10).

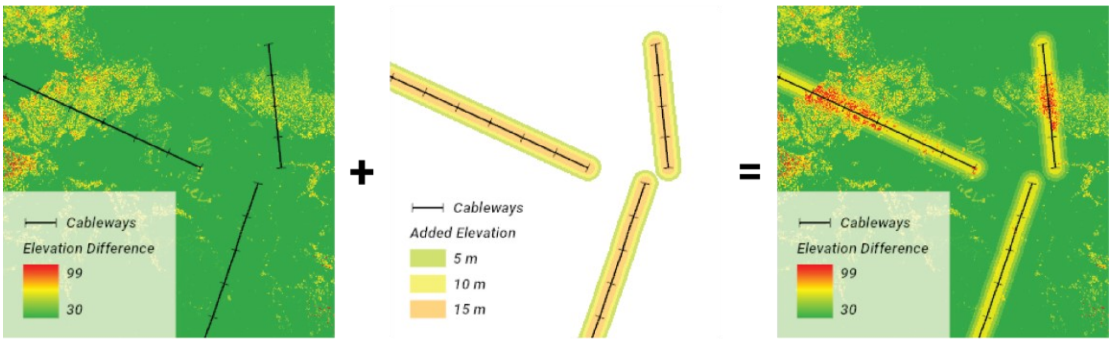

Figure 10: DSM Modifications Based on Artificial Obstacles

Beside the vertical modifications, the Low-Flight-Altitude Elevation Model (LAFEM) also takes lateral considerations to ensure that drone routes are defined distant to the slopes of a valley or a building, applying transformations based on spatial filtering methods (Gonzalez & Woods, 2018). Spatial filters have broad uses on image processing applications, allowing to transform images according to specific characteristics of them (Gonzalez & Woods, 2018). These filters can modify a spatial raster by replacing pixel values according to a function of the values of the pixel and its neighbours, moving a kernel over the image (Gonzalez & Woods, 2018). Theses functionalities can be used over the modified elevation model, to dilate areas relative to high elevation points based on maximum values or generate a smoothed surface base on the average of the elevation values (de Smith et al., 2021). The following example shows how the modified elevation model can be transformed using spatial filter (Figure 11), based on a 3x3 kernel to dilate the areas around high points over the land and then generate a smooth surface to route the flight plans.

Modified DEM

20	20	20	30	40	60
30	30	40	30	50	50
50	40	50	40	40	40
60	50	60	30	20	30
70	80	60	40	20	30
60	70	60	50	30	20

Maximum Filter

30	40	40	50	60	60
50	60	60	60	60	60
60	60	60	60	50	50
80	80	80	60	40	40
80	80	80	60	50	30
80	80	80	60	50	30

Mean Filter

45	47	52	55	58	60
50	51	54	56	57	57
65	66	64	59	53	50
73	73	69	60	49	43
80	80	73	62	47	40
80	80	73	63	47	40

Figure 11: Spatial Filters Applied to LAFEM

The process implemented to generate LAFEM surfaces was automatized using a geoprocessing model, that integrates an accessible workflow to modify the elevation models to generate barrier-aware surfaces to generate optimal drone flight paths in highly restricted airspace (Hildemann & Verstegen, 2023). This workflow uses specific cartographic inputs to run pre-programmed geoprocessing tools based in the ArcGIS Pro 3.1 Model Builder application, which allow automate the management, processing and edition of spatial information using a visual programming language (Esri, 2023f).

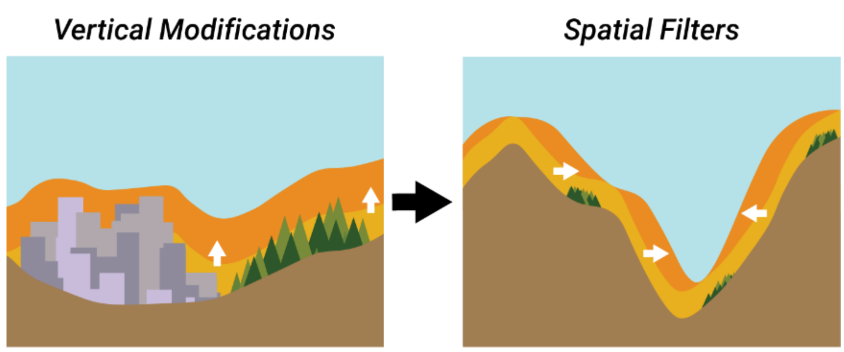

Figure 12: Transformations Applied to Generate LAFEM

The geoprocessing model uses a high-resolution DSM and the safety threshold altitude value in meters as parameters to perform a sum to exaggerate the initial elevation values.

The resulting raster is a lifted version of the original, which could be also modified summing the additional elevations referred to obstacle approximation zone buffers as raster, or be let as cero (0) to not generate any additional vertical modification (Figure 12). Then are applied spatial filters as focal statistics to enhance the maximum values of the surface model, extending horizontally the areas around high obstacles, and finally smoothing the resulting surface using an average to get the Low-Flight-Altitude Elevation Model (LAFEM) (Figure 13).

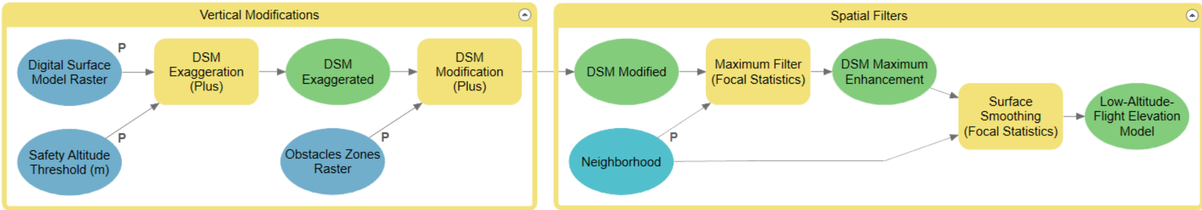

Figure 13: LAFEM Geoprocessing Model

Regarding this research was defined the safety threshold for the province of South Tyrol as 30 meters, to ensure that drone operations can be planned over the high vegetation and buildings of the region, according to the local differences between surface and terrain models (Sato & Sekiguchi, 2014). The calculations were made using surface models of 2.5 meters resolution from 2006, provided by the local geoportal (Südtiroler Bürgernetz, 2023). The spatial filters were adapted to the raster characteristics to improve the results, using a 10-pixel radius circular kernel (25 meters), to avoid sharp edges on the generated surfaces to plan effective drone routes (Gonzalez & Woods, 2018) (Figure 14).

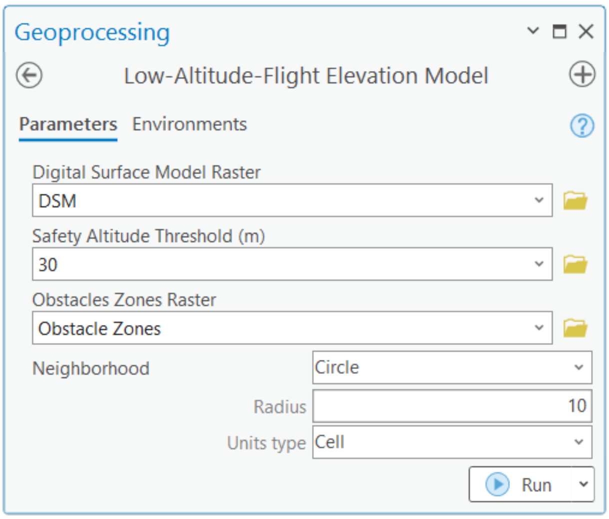

Figure 14: LAFEM Inputs Interface

3.5. UAS-AED Missions Routing Workflow

The study of optimal emergency drone service networks has estimated promising time reductions in the response to cardiac arrests in rural scenarios by delivering AED through automatized UAS flights (Lim et al., 2022b). However, in mountain regions this would require to implement sophisticated routing strategies, capable to adapt the missions to local topographic variations in a 3D environment, finding the optimal path through a challenging terrain while considering external obstacles (Wankmüller et al., 2020). Which could result in to shorter response times towards emergencies in remote settings (Wankmüller et al., 2020).

Recent studies related to drone delivery services and urban mobility networks, have consider the least-costs path method as a suitable approach to define effective flight plans in highly restricted three-dimensional airspace (He et al., 2022; Hildemann & de Campolide, 2019). This is a method that relies on a detailed cartographic models and can be used find paths for aircraft over certain areas according to a relative cost (Hildemann & de Campolide, 2019).

This method was implemented to propose an urban air-taxi network in the city of New York (USA), which has a dense urban fabric and a highly restricted airspace (Hildemann & de Campolide, 2019). Using a geoprocessing workflow based in ArcGIS Model Builder, to design paths for helicopters in a three-dimensional space considering flight regulations to find the routes with the minimal accumulated cost. In a further research, this approach was enhanced using evolutionary algorithms considering additional variables such as noise and energy consumption, to improve the results of the least-cost paths around restricted areas (Hildemann & Verstegen, 2023).

Another remarkable study implemented this method to design a drone-base delivery network in the city of Hangzhou, China. (He et al., 2022). They used a novel space cost function to design routes along a tube-based network finding paths in a dense urban environment (He et al., 2022). Their approach permitted to stablish fixed delivery routes based on the airspace utilization using a path finding algorithm, that identifies the minimum total cost between a start and finishing nodes along a spatial matrix (He et al., 2022).

The least-cost paths are part of the accumulated cost surface methods, which are widely used spatial analysis procedures based on Geographic Information Systems (GIS) to find the best pathway across continuous surfaces (de Smith et al., 2021). These methods can be particularly useful when is required to minimize the cost or risk of a route associated to its location (Murekatete & Shirabe, 2021). There are multiple efficient methods to define the minimum cost route between two points, being Dijkstra's Algorithm and its variants some of the most notable solutions (Murekatete & Shirabe, 2021).

The least-cost path models, implicitly or explicitly relies on the aggregation of individual cost values across a cost surface (Murekatete & Shirabe, 2021). Which values indicate a determinate cost per cell, indicating a cost per unit length within the cells of the spatial grid (Murekatete & Shirabe, 2021). When a path is calculated upon these surfaces, each segment contains the product of the length of the line and the values of the underlying cells (Murekatete & Shirabe, 2021). Therefore, it is assumed that the less costly pathways generated with these methods are more suitable for a certain use (Murekatete & Shirabe, 2021).

Regarding a spatial raster, where the cells of a grid are assumed to be adjacent to each other sharing an edge or vertex, paths can be represented by a sequence of adjacent cells (Murekatete & Shirabe, 2021). Therefore, in raster-based methods it is commonly calculated the distance of a path between adjacent cells of a cost surface, according to the straight-line distance between their centers multiplied by their mean value (Murekatete & Shirabe, 2021). According to Murekatete & Shirabe (2021), this process uses the following equation to determine the length of a path $\boldsymbol{P}$ on a surface $\boldsymbol{f}$, which is detonated by $\boldsymbol{I_{sum}(P,f)}$. Where $\boldsymbol{f(i)}$ and $\boldsymbol{I(i,j)}$ indicate the value of a cell $\boldsymbol{i}$ on a surface $\boldsymbol{f}$ and the straight distance between the center of the cells $\boldsymbol{i}$ and $\boldsymbol{j}$ respectively (Murekatete & Shirabe, 2021).

$$\boldsymbol{I_{sum}(P,f)} = \sum_{\boldsymbol{(i,j) \in P}} \left[\left(\frac{\boldsymbol{f(i) + f(j)}}{\boldsymbol{2}} \right) \times \boldsymbol{I(i,j)} \right]$$

According to this formula, if $\boldsymbol{f}$ refers to the cost, the equation defines the cost-length. (Murekatete & Shirabe, 2021). Therefore, a least-cost path refers to a path that minimizes this length over surface. (Murekatete & Shirabe, 2021).

In this research was considered a method based on the stated principles, aiming to determine effective drone routes to deliver defibrillators in Alpine regions, using the Low-Altitude-Flight Elevation Model (LAFEM) as the surface to calculate the pathways. The workflow proposed to plan UAS-AED Missions, uses the Distance Accumulation algorithm integrated in the Distance toolset of ArcGIS Pro 3.1 to determine Optimal Paths (Esri, 2023b). This method was selected because it extends the capabilities of commonly used algorithms that rely on differential geometry to find paths through 8-way direction networks, reconstructing a continuous accumulative surface in all directions considering the slopes to calculate paths based on true costs and distances (Esri, 2023b). In a scenario where all the edges of a grid have the same weight (Figure 15), this algorithm is able to find an optimal path ($\boldsymbol{AB}$) that can be shorter than a path retrained to the network directions ($\boldsymbol{AB'B}$) (Esri, 2023b). The sum of these differences could result into shorter flight plans, which could make a relevant difference in the performance of automatic drone missions to deliver defibrillators mountain environments (Wankmüller et al., 2020).

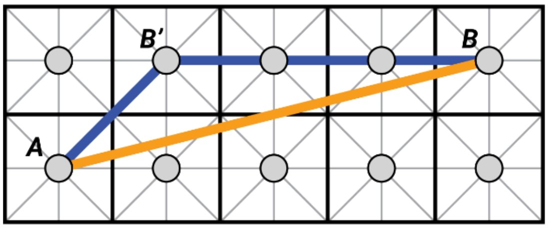

Figure 15: Optimal Path and Shortest Network Path (Esri, 2023b).

The mission routing workflow proposed in this research, require to define first the location of the drone stations and the spatial restrictions in the studied area to identify possible barriers according to local regulations (EASA, 2022). Once the location of the deployment stations is known, is required estimate the distance accumulation from them using the Low-Altitude-Flight Elevation Model (LAFEM). To generate the accumulated surface was considered the Distance Allocation geoprocessing tool of ArcGIS Pro 3.1, because this implements the mentioned Distance Accumulation algorithm to generate raster outputs of distance accumulation, back-direction and distance allocation from source points (Esri, 2023d) (Figure 16).

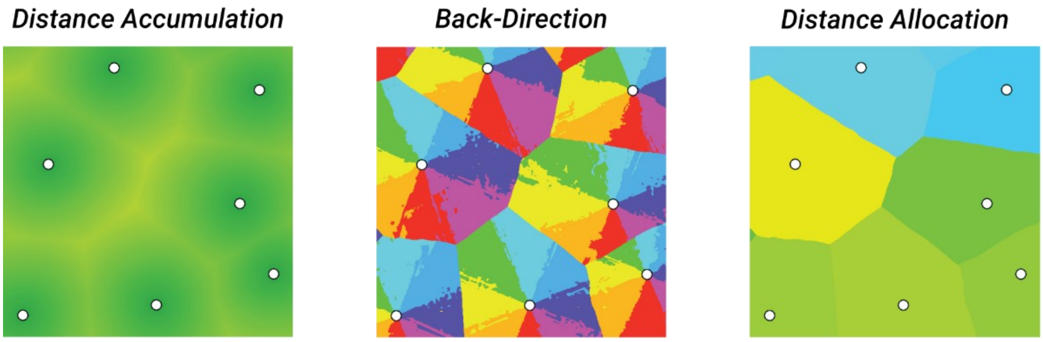

Figure 16: Distance Allocation Raster Outputs

This process generates an accumulated cost distance raster from a point layer using a surface model to consider terrain variations, spatial barriers and a cost surface to weight the values, as well as optional vertical and horizontal factors, adapting the distance calculations around the obstacles (Esri, 2023d).

During the calculation of the distance accumulation was only considered the LAFEM surface, that already counts with vertical and horizontal adjustments. It was not considered an additional cost surface or factors to weight the calculations, because this might adapt the final routing outcomes giving priority to other variables, such as land use (Hildemann & de Campolide, 2019). In this case, the objective was to find the shortest distance in highly a variable terrain, calculating straight-line distances while avoiding dangerous or prohibited zones, aiming to reduce response times towards life-threatening emergencies assuming that permissions for the operation would be granted.

The distance accumulation raster (Figure 16), generated with this process shows a continuous surface where the distance values increase linearly from base locations, considering slope differences and obstacles. The back-direction raster, refers to the direction towards the closest source point, considering a range of 360 degrees. While in the distance allocation surface, are used the shortest distance and direction associated to a point to segment the interest area depending on the closest location, which could be used to identify the operation range between different stations.

Once the accumulated distance and back-direction surfaces have been calculated for each station of the proposed drone service network, it would only require to have emergency site locations to start the routing process. Using given positions, the map-base process initiates calculating the optimal path towards the closest drone station estimating the shortest straight-line distance and returning a 2D vectorial pathway. This is generated using the Optimal Path as Line tool of ArcGIS Pro 3.1, which is capable of finding paths calculating straight-line distances and optionally adapting the routes according to barriers or surface slope variations (Esri, 2023a). This process was applied in a sample scenario using fictional emergency sites at different distances (Figure 17), showing the possibility of generating multiple optimal routes simultaneously and their allocation towards the closest drone station.

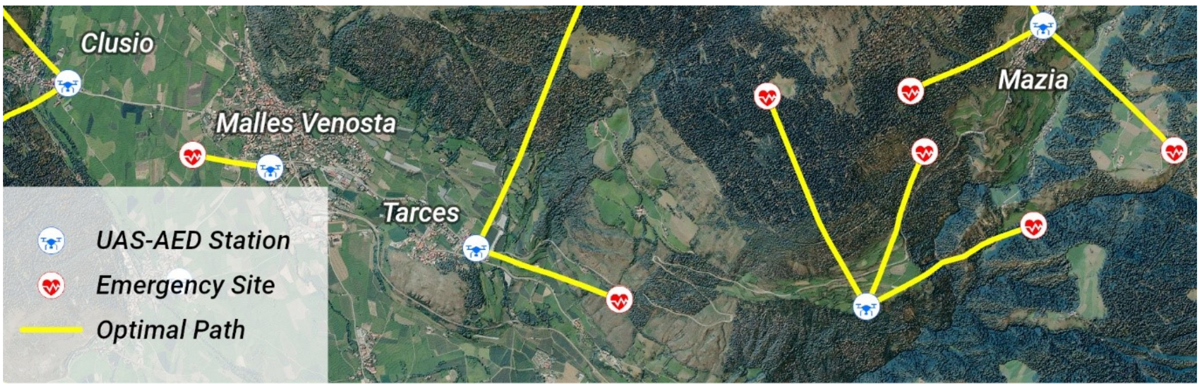

Figure 17:Sample 2D Optimal Paths (Malles Venosta, South Tyrol, Italy)

Since the 2D pathways were oriented originally from the emergency point towards the closest station based on the accumulated distance, was also required to reverse the vector line geometry, orienting the resulting pathways from the UAS-AED station to the emergency sites, before initiating processing the information in a 3D environment.

During the optimal path calculation was used the Low-Altitude-Flight Elevation Model (LAFEM) as part of the accumulated distance, in the following step this model will be considered again to give 3D properties to the route vector. Using the geoprocessing tool Interpolate Shape, can be performed a bilinear interpolation along the optimal path polyline, adding elevation values to the vertices of this vector based on the surface model sampling distance (Esri, 2023e).

The bilinear interpolation is a widely used interpolation method in computer vision and image processing, which aims to calculate the value of a point $\boldsymbol{P}$, using the weighted average of the values of the points $\boldsymbol{Q}_{11}$, $\boldsymbol{Q}_{12}$, $\boldsymbol{Q}_{21}$, and $\boldsymbol{Q}_{22}$ as corners of a rectangle (Szczepanek, 2023). According to Szczepanek (2023), this is calculated using the following equation. Where are first performed two linear interpolations in the x-direction (horizontal), to calculate the value of $\boldsymbol{P}$ using another linear interpolation in the y-direction (vertical) (Szczepanek, 2023).

$$\boldsymbol{P} = \frac{(x_2 - x)(y_2 - y)}{(x_2 - x_1)(y_2 - y_1)}\boldsymbol{Q}_{11} + \frac{(x_2 - x)(y_2 - y)}{(x_2 - x_1)(y_2 - y_1)}\boldsymbol{Q}_{21} + \frac{(x_2 - x)(y_2 - y)}{(x_2 - x_1)(y_2 - y_1)}\boldsymbol{Q}_{12} + \frac{(x_2 - x)(y_2 - y)}{(x_2 - x_1)(y_2 - y_1)}\boldsymbol{Q}_{22}$$

Finishing this process will be obtained a 3D feature that contains a detailed optimal path to define the drone route over a 3D environment. The resulting vector can already be displayed using a 3D mapping interface to see how the modifications implemented in the Low-Altitude-Flight Elevation Model (LAFEM) affects the route, keeping a constant altitude threshold over the terrain while following its variations according to a detailed elevation model. This can be seen generating drone routes towards sample emergency sites in Alpine Regions (Figure 18).

Figure 18: Sample 3D Optimal Paths (Malles Venosta, South Tyrol, Italy)

The trajectory of a drone route is defined by waypoints that contains a set of XYZ coordinates, that require to be carefully planned to execute effective flights (Raivi et al., 2023). Therefore, the continuous 3D vector of the route generated, require to be simplified into a less complex pathway while preserving critical elevation points over the terrain, allowing the UAS to flight through challenging environments safely based on a predefined optimal path.

To simplify the vector line preserving the critical points of the route, was considered the Douglas–Peucker algorithm or iterative end-point fit algorithm (Meng, 2021). This method reduces de number of points of a curve preserving a rough shape of the original line, based on a simplification tolerance parameter (ε) that controls the degree of coarsening, defined by the distance between the original points and the simplified curve (Meng, 2021) (Figure 19).

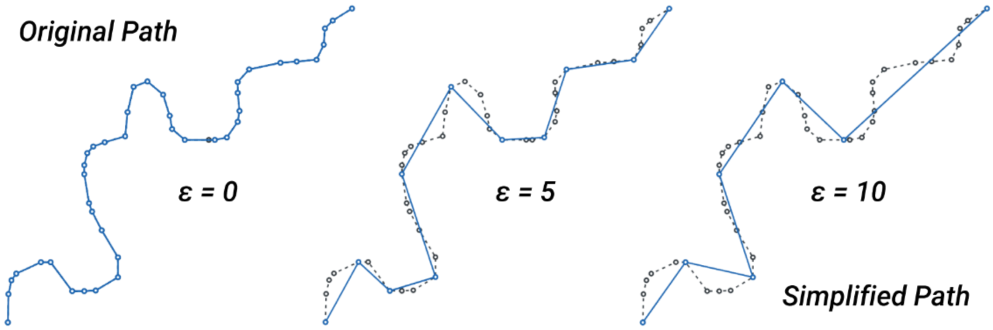

Figure 19: Douglas-Peucker Path Simplification (Meng, 2021).

This method was implemented using the Simplify 3D Line geoprocessing tool in ArcGIS Pro 3.1, obtaining a vector with reduced number of vertices keeping a safe altitude over the terrain. To define an acceptable tolerance simplification parameter was require to run multiple sample scenarios, until getting a route able to follow the terrain variations without requiring redundant waypoints. This was important to analyze prior the field test to avoid collisions across a steep terrain, as the mountain surrounding the Lake Braies (Figure 20), where a high simplification tolerance applied to the optimal path might cause impacts with the slopes nearby.

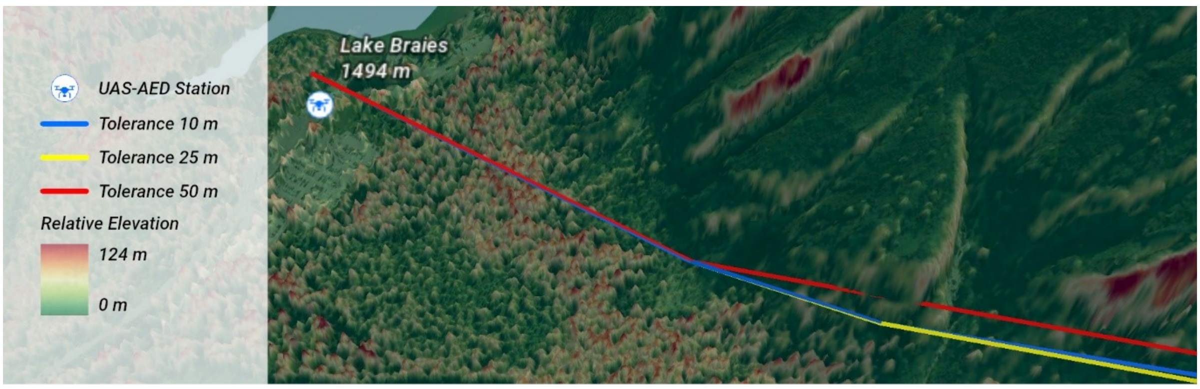

Figure 20: 3D Routes with Different Simplification Tolerance (Lake Braies, South Tyrol, Italy)

Once the 3D optimal path has been simplified are generated points from its vertex, which have integrated in their geometry the elevation values of the Low-Altitude-Flight Elevation Model (LAFEM). Even though, the table associated to these points do not count by default with the coordinate values. Therefore, the workflow requires to add numerical fields to the table (Double, 64-bit floating point) for each of the XYZ coordinates and calculate their geometry values using a local coordinate system, to generate a table with the position of each vertex as waypoints. This table is finally exported to be adapted according to the specific routing format use by the UAS provider.

This workflow was automatized using the ArcGIS Pro 3.1 Model Builder application following three stages (Figure 21). The first starts generating the optimal path from an emergency point based on the surface accumulation and back direction raster predefined from the UAS-AED stations. The following procedures gives to the resulting path 3D attributes and simplify the vector to generate the desired waypoints. Finally, are calculated the coordinates of the waypoints that will define the drone trajectory, to export then as a table that can be adapted according to the drone routes parameters.

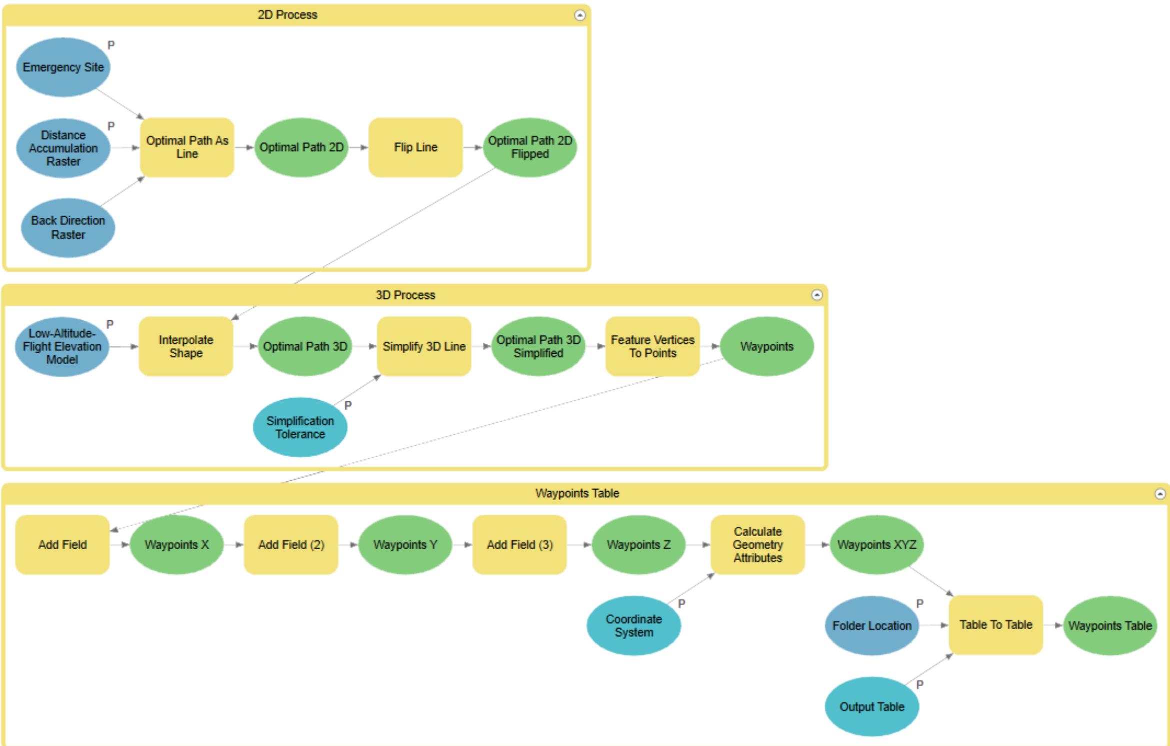

Figure 21: UAS-AED Routing Geoprocessing Model

In order to run this model is required to perform previously the calculation of the surface accumulation and back direction surface based on the Low-Altitude-Flight Elevation Model (LAFEM) to get the surface to generate the optimal path towards the emergency points.

This model also relies on the location of the emergency site as a point vector input to route the pathway towards it. As well as define an acceptable tolerance simplification value to avoid collisions according to the terrain characteristics and the coordinate system in which the output coordinates will be required to perform the flight (Figure 22).

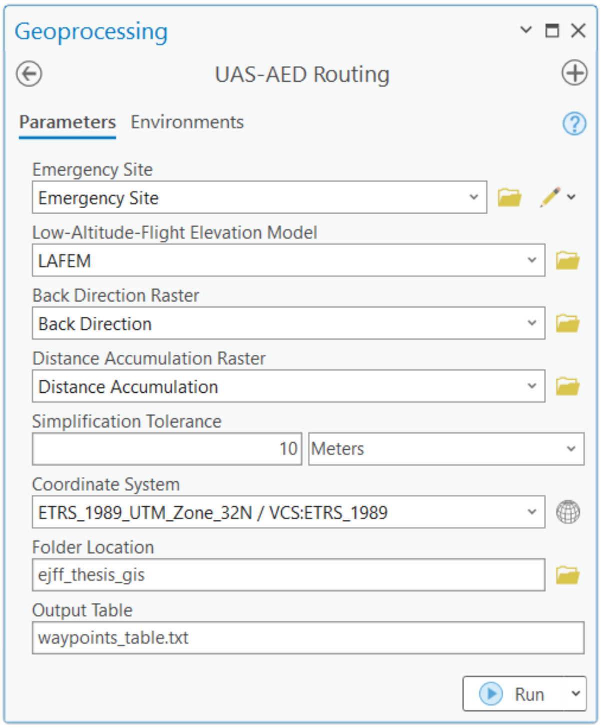

Figure 22: UAS-AED Routing Inputs Interface

Regarding this research was considered a 10 meters tolerance value, as a general measure to simplify the emergency drone delivery routes in Alpine regions to test the workflow, even though this still require further testing to assure its safe implementation. In this research was used the horizontal coordinate system ETRS 1989 UTM Zone 32N and ETRS 1989 for vertical reference respectively.

3.6. UAS-AED Missions Effectiveness Testing

The proposed workflow generates pathways that could be considered as an alternative to route automatic drone missions over challenging terrain. However, before implementing this method to assist cardiac arrest by delivering defibrillators, it is important to test these preliminary results on the field, to analyse how effective are the proposed optimal paths in reducing the flight times towards a remote location while following terrain variations.

There are few studies that have analysed the performance of drones to deliver medical supplies in mountain environments, which have consider mainly a straight-line approach or manual flights simulating real emergency scenarios (P. Fischer et al., 2023; Van Veelen, Roveri, et al., 2023; Wankmüller et al., 2020, 2021). These tests are meaningful to demonstrate how impactful drones can be to support Search and Rescue (SAR) Missions and delivery AED (Wankmüller et al., 2021).

Manual flights have shown that drones can be effective to locate a victim based on visual contact and remote sensing, making possible the early delivery of medical supplies (Van Veelen, Roveri, et al., 2023). Even though, mountain areas are especially challenging for aerial rescue operations due to changing weather conditions, obstacles, vegetation and poor GPS coverage (Van Veelen, Roveri, et al., 2023). Therefore, it would be feasible to reach emergency calls in a remote location relying on automatic drone missions, to reduce the response time prior the arrival of first responders (P. Fischer et al., 2023).

In this research the field tests are focused on comparing the time to reach hypothetical emergency sites in mountain environments, using the proposed optimal paths that follows the terrain variations, a straight-line approach that keeps a constant elevation using the Euclidean distance and a manual flight (Figure 23).

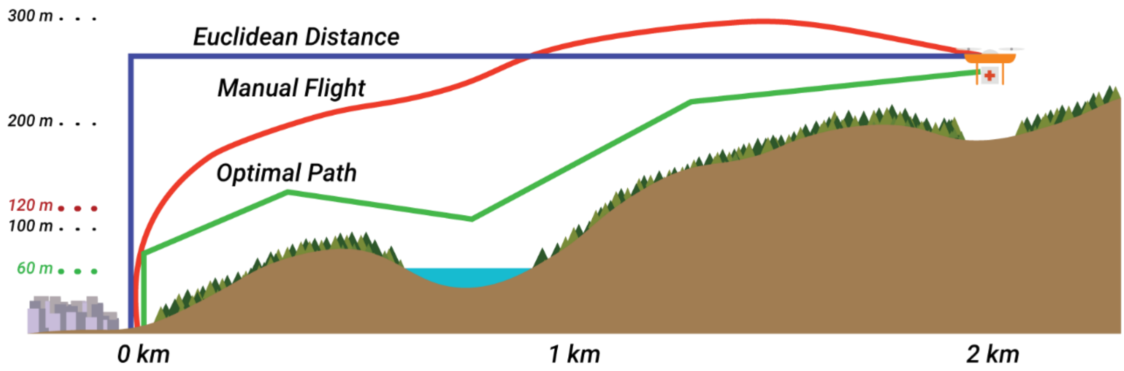

Figure 23: Routing Approaches Comparison

These tests allow to analyze the overall effectiveness of the proposed routing workflow in different study cases. Supporting the refinement of the routing workflow itself, making possible to adjust the parameters considered to estimate the drone routes base on empirical knowledge gathered during the missions and the input of the crew members. Aiming to integrate this method as part of a solution for first responders based on cartographic information, to deliver defibrillators in Alpine Regions.

4. Experimental Setup

To analyse the general distribution and coverage that an emergency drone service network could have in Alpine Regions, based on the proposed methods, was selected the Autonomous Province of South Tyrol in Italy as a regional model study case. Due to the important role that play mountain activities in this area (Scuttari et al., 2023), and the large amount of facilities dedicated to these (IDM Südtirol, 2023). Using this approach, was selected the Lake Braies, which is a location highly visited by tourists of this province (Martiny, 2023). To refine the routing workflow prior the field tests, running multiple model scenarios in a diverse mountain environment from a potential UAS-AED station location.

To demonstrate the effectiveness of the proposed method, contribute with the objectives of the DRONE-AED project (Van Veelen, Mendicino, et al., 2023), and evaluate the real impact of this research, were also selected two practical exercises, simulating two seasonal mountain sport activities in the Province of South Tyrol (Romeo et al., 2021). Providing AED inside recreational ski resorts and during mountain trail running races, in the areas of Corvara in Badia and Ritten respectively (Figure 24).

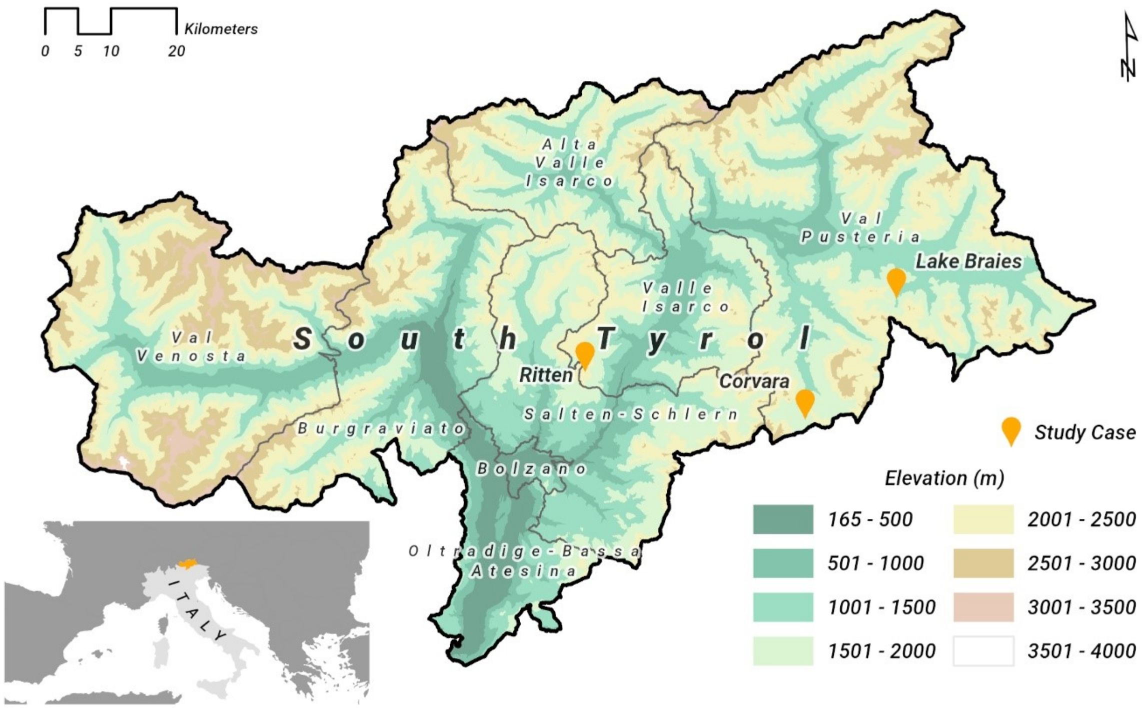

Figure 24: Study Cases

4.1. Emergency Drone Service Network (South Tyrol)

The Alpine Regions group some of the most relevant mountain areas of Europe (Romeo et al., 2021). Extended through eight countries according to the Alpine Convention (Austria, France, Germany, Italy, Liechtenstein, Monaco, Slovenia and Switzerland), the Alps have outstanding natural and cultural heritage, important urban areas and a vast service infrastructure, sustained by an economy based mainly on agriculture and tourism (Elmi, 2018). Which is reflected in the coverage of its Emergency Medical Services (EMS), that can reach any area of the region within 60 minutes coordinating ground and air operations (Brugger et al., 2021).

The Autonomous Province of South Tyrol is the northernmost region of Italy, located near the centre of the Alps. This province has an unique combination of rugged Alpine environments and Mediterranean sceneries that attracts millions of tourists every year (IDM Südtirol, 2023). It has a surface of 7,400 square kilometres, in a territory composed by mountains and valleys, and a population over 530,000 residents, located primarily in the capital city of Bolzano, and settlements as Merano, Bressanone or Brunico (Scuttari et al., 2023).

The exceptional landscapes of South Tyrol receives over 7 million visitors per year, which represents both an economic benefit for the local economy and pressure on its services and inhabitants (Scuttari et al., 2023). The high number of people in mountain environments (Figure 25) also increases the use of mountain emergency services, pushing the need to improve the medical care offered in these areas (Brugger et al., 2021).

Figure 25: Crowded mountains of South Tyrol (Corno Bianco, 2316 m)

Figure 26:Alpine huts of South Tyrol (Schlernhaus, 2457m)

This province counts with the AVS South Tyrol Mountain Rescue team, since 1948, which has around 1,000 volunteer rescue members and 50 dog handlers (Brugger et al., 2021). There are 3 ambulance helicopters to cover the province (Wankmüller et al., 2020). As well as 7 public hospitals and 2 privates (ASTAT, 2021), and multiple fire brigade stations associated with the National Fire and Rescue Service (Vigili del Fuoco, 2023). Which could benefit from an emergency drone network to support their historical labour (Wankmüller et al., 2020).

This study case considers primarily the first responder stations as potential sites for UAS-AED deployment stations for the proposed emergency drone service network, as well as other facilities, such as those related to mountain tourism as alternative sites (Wankmüller et al., 2020). Like the vast network of Alpine huts established in South Tyrol (Figure 26), which counts more than 100 locations in the mountains (IDM Südtirol, 2023).

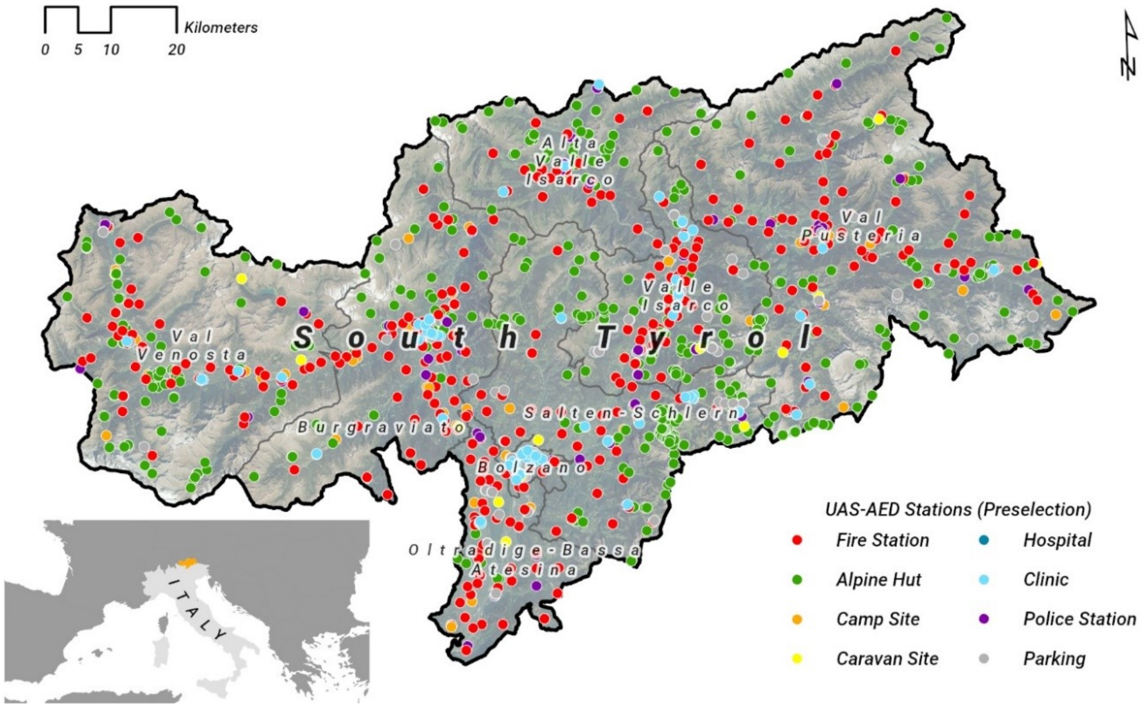

Figure 27: UAS-AED Stations Preselection, South Tyrol

As a starting point to define the emergency drone services network of South Tyrol, is first gathered the geographic information of the relevant facilities in the province (Figure 27). These locations were filtered from open data provided by contributors in OpenStreetMap (OpenStreetMap, 2023). Among all the locations available in this zone, is applied a query that extract feasible locations for potential UAS-AED stations according to their class (fclass).

This selection considers locations related to first responders to deploy Emergency Medical Services (EMS), such as fire rescue stations(Wankmüller et al., 2020), and facilities related to health care as hospital and clinics. Also, alternative locations related to local tourism, as Alpine huts, camp sites and caravan sites, which can be in some cases the only facilities equipped with electricity and first aid equipment in a vast mountain sector (Wankmüller et al., 2020). This research also considers police stations as feasible locations to deploy the drones, due police officers can also assists OHCA (Brugger et al., 2021), and vending parking lots with electricity access, due these can be found in the starting points of important hiking trails.

Once the initial feasible locations for the network are defined, these are filtered spatially using the suitability model described previously Methodology). This suitability model considers the UAS Geographical Zones and the classified land use to define roughly how suitable would be to place a drone station according to an spatial overlay analysis (Ahlqvist, 2009).

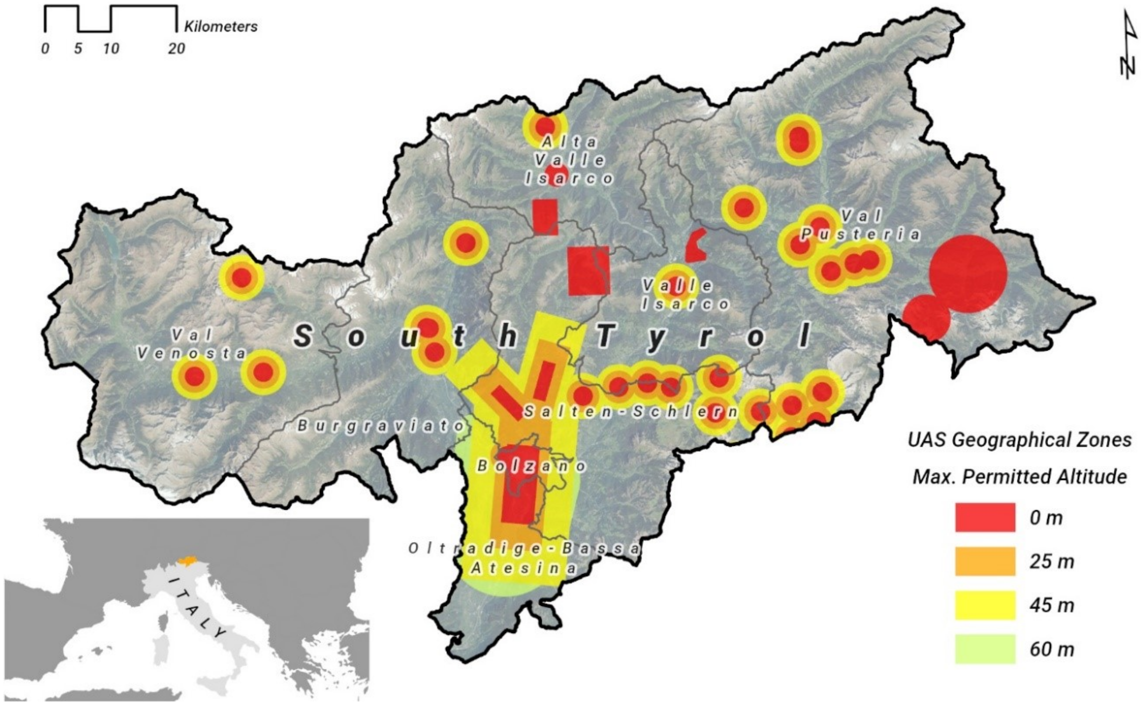

Figure 28: UAS Geographical Zones

The UAS Geographical Zones (Figure 28), are based on the local aerial regulations applied to civil drone operations, according the Italian Civil Aviation Authority (ENAC) (d-flight, 2023). In this research these are grouped using the maximum permitted altitude of permanently defined areas, established in the approximation zone to airports or any location related to manned aviation (EASA, 2022). As well as military, administrative or any other facility, considered dangerous to be overflown by drones (EASA, 2022).

The altitude constraints are more restrictive while getting closer to them and impose sudden geofences to prevent any unwanted drone operation nearby. In South Tyrol, these refer primarily to the main civil airport in Bolzano, and multiple heliports used by air ambulances and tourists (Wankmüller et al., 2020). However, in the rest of the province can be carried out civil operations up to 120 meters from the terrain level, following special considerations depending on the aircraft (EASA, 2022).

Regarding the land use (Figure 29), is considered the most recent spatial characterization of South Tyrol provided by the local official geoportal (Südtiroler Bürgernetz, 2023). This spatial layer is classified according to how feasible would be to place a drone station along them, using the predefined categories as a refence and the local regulations related to UAS (EASA, 2022). Dangerous zones as the mentioned before are considered as prohibited to place a drone station. The areas that require special considerations in order to deploy a drone, such dense urban fabrics or near the street networks, are seen as restricted and thus less feasible. The rest of the areas that are open space or sparce urban fabrics, do not have major restrictions to operate drones, therefore these are considered as feasible. There are some other areas that do not have specific restrictions, but are considered as unfeasible, like water ways, debris zones, glaciers or disposal areas, in which would be impractical to place an UAS-AED station at first glance.

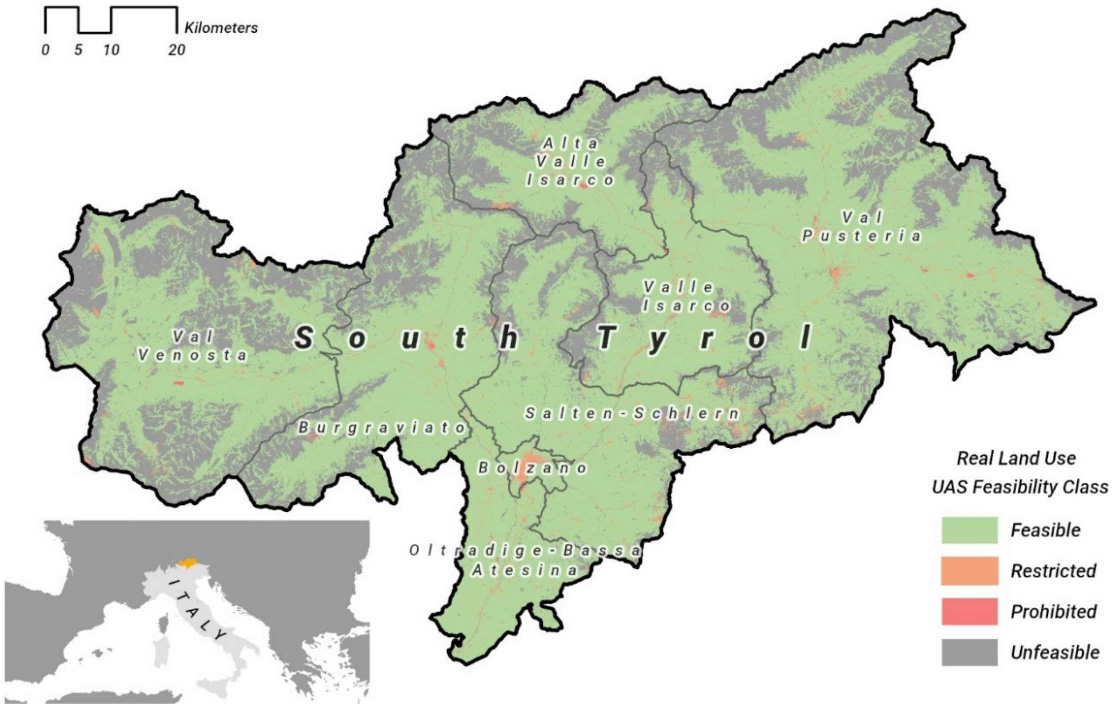

Figure 29: Real Land Use Classified, South Tyrol

Integrating this information as spatial variables in an overlay analysis (Ahlqvist, 2009), is possible to define and index that refers to those areas that are more or less suitable to place a desired facility (Habib et al., 2020), such an UAS-AED station. According to the methodology (3.1. Methodology), the different classes of these two layers are assigned a weight and sum up to generate the spatial model of UAS-AED Placement Suitability. This model is generated with values in the range 0 – 100, been taken as a suitability percentage index to place a drone station according to the local regulations (ATM-09A. ENAC, 2021). Those areas without major restrictions for drone operations area represented with the highest values, while the prohibited have the lowest (Figure 30).

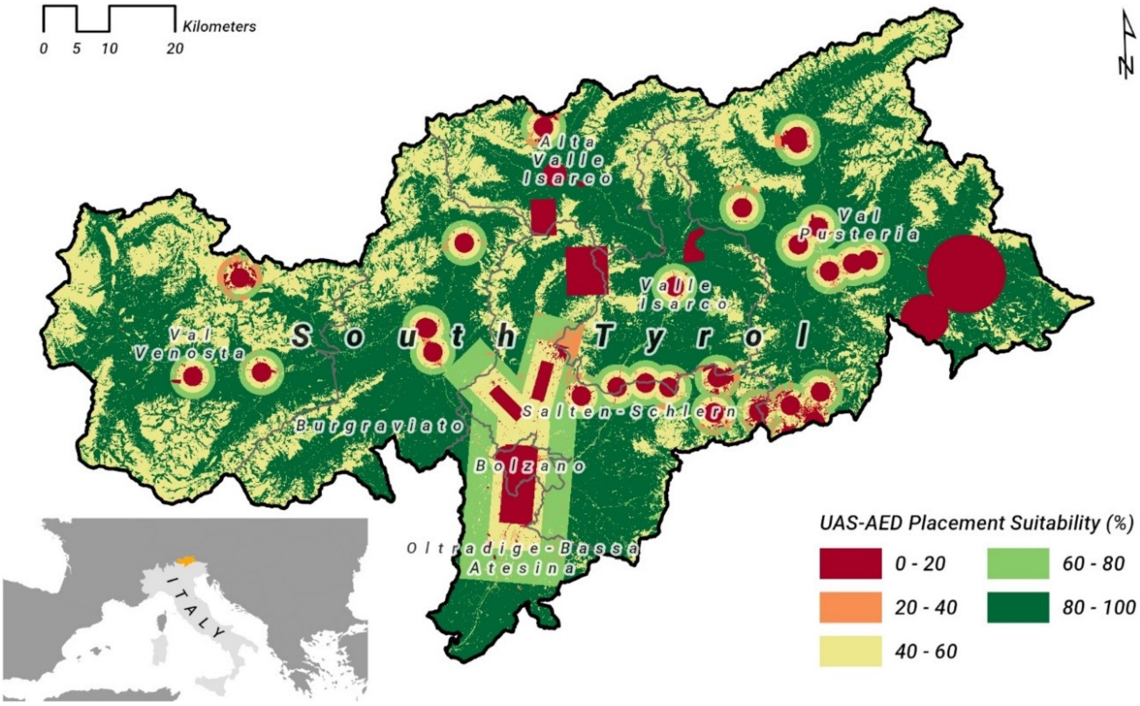

Figure 30: UAS-AED Placement Suitability, South Tyrol

According to this model, open rural areas or those with sparse urban fabrics, away from dangerous zones, are the most suitable to place the UAS-AED stations in South Tyrol, which are extended primarily in mountain zones. Even though, have to be considered that 25% of the province are protected areas, including the mountains of the Dolomites declared UNESCO World Natural Heritage in 2009 (Scuttari et al., 2023). These areas are designed as ENV-002 Geographical Zones, which would require the authorization of the administration of the natural parks or protected areas, to allow automatic drone missions in case of life-threatening emergencies (ENAC, 2022). Such authorization to operate in protected areas is assumed as granted by this research, to depict a network that can also operates across them.

Once the suitability to place the drones has been calculated, this information is used to filter the preselected locations. In this research are considered primarily the facilities placed in zones over 50% of suitability, assuring the possibility to launch the drones in feasible areas (Figure 30). The filtered locations are now analysed according to its relative density and proximity with each other. A clustering method based on the nearest neighbours is used for this (Methodology), grouping the facilities that are within 1 km, because this is the maximum distance drones can actually operate beyond visual line of sight (BVLOS) in the area of interest (EASA, 2022). Using these clusters are identified areas with redundant groups of facilities, to select directly from them specific locations according to their class, giving priority to fire rescue stations (Figure 31).

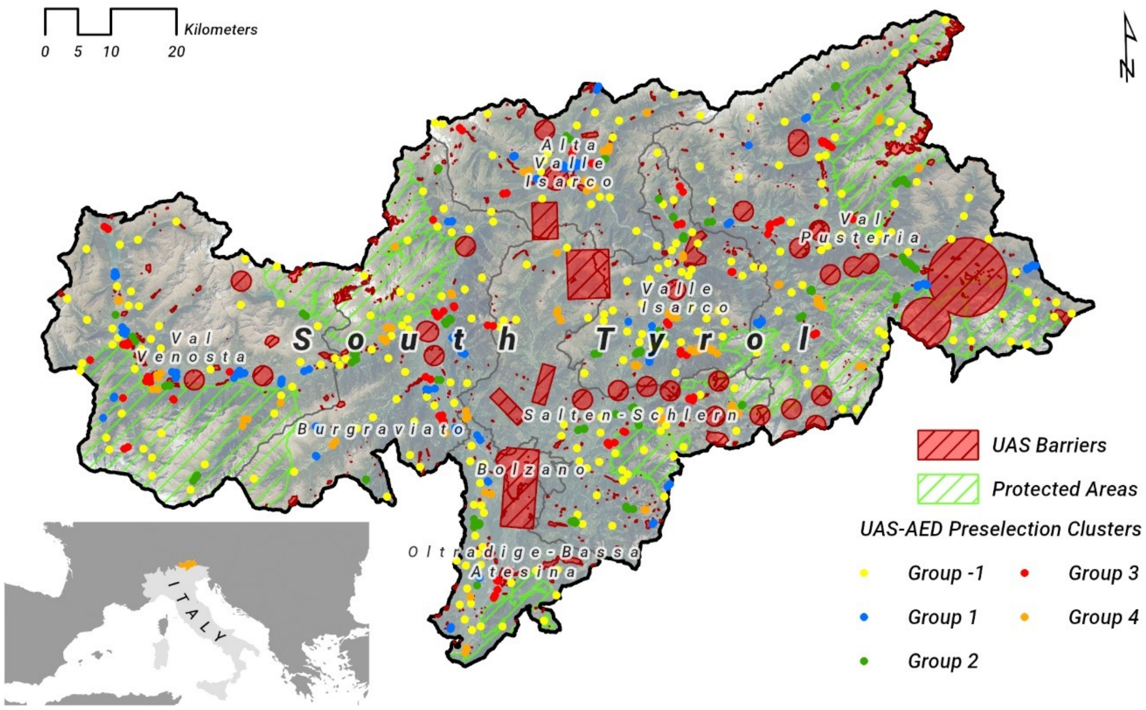

Figure 31: UAS-AED Stations Preselection Clustering, South Tyrol

In this selection, is also considered the location of the facilities in relation to protected areas and barriers defined by zones that are prohibited to fly, including natural monuments such as the biotopes of South Tyrol. It is selected at least one facility per local cluster group to assure the coverage of that area using as few drone stations as possible (Figure 31)

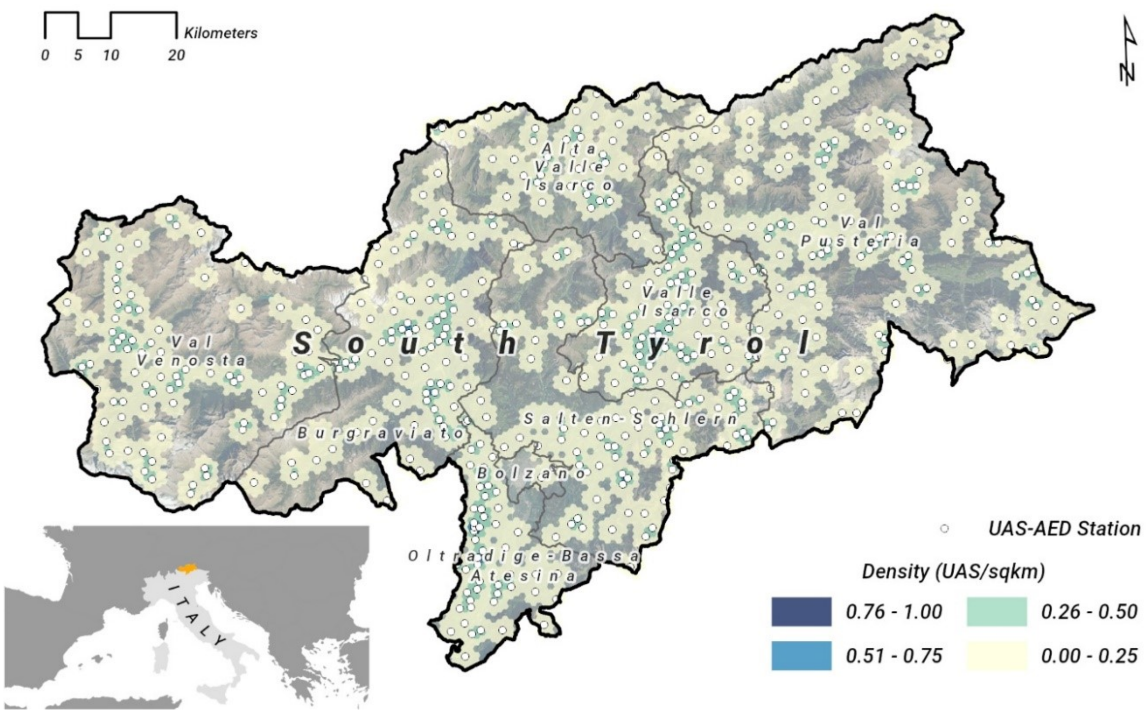

Figure 32: UAS-AED Stations Density, South Tyrol

Using this approach was obtained a set of potential locations, that are the base of the proposed emergency drone service network, which is determined according to the existing facilities in the Province of South Tyrol away of dangerous or restricted zones. After the filtering and selection process (3.2. Methodology), the distribution of the potential network showed a relative low density across the province (Figure 32), locating most of the stations in the valleys or near main settlements. Even though, the use of alternative deployment sites, such Alpine huts, might extend the coverage of this potential network towards the mountains.

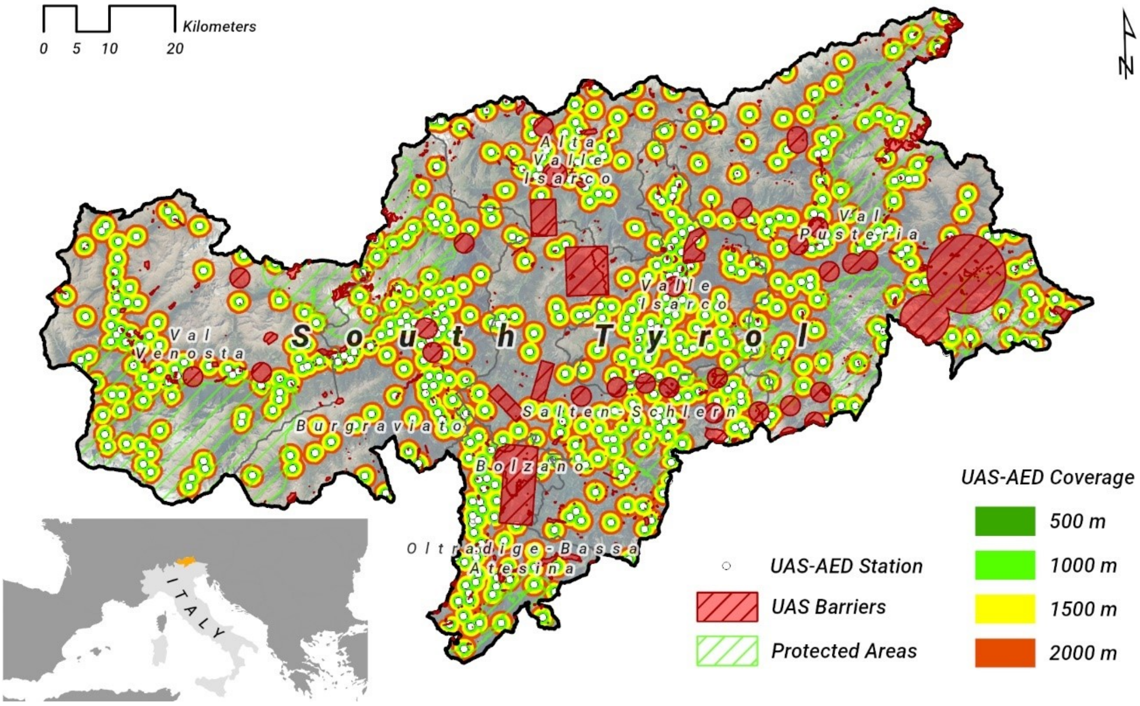

Figure 33: UAS-AED Network Potential Coverage, South Tyrol

Aiming to generate the vast possible effective coverage using the smallest number of UAS-AED stations, is estimated the spatial range the proposed network would have in the Province of South Tyrol (Figure 33). Therefore, are used these locations as initial points to calculate the accumulated distance over the Low-Altitude-Flight Elevation Model (LAFEM), which integrates UAS barriers to prevent operations in dangerous or prohibited zones, adapting to terrain variations (Low-Altitude-Flight Elevation Model (LAFEM)). The resulting coverage is limited to the maximum extend drone operations can actually reach, which is 2 km being supported by airspace observers (EASA, 2022). Even though, this distance from the stations could not ensure a full coverage of the province based on the existing facilities, these areas would be reachable using drones to deliver an AED under 10 minutes, which is acceptable to provide support to Out-of-Hospital Cardiac Arrests (OHCA) (Brugger et al., 2021).

4.2. UAS-AED Routing (Lake Braies)

The Lake Braies, also known as Pragser Wildsee, is one of the most captivating lakes in Italy, located in the Fanes-Senes-Braies Nature Park to the east of South Tyrol (Figure 24). The lake is nestled in a steep rocky valley basin, surrounded by dense forests and dominated by the Croda del Becco (Seekofel) Peak (2810 m) (Figure 34) (Tourist Office Pragser Tal Valley, 2023). This lake is a very frequented destination by the visitors of South Tyrol, which have pushed the local government to establish limits to the daily amount of people entering the area, in order to keep it in a manageable level especially during Summer (Griffin, 2023).

A place with such frequency of visitors should ideally count with an accessible AED, available for first responders and bystanders in case of OHCA (Elsensohn et al., 2006). Considering that accessible hiking routes, as those that surrounds this lake, can be easily visited by elderly people with pre-existing cardiovascular and respiratory diseases, which increases their chances of suffering sudden cardiac arrests (Brugger et al., 2021). Furthermore, it could be beneficial to have nearby a drone capable of transporting a defibrillator rapidly across the lake or to the pathways used by numerous hikers.

Figure 34: Lake Braies and Peak Croda del Becco (Seekofel) Peak (2810 m) (Kottersteger, Wisthaler & Auer. Tourist Office Pragser Tal Valley, 2023)

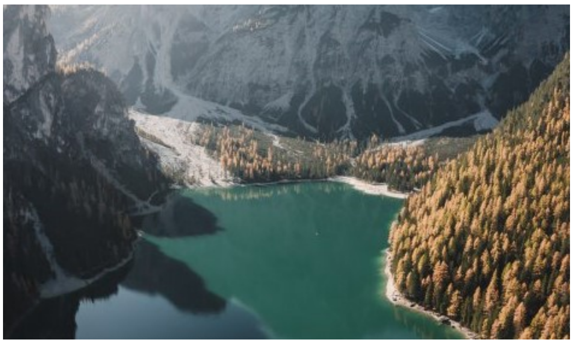

Figure 35: Lake Braies Aerial Perspective (Kottersteger, Wisthaler & Auer. Tourist Office Pragser Tal Valley, 2023)

This study case simulates a scenario in which multiple drone routes could be planned based on the described method (Methodology), from a potential UAS-AED station located near the touristic facilities in the entrance of the Lake Braies. The emergency sites are located on hiking paths at different distances and elevations from the sample station, aiming to test the automatic routes generated by the designed workflow over diverse topographic conditions in a realistic context (Figure 35). These tests are aligned with the objectives of the DRONE-AED project, that is planning to evaluate the performance of drones to deliver defibrillators in this location with the cooperation of local rescue teams (Van Veelen, Mendicino, et al., 2023).

The UAS-AED deployment site is defined nearby the Lago di Braies Hotel (1494 m), with relatively easy access to the lake pathways and hiking routes (Figure 36). The major concerns routing a drone in this scenario are the steep rocky slopes of the basin, trees over 20 meters and possible restrictions to fly over the lake, assuming favorable weather conditions. The selected emergency points are divided in two groups of four, located in the hiking paths of the mountains nearby (H), and the pathways around the Lake Braies (L).

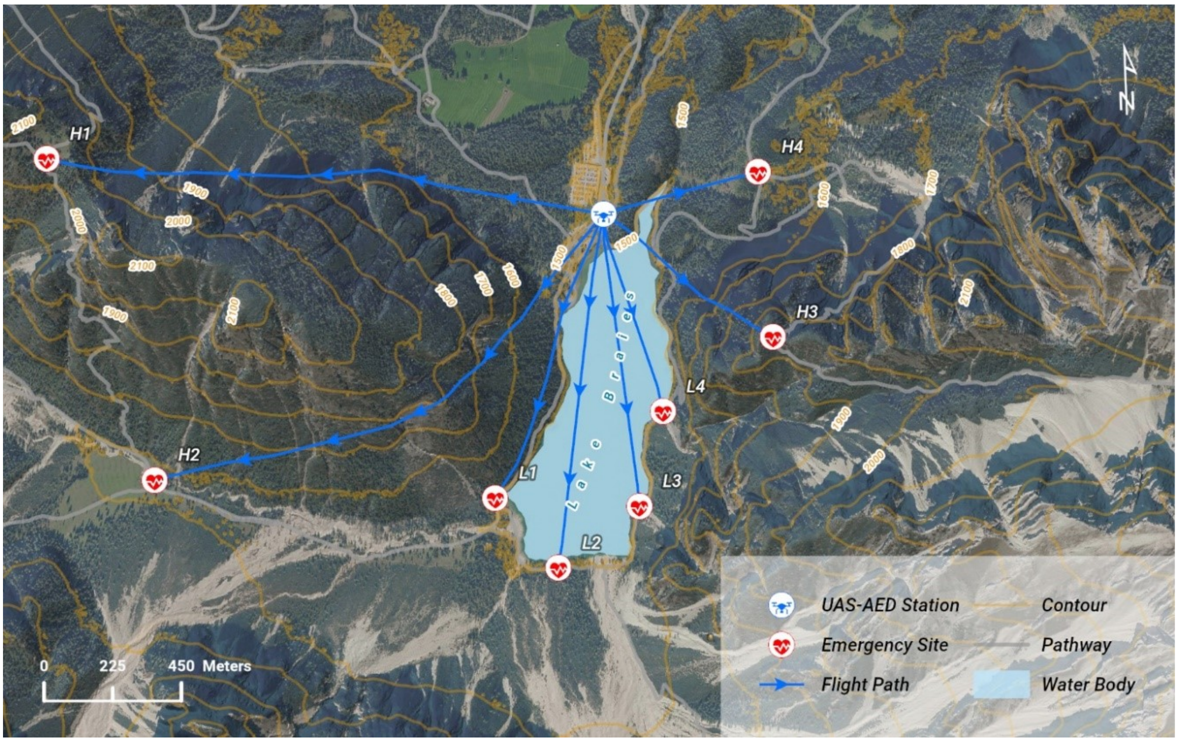

Figure 36: UAS-AED Routes, Lake Braies

Running the semi-automatic workflow proposed to design the flight paths UAS-AED Missions Routing Workflow, using the emergency sites as destination points, is possible to get the optimal routes that adapt to the topographic variations in the shortest distance. Since the routes are calculated over the presented Low-Altitude-Flight Elevation Model (LAFEM), these consider a safety threshold to fly over a detailed surface model, which is defined at 30 meters in this study case. In the routes can be appreciated how the these follow the slopes, aiming to get to the emergency site finding the shortest possible distance (Figure 37). In some paths without major obstacles in between (L2, L3, L4 and H4), these follow a straight line towards the destination considering only altitude variations if needed. In cases where is not possible to define full straight paths due to slope variations (L1 and H3), are considered automatically minor trajectory adjustments. While in cases with notorious topographic variations (H1 and H2), can be seen major changes aiming to optimize the generated path across the slopes.

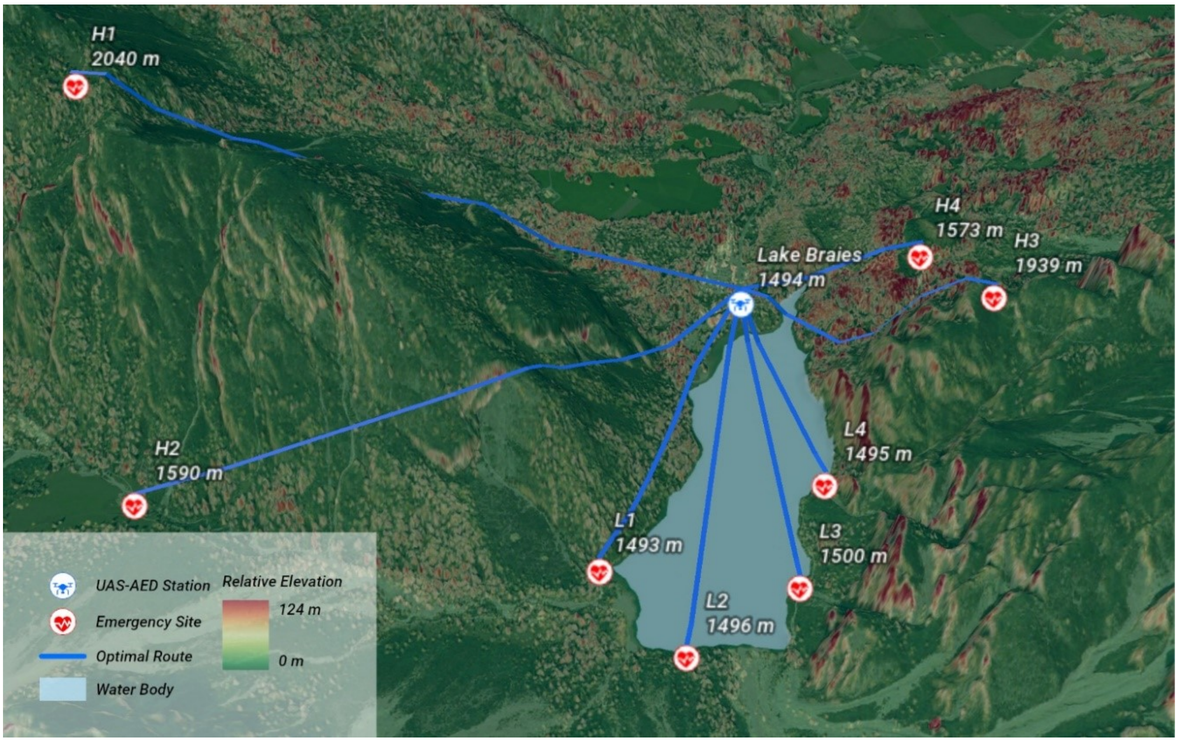

Figure 37: UAS-AED Routes 3D, Lake Braies

To highlight the differences between the routes generated with the proposed map-based workflow UAS-AED Missions Routing Workflow, will be analyzed in detail three of the sample routes. The flight path towards the emergency point L2 (1496 m), goes across the Lake Braies following a straight line (Figure 38). Even though there are only 2 meters of elevation difference between the station and the emergency site, the surface alterations caused by the vegetation near the starting and finishing points, make the workflow adapt to these as obstacles, considering several variations in the altitude of the resulting waypoints. The estimated shortest distance between these points is actually 1,166.53 meters, even though the altitude variations considered by the model makes the final path outcome length 1,177.30 meters, using a tolerance of 10 meters to simplify the path (Figure 39).

Figure 38: L2 Route, Lake Braies

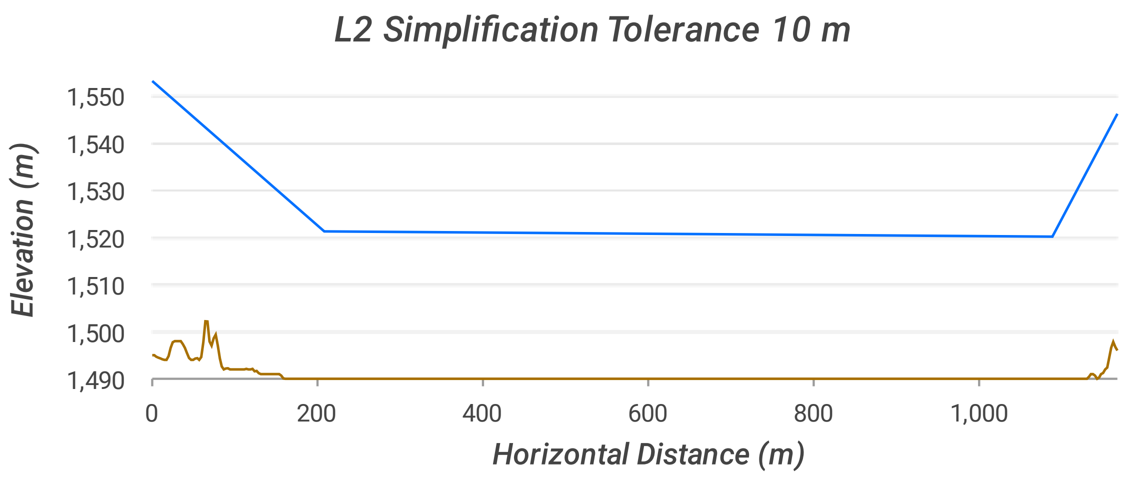

Figure 39: L2 Route, Simplification Tolerance 10 m

The capacity of the proposed workflow to adapt the routes to terrain variations can be seen clearly in the route H3 (Figure 40). This emergency site is located on a viewpoint to the lake (1939 m), relatively close to the station, but separated by a steep slope over 400 meters higher. To reach this place, the workflow suggests a path that goes in a rather straight line considering major altitude adjustments in each waypoint to avoid colliding the rock wall or its vegetation. Cases like this shows the importance of including lateral adjustments to the Low-Altitude-Flight Elevation Model (LAFEM), ensuring the paths to be horizontally distant to the actual surface based on a detailed elevation model (3.4. Methodology).

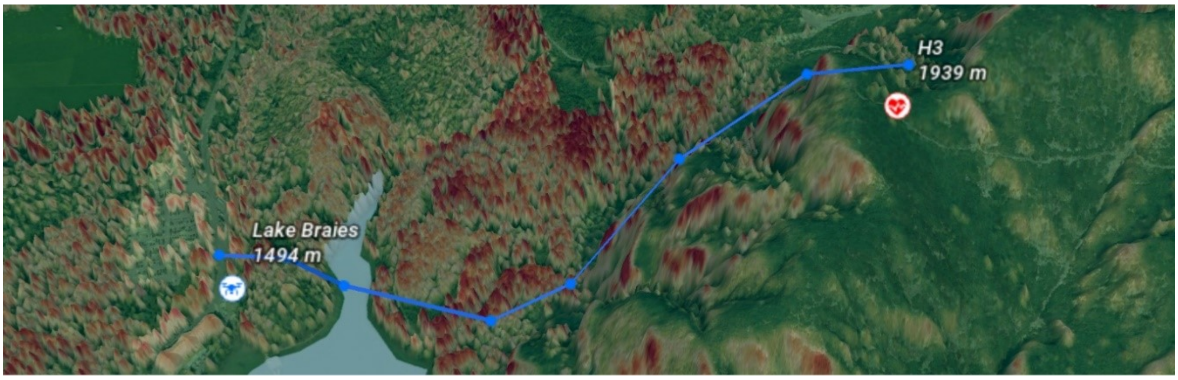

Figure 40: H3 Route, Lake Braies

The horizontal distance between these points is 686.18 m, even though the vertical distance adjustments extend the optimal path proposed to 915.89 m. In cases like these could be considered to fly the drone directly to the required altitude over 400 meters and reach the desired location, but surpassing the maximum permitted high of 120 meters would be dangerous to any person or good near the operation, not to mention that if an ambulance helicopter is involved, the drone would become an important risk factor for this and its crew.

Designing automatic drone paths based on the proposed cartographic method, also required to test different parameters to simplify the final results. In this study case were considered different meters of tolerance to simplify the resulting lines based on the method Douglas-Peucker (Meng, 2021). In steep slopes as those faced to reach the point H3, if are considered high levels of tolerance in the line simplification to minimize the number of waypoints (Figure 41), this would result in a path that collide with the terrain underneath. Therefore, in further practical tests is considered 10 meters as tolerance to simplify the continuous paths and generate the trajectory waypoints.

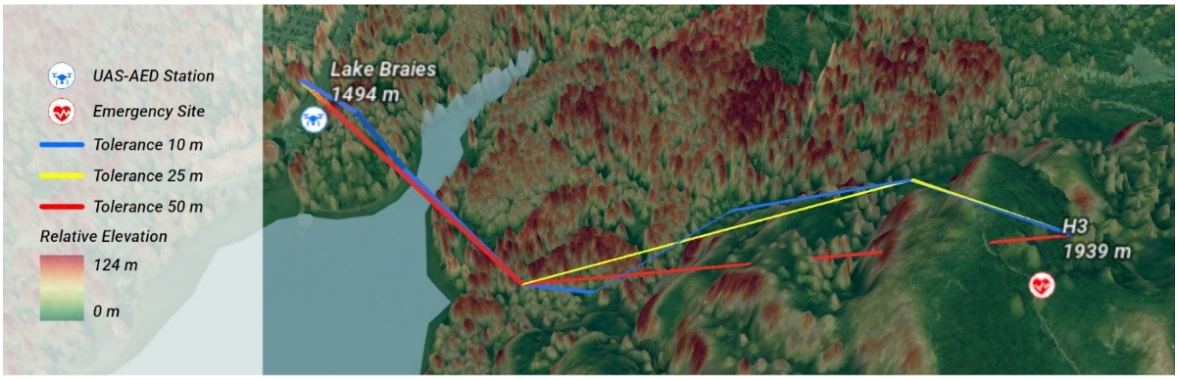

Figure 41: H3 Route Simplification Tolerance Difference, Lake Braies

Another example that shows the potential of the proposed workflow to find optimal paths around high mountains, is the route towards the emergency site H2 (Figure 42). In this case a straight path from the station to the emergency would have to fly over a steep mountain 500 meters higher than the initial point. While the path generated, finds a lower suitable way to reach the desired location considering the slopes differences based on the accumulated distance (Murekatete & Shirabe, 2021).

Figure 42: H2 Route, Lake Braies

This path keeps the altitude threshold following the terrain variations, ensuring a safe flight in the shortest possible distance across a mountainous environment (Figure 43). Which could be helpful to avoid unnecessary manoeuvres over high lands, causing the arrival of the AED to take longer (Wankmüller et al., 2020).

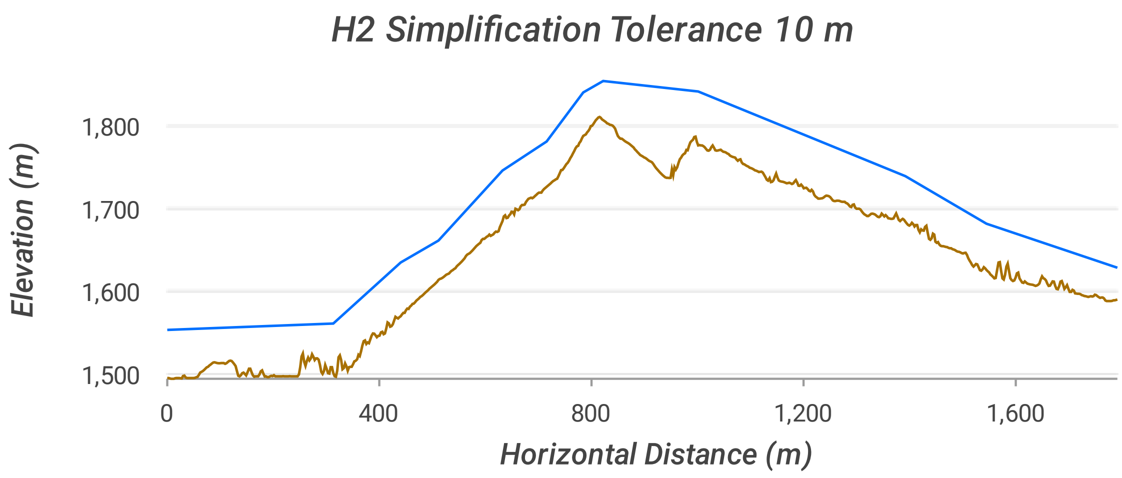

Figure 43: H2 Route, Simplification Tolerance 10 m

Since the proposed method relies on the accumulated distances calculated from the UAS-AED station UAS-AED Missions Routing Workflow, this could be adjusted using barriers as geofences to prevent operations to fly over dangerous or restricted zones. As an example, is used the Lake Braies as a barrier to route the operations on the pathways surrounding the lake (L), causing the workflow to adapt the routes around this area. The effect of the barrier on the accumulated distances can be seen graphically using the output surface, where the distances around the lake are larger than those measured over it (Figure 44). This characteristic could be helpful to design automatic routes in highly restricted environments (He et al., 2022).

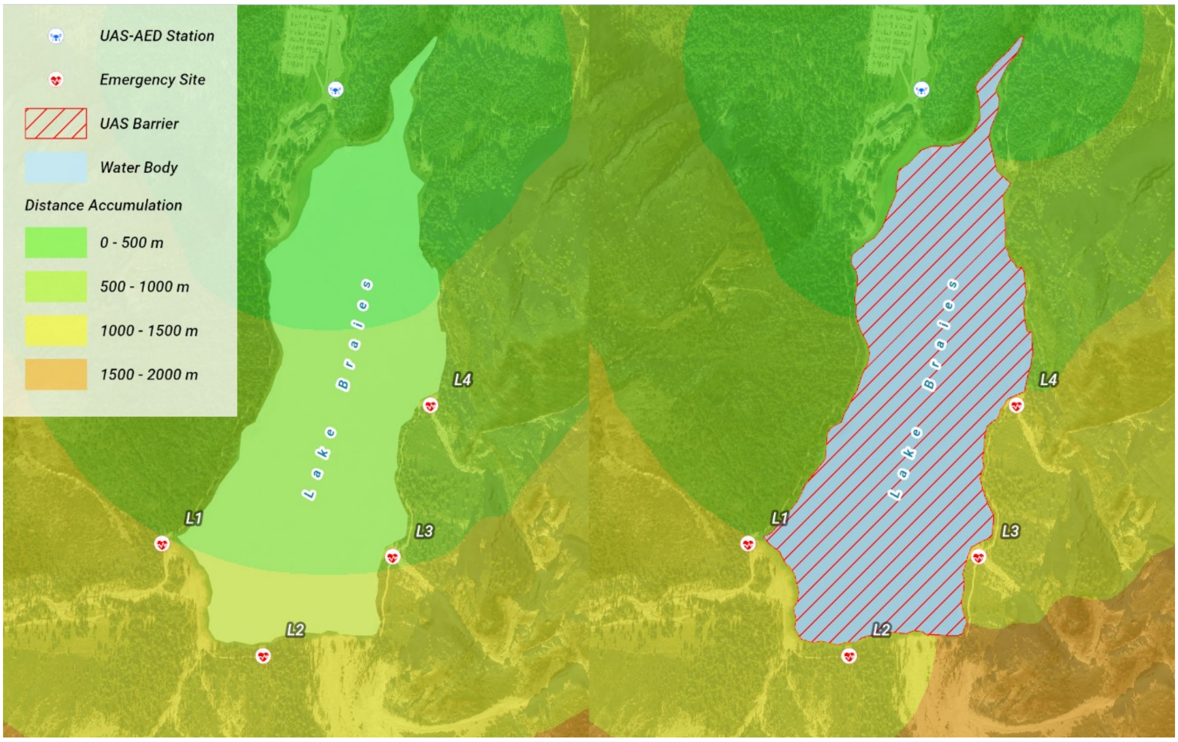

Figure 44: Distance Accumulation Adaptation, Lake Braies

As the result of the surface accumulation adaptation, the routes generated considering a barrier are calculated finding the optimal path around the obstacle (Figure 45). This could make the flights take longer to arrive the emergency points, but also be useful to avoid at all cost flying over security zones or densely populated areas, which might increase the risk of the operation.

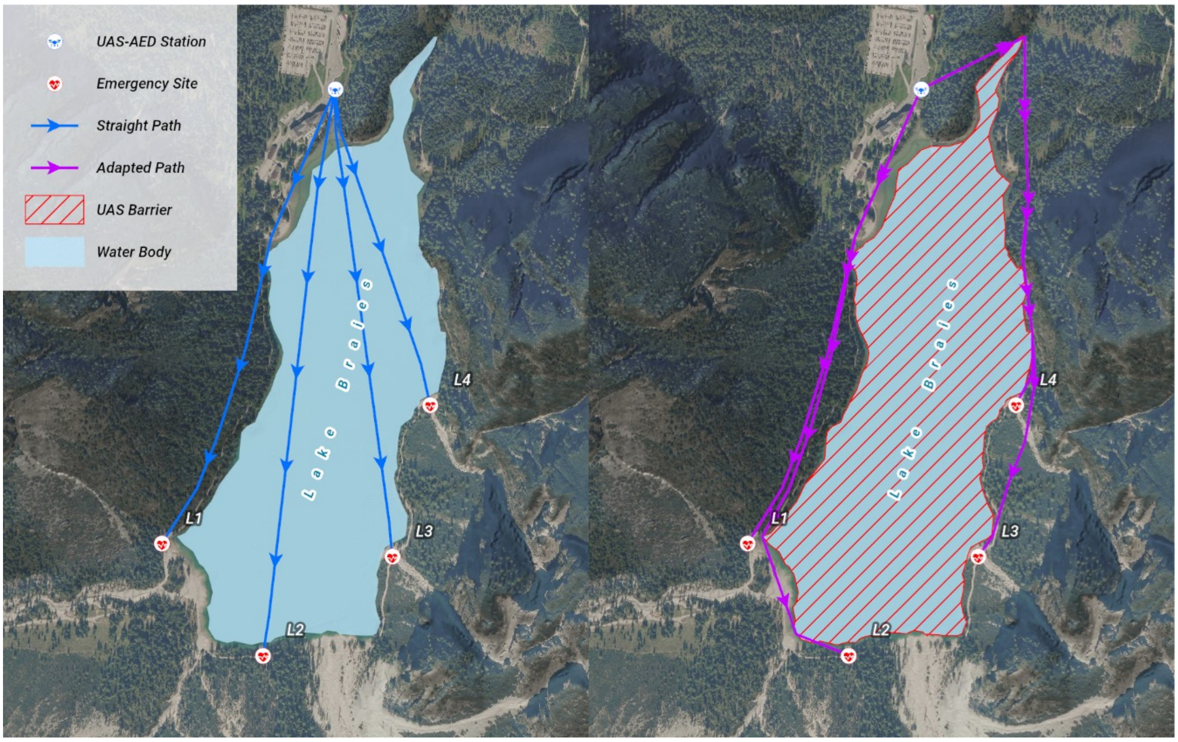

Figure 45: Optimal Paths Adapted to Barriers, Lake Braies

Considering the potential of the resulting paths, some of them will be tested in the Lake Braies as part of the DRONE-AED project simulations (Van Veelen, Mendicino, et al., 2023), supporting their endeavor to develop a suitable solution to deliver defibrillators using UAS, aiming to improve the positive outcomes of cardiac arrests in mountainous areas.

4.3. Recreational Ski AED Delivery (Corvara)

The culture of recreational ski in Italy, can be tracked back for more than a century (Vanat, 2021). Within the millions of tourist that receive South Tyrol, the number of ski resort visitors in the Italian Alps keeps increasing every year (Vanat, 2021). In average, these visitors are predominantly men above 35 years old (Schwartz, 2013). Which considering the high impact of this sport, increase the risks and likelihood of cardiac arrests (Brugger et al., 2021).

Corvara in Badia, was the first place to introduce dedicated ski lifts in Italy and is one of the most visited locations to practice this activity in South Tyrol (Figure 24) (Vanat, 2021). The Gardena Ski Resort (Figure 46), has received more than 5 million visitors during the last five years (Vanat, 2021). For this reason, the ski slopes of this zone were selected simulate and test the AED delivery.

Figure 46: Ski Lifts of Badia (Dolomiti Superski, 2023)

Figure 47: Capanna Nera in Alta Badia (YesAlps, 2023)

In this study case, the victim is located at the side of a slope, shortly after the ski lift, where people start to do high intensity physical activity in Crep de Mont (1136 m). The drone station is selected according to its coverage range (3.3. Methodology), being deployed an UAS-AED near the Capanna Nera hut (Figure 47), which counts with electricity and first aid supplies.

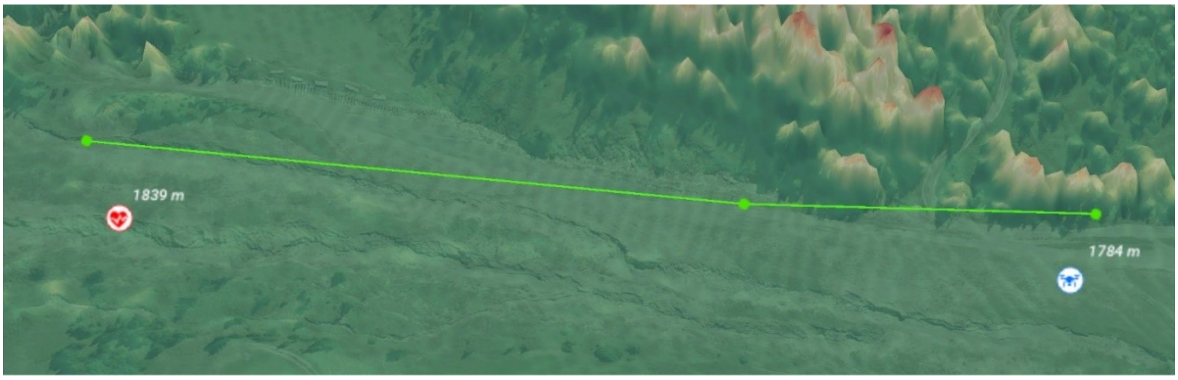

Figure 48: Automatic Flight, Corvara

The test consisted in simulating the provision of an AED with an automatic flight (Figure 48), and a manual flight conducted by a skilled remote pilot (Figure 49). Being these the first flights based on a flight path generated with the proposed method UAS-AED Missions Routing Workflow, was preferred to make them in a rather controlled area without sorting major obstacles and during Summer (Figure 50). The elevation difference between the drone base and the emergency site was 55 meters and the horizontal distance of the operation 295.77 meters, keeping constant visual line of sight (VLOS) with the aircraft

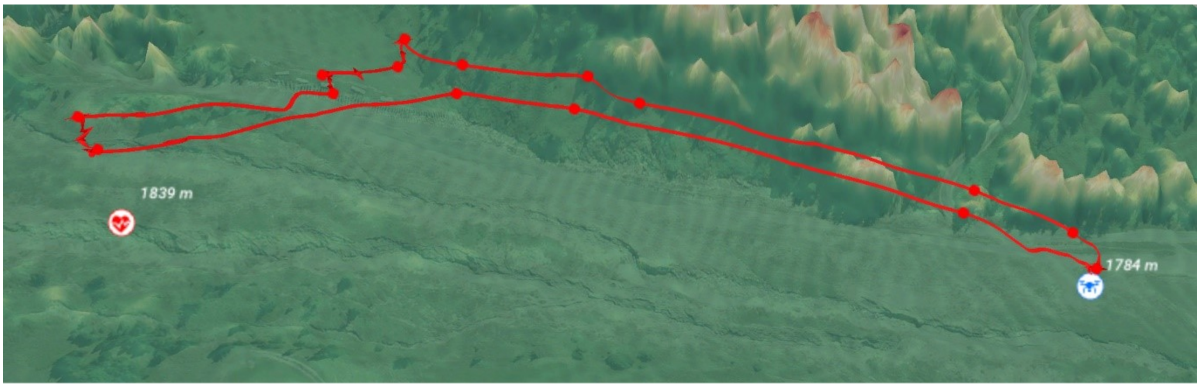

Figure 49: Manual Flight, Corvara

The experiment took place in a field campaign during June of 2023, using an UAS platform Soleon, model Octagon x8 flat, an octocopter adapted for mountain applications provided by Eurac Research (Figure 51) (Appendix 1). This device is equipped with GPS and navigation systems, capable to perform autonomous flights up to 25 minutes and drop packages.

Figure 50: Ski slopes of Corvara in Summer

Figure 51: Soleon Octagon provided by Eurac Research

In this test only a manual flight was done to the emergency site and back, to drop the AED at the location of the patient. This mission took 02:30 minutes to deliver the package and lasted 04:10 in total. Even though the manual flight approach is usually faster and direct, finding the location in the distance might take longer relying solely on the trained eye and the experience of the remote pilot, resulting to be less time-effective than the automatic missions estimated towards the same emergency point.

4.4. Mountain Trail Running AED Delivery (Ritten)

Mountain trail running is a discipline sport that consist in running mountainous environments characterized by abrupt terrain changes. Practicing this sport athletes encounter continuous elevation variations and are consistently exposed to fluctuating weather conditions (Carel Viljoen et al., 2022). Therefore, this activity demands for them to have optimal physical conditions and mental preparation to prevent incidents (Carel Viljoen et al., 2022).

In the Italian Alps, are implemented strict regulations for those who wants to participate in trail running competitions (e.g., physical sport examinations). Even though, it still persists the risk of incidents due to the number of participants above mid-age (Metzler, 2022). In average, over 45% of people enduring mountaineering activities are older than 40 years old, and 15.3 to 28% of them experience pre-existing cardiovascular diseases (Brugger et al., 2021).

In this study case was selected a location in Ritten (Figure 24), near the route of the Südtirol Ultra Skyrace (Figure 52), a recognized ultramarathon that takes place in the mountains of South Tyrol and attracts more than 500 athletes annually (Südtirol Ultra Skyrace, 2023). The emergency site is situated in the proximity to the summit of the Rittenhorn mountain (2261 m), shortly after a challenging ascent in the race, which requires intense physical effort from athletes to reach (covering 22.5 km with an accumulated elevation gain of 2000 meters).

Figure 52: Südtirol Ultra Skyrace 2023 (Südtirol Ultra Skyrace, 2023)

Figure 53: Ritternhorn Alpine Hut (2261 m)

The position of the drone is located in near the Rittnerhorn hut (2261 m), which has a restaurant with electricity and first aid medical supplies. In close proximity to this hut, there is a ski lift and a radio antenna, which add complexity to the operation, along with a significant number of visitors passing by (Figure 53). Regarding the simulated emergency site, this is located along a trail approximately 725 meters away from the drone, and at an elevation 130 meters lower than the take-off and landing place (Figure 54).

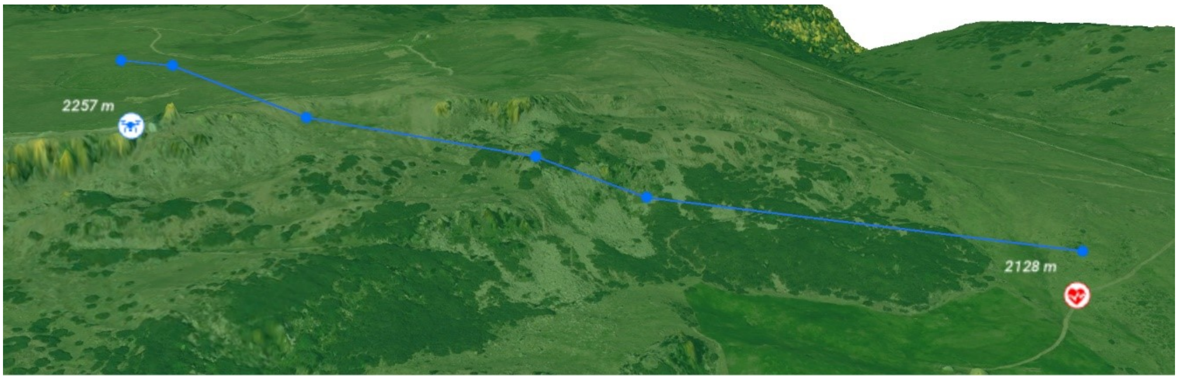

Figure 54: Flight Plan, Ritten

This test consisted in simulating the provision of an AED with automatic flights that follow the changes of the terrain, to demonstrate the effectivity of the proposed workflow based on cartographic methods (UAS-AED Missions Routing Workflow). Therefore, the route was planned to reach the emergency point navigating the drone through a rough terrain, flying over cliffs and steep slopes covered with bushes (Figure 55), providing a rigorous scenario for evaluating the automatic flight path in a challenging environment with substantial elevation differences.

Figure 55: Rough terrain to run the flight tests, Ritten (2257 m)

Figure 56: MavTech Q4X provided by MavTech

The experiment took place in two field campaigns during July of 2023, using a platform Q4X quadcopter provided by MavTech (Figure 56). This drone is currently under development, being improved to perform flights under extreme conditions to support emergency operations as part of the DRONE-AED project (Van Veelen, Mendicino, et al., 2023). It counts with an endurance of 40 minutes, can carry a payload up to 5 kg and was adapted for these tests with a dropping system to deliver an AED using a small parachute (Appendix 1: 1).

In Ritten were flown three automatic missions using a flight plan based on the proposed method, considering manual take-off and landing procedures, to avoid possible collisions with the radio antenna nearby (Figure 53).

The first flight (Ritten 1) used the defined path to set the trajectory towards the emergency point, bringing back the platform manually (Figure 57).

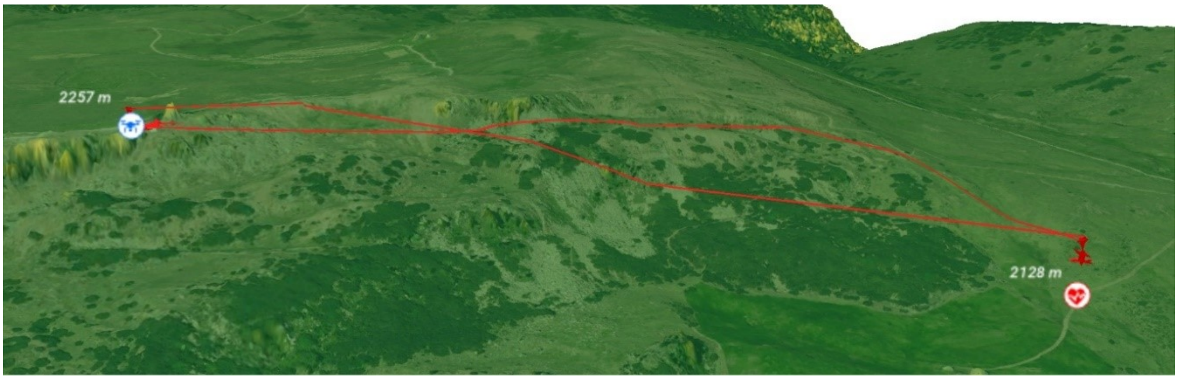

Figure 57: Flight Ritten 1, Ritten

The flight Ritten 1, followed the terrain variations using a safety threshold of 40 meters above the surface, approaching the location of the patient by descending 20 meters, to drop the AED 20 meters above the desired location. To conclude the flight the platform was piloted manually. The distance of the full flight was 1,638.50 meters, delivering the AED in 03:36 minutes, to finalize the total mission in 10:11 minutes (Figure 57).

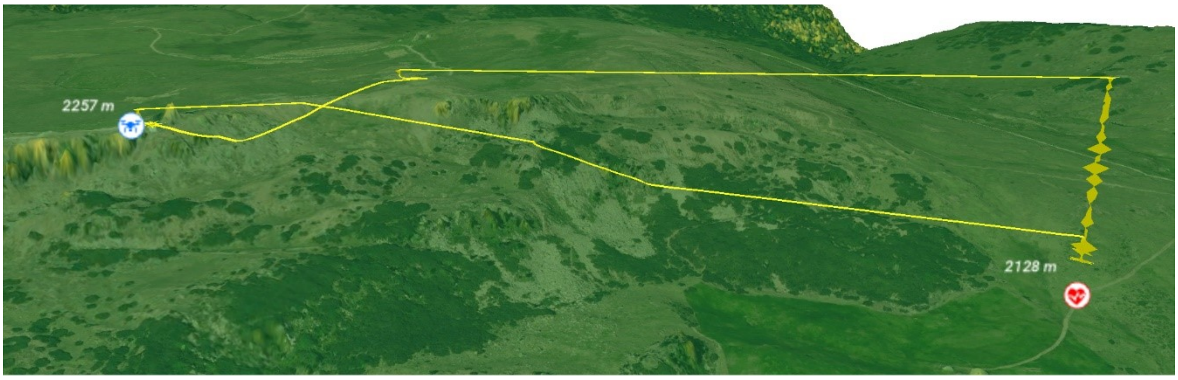

Figure 58: Flight Ritten 2, Ritten

The second flight (Ritten 2), performed also the initial part towards the emergency site following the predefined plan adapted to the terrain, considering a safety threshold of 40 meters above the surface and approaching to the location of the patient by descending 20 meters (Figure 58). Even though, in this case the return was set to be a direct flight keeping a constant altitude. In an approach similar to the implemented in the simulations made by Wankmüller in South Tyrol (Wankmüller et al., 2020). The drone flew back effectively to base point in a straight line, but required a considerable time to reach the desired altitude prior the return. This mission total distance was 1,736.63 meters, was delivered the AED in 03:39 according to the map-driven route and finalized using the Return To Home (RTH) mode, taking 06:45 minutes in total.

During the last flight of this study case (Ritten 3), was followed the plan generated with the proposed method towards the emergency site and back (Figure 59). Considering the successful performance of the previous flights adapting safely to the terrain variations, was set the altitude threshold to 30 meters above the surface, requiring to descent only 10 meters to drop the AED in the desired position. The distance of this flight was 1.532.16 meters and took 05:29 minutes in total, delivering the AED in 02:59 minutes.

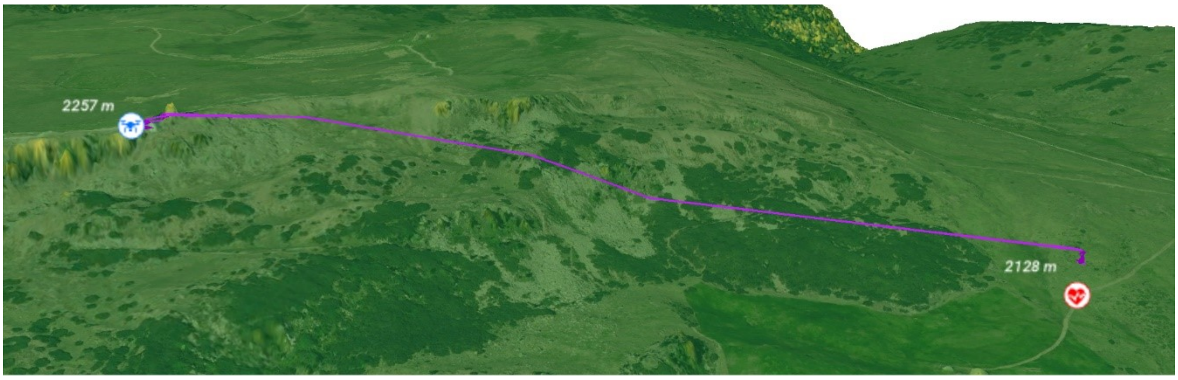

Figure 59: Flight Ritten 3, Ritten

Each flight was performed considering a horizontal speed of 7 m/s, using a vertical climbing rate of 3 m/s. Due to the distance of the emergency site, the drone flew beyond visual line of sight (BVLOS) from the remote pilot. Even though, in the destination point, was also an experienced observer tracking the operation, receiving the AED and keeping continuous communication with the remote pilot via radio.

When comparing the flights against the original plan generated using the proposed method (UAS-AED Missions Routing Workflow), it can be observed that the trajectories in all three cases adapted fairly well to the terrain variations, resulting into successful AED deliveries around 03:00 minutes. Which suggest that the proposed workflow based on cartographic methods to generate drone routes in mountain environments, holds a promising alternative to plan the routes to deliver AED. Even though, this would require further tests and automation, to be fully integrated with an automatic solution that permits first responders rely on the potential of drones to deliver medical supplies to provide early medical assistance in remote scenarios.

5. Results and Discussion

The summary of the findings obtained from the experimental setup study cases is presented in this chapter, addressing the overarching objective of designing a map-driven distributed emergency drone service network, enabling the localization of suitable areas and suggesting time-effective strategies for delivering AED in Alpine Regions.

The results are divided in three sections referring to the milestones reached during the research, regarding the description of the distribution and coverage of the proposed emergency drone service network in South Tyrol, considerations for map-driven UAS-AED mission routing in mountain environments and the analysis of UAS-AED missions performance following terrain variations.

5.1. Emergency Drone Service Network Distribution and Coverage

The suitable areas to provide emergency services based on drones, are defined in this research by the combined weighted analysis of the spatial regulations regarding these aircrafts, in the form of UAS Geographical Zones and the land uses where would be feasible to deploy them (3.1. Methodology). Based on the spatial overlay of the mentioned information (Ahlqvist, 2009), is generated a suitability index that assign the higher values to zones, such as open rural areas or those with sparse urban fabric, with few or non-restrictions to operate drones according to the local regulations (ENAC, 2022). Excluding specific areas that are restricted for drone operations for safety reasons, as happens in a small military area in the town of Malles Venosta in South Tyrol (Italy) (Figure 60), even though being possible to operate in its neighbouring zones.

Figure 60: UAS-AED Placement Suitability, Malles Venosta (South Tyrol)

In South Tyrol, zones with high levels of suitability are prolonged in the vast mountainous rural areas of the province (Figure 30), being this an opportunity to extend the coverage of Emergency Medical Services (EMS) using drones, away from highly restricted flight zones.

However, this would require to work in direct cooperation with the administration of the multiple protected areas in the province, to make possible flying the drones across them using automatic missions in case of life-threatening emergencies (ENAC, 2022).

The suitability model index to determine where to would be possible to operate the drones, was used to filter spatially a set of potential facilities, in which could be placed the drone stations to deliver AED. The selection of these facilities aimed to select primarily fire rescue stations and Alpine huts in highly suitable areas, considering these as the first options to locate the drones in South Tyrol (Wankmüller et al., 2020). Even though, were also selected alternative sites in remote locations, to extend the coverage range of the proposed network, due to the limited number of facilities available in mountainous regions.

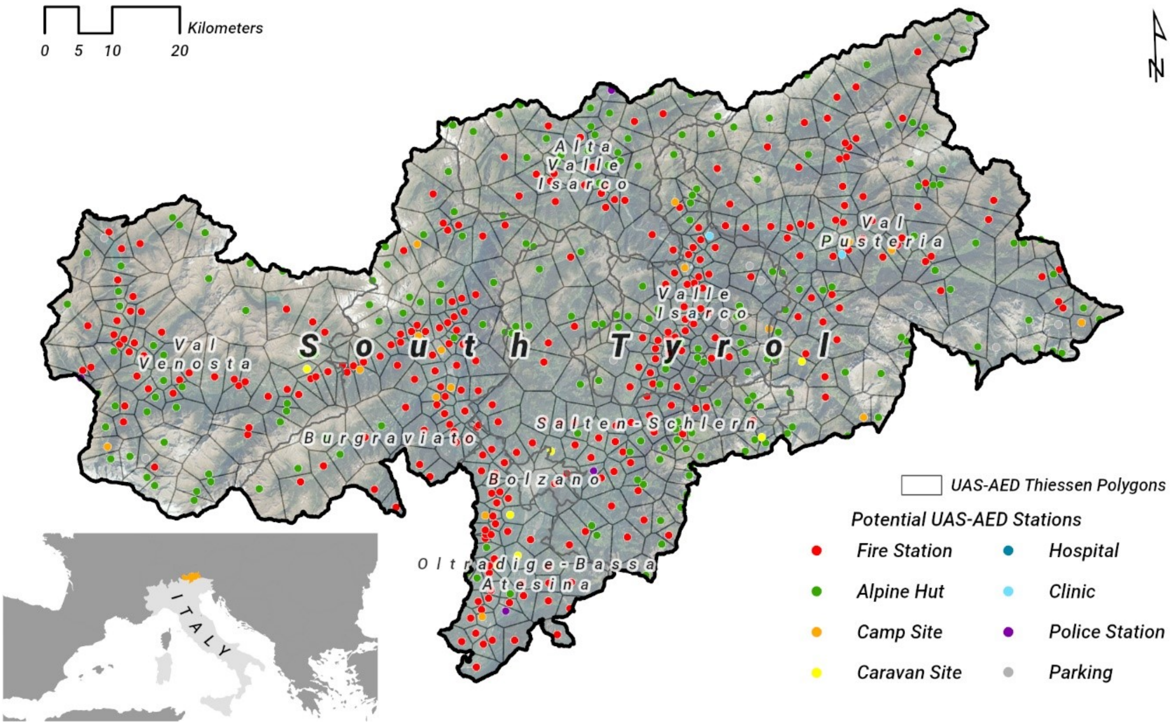

Figure 61: Potential UAS-AED Stations, South Tyrol

In the final selection of potential locations for UAS-AED stations in South Tyrol (Figure 61), are suggested 542 places, which could be established a vast network of emergency drone services. This network could be deployed extensively from the fire rescue stations (289), backed up by numerous Alpine huts (211), located in the farthest places of mountain sectors. Whitin the proposed locations, were also selected 42 facilities that correspond to alternative locations that could be considered too (Figure 62).

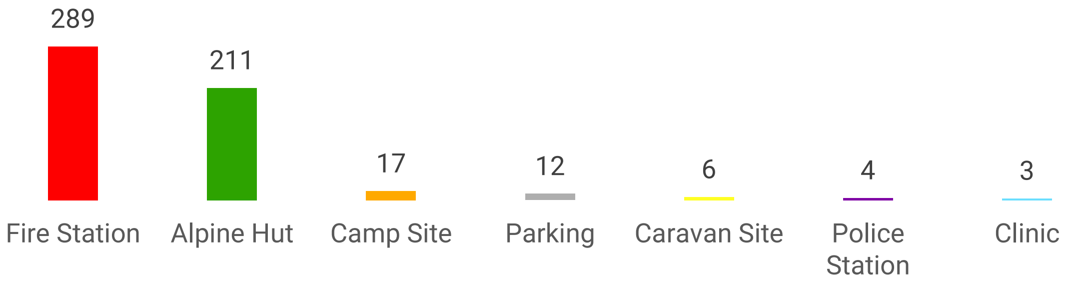

Figure 62: Potential UAS-AED Station Classes

In the selection of proposed locations, it is assumed the good will of the first responders and owners respectively, to allocate a drone station inside or nearby their facilities. Aiming to generate the vast possible coverage, using the smallest number of drones. However, this would require an important investment to adapt the different sites in order to deploy UAS-AED missions and make this a feasible solution to assist cardiac arrests in remote locations. During recognition visits to some Alpine huts in South Tyrol (Figure 26), the personnel mentioned that they count with first aid kits, but do not have Automatic External Defibrillators (AED) or training to use these devices, which is a need that also require to be addressed.

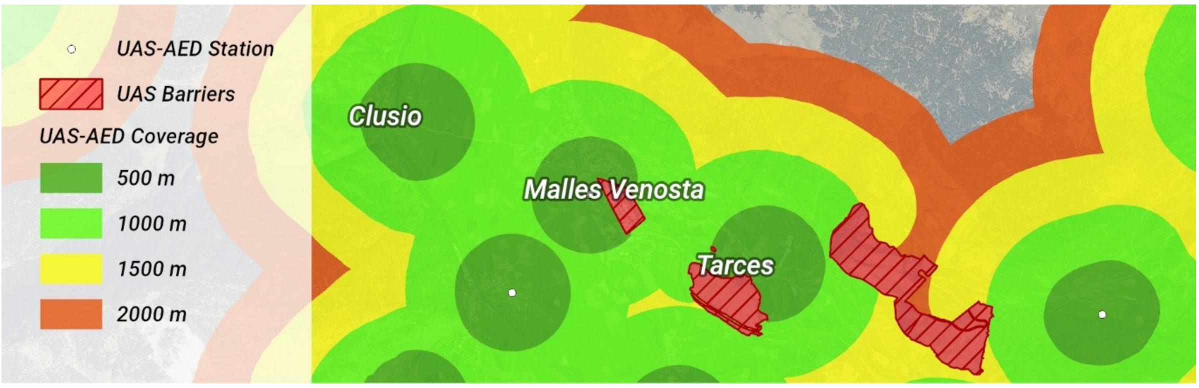

Figure 63: UAS-AED Distance Coverage, Malles Venosta (South Tyrol)

Using these locations as a starting point, was estimated the coverage that the proposed network could have in the Autonomous Province of South Tyrol, Italy. This was calculated based on the accumulated distance from the stations (Murekatete & Shirabe, 2021), using the Low-Altitude-Flight Elevation Model (LAFEM) proposed to generate a closer approximation to the real extent of the coverage, considering geofences as barriers for the missions. These barriers not only prevent the drones from flying over prohibited or dangerous zones, but could also be used to exclude the operations over populated areas or zones ecologically vulnerable as the biotopes of the province. Following the stated example in Malles Venosta (South Tyrol), can be seen how the coverage areas extend from the proposed stations, adapting their range according to predefined barriers, such as biotopes or military zones (Figure 63).

Even though drones has the potential to fly over long distances at a high speed carrying medical supplies (Cheskes et al., 2020), local regulations constraint their operation range in order to control the activities that take place in low-altitude airspace (EASA, 2022). In recent years, there have been important developments towards the design of a manageable airspace in which drones and manned aviation can interact safely, as is the U-Space project (Xu et al., 2020). However, the current legal framework to operate UAS in Europe, do not recommend drone missions beyond visual line of sight (BVLOS) over 1 km or maximum 2 km in case of counting with the support of an airspace observer (EASA, 2022). Therefore, the coverage estimation of the service area regarding the proposed network, is calculated up to 2 kilometres from the potential position of the UAS-AED stations (Figure 33).

Table 3: Surface Covered by the Proposed UAS-AED Network, South Tyrol

District	Surface	UAS-AED Coverage	UAS Barriers
Bolzano	52 km^2	28%	58%
Burgraviato	1,100 km^2	52%	03%
Valle Isarco	624 km^2	68%	07%
Val Pusteria	2,071 km^2	42%	12%
Salto-Sciliar	1,037 km^2	54%	11%
Oltradige-Bassa Atesina	423 km^2	68%	10%
Val Venosta	1,441 km^2	41%	03%
Alta Valle Isarco	650 km^2	48%	07%
South Tyrol	**7,399 km^2**	**49%**	**08%**

The proposed emergency drone service network could cover the total extent of 49% of the Autonomous Province of South Tyrol (Table 3). Making possible to reach 7,399 km^2 within 10 minutes using drones to deliver AED in case of Out-of-Hospital Cardiac Arrests (OHCA), flying at 3 to 10 s/m. Even though, has to be addressed that this coverage is not uniform for the entire province, being more extended in districts such as Valle Isarco or Oltradige-Bassa Atesina (68% each), because of the higher number of suitable facilities located in their territory. Furthermore, there are important barriers for the operations, limiting a full coverage of the province due to the UAS Geographical Zones, as in Bolzano that 58% of its surface has prohibitions to operate drones, addressing the close proximity to the local airport.

To prioritize in which of the selected areas would be feasible to start the implementation of these solutions, further research could study the spatial distribution of the historical data regarding OHCA occurrence in the Province of South Tyrol (Ball et al., 2022). Defining hotspots to these time-critical events, in order to optimize the allocation of the drone stations, supporting the historical labor of the first responders in this mountainous region, with chances of improving the odds of positive outcomes to victims of cardiac arrests.

5.2. Map-Driven UAS-AED Mission Routing in Mountain Environments

Addressing the need of a suitable routing method for drones to deliver defibrillators across the Alpine mountain environments (Wankmüller et al., 2020). This research proposes a workflow based on geographic information management and geoprocessing techniques, to generate optimal flight paths capable to overcome effectively terrain variations (Figure 64).

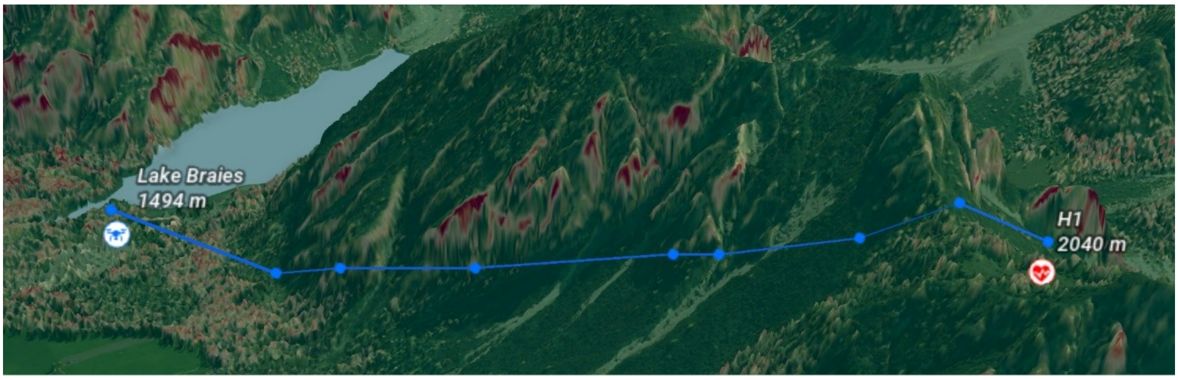

Figure 64: H1 Route, Braies

Relying on a detailed surface reconstruction, this workflow creates a modified elevation model that integrate obstacles, barriers and a vertical safety threshold to route optimal paths based on least-cost path and distance accumulation methods (Murekatete & Shirabe, 2021). This was integrated as a semi-automatic geoprocessing tool using the Model Builder application of ArcGIS Pro 3.1, which runs a preset of cartographic methods from the location of a determined drone station towards an emergency point (3.5. Methodology).

This workflow was designed to be used flying over the steep slopes of the Alpine mountains. Demonstrating versatility to adapt its results over different kinds of terrains, aiming to find the shortest way at a determined altitude above the surface level. Creating a vectorial pathway that is transformed into trajectory waypoints, being simplified according to a tolerance parameter. The simplification used is based on the Douglas–Peucker algorithm (Meng, 2021), which reduces the number of points along the line. Therefore, this has to be carefully implemented to avoid collisions with the vegetation or the slopes of a mountain (Figure 65).

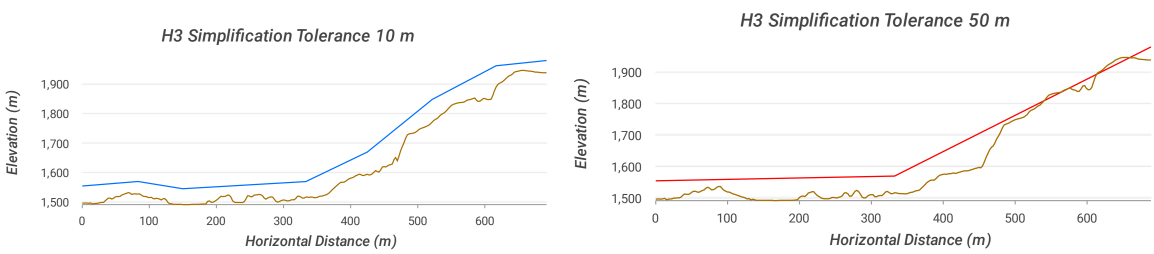

Figure 65: Simplification Tolerance Comparison, H3 Route (Braies)

To generate the routes the proposed method requires to start from a predefined starting point, from which was created previously the accumulated distance surface to determine the paths. Therefore, this workflow constraints the operation to initiate from a set of known points. Limiting the easy adaptation of the process in cases where the starting point of the mission changes in the last minute, requiring additional spatial data management processes to generate the routes from the new locations.

The final product of the routing workflow is a table of coordinate points, calculated from a detailed cartographic model. Which require of additional data transformation processes in order to get the desired format readable by the UAS, according to the requirements of the manufacturer. Therefore, this still require to be improved, being fully automatized to generate timely the desired routes and incorporate this into a feasible solution to deliver AED.

The proposed workflow presents an alternative to generate routes in remote areas, where there are not available predefined aerial routes for drones (He et al., 2022). Being capable to generate a map-driven solution to assist effectively emergencies, such as cardiac arrest. Furthermore, the possibility of incorporating geofences in the workflow or adapting the inner parameters to determine least-cost paths according a different set of spatial variables. Could make this a feasible routing option for carrying other kind of goods effectively in different scenarios, such as commercial delivery.

The possibility to plan drone routes at a defined altitude level based on detailed cartographic models, could also make possible incorporating this workflow to the current efforts of designing the U- Space (Xu et al., 2020). Aiming to establish a manageable low-altitude airspace, where UAS and manned aviation could interact safely, exploiting the potential of these platforms to provide services in remote settings as in urban environments.

5.3. UAS-AED Flight Performance Following Terrain Variations

To demonstrate the effectiveness of the proposed method and evaluate the real impact of this research in Alpine environments, two practical scenarios were conducted. These field campaigns focused on testing the overall performance of the drones following flight paths adapted to terrain variations and measuring the time to deliver effectively AED in remote emergency sites, comparing different routing approaches implemented in mountain rescue.

During a study case that simulated the delivery of an AED in a ski resort of Corvara in Badia (South Tyrol, Italy) (4.3. Experimental Setup), was evaluated the actual performance of a trained remote pilot flying manually the UAS towards the emergency point (Figure 66).

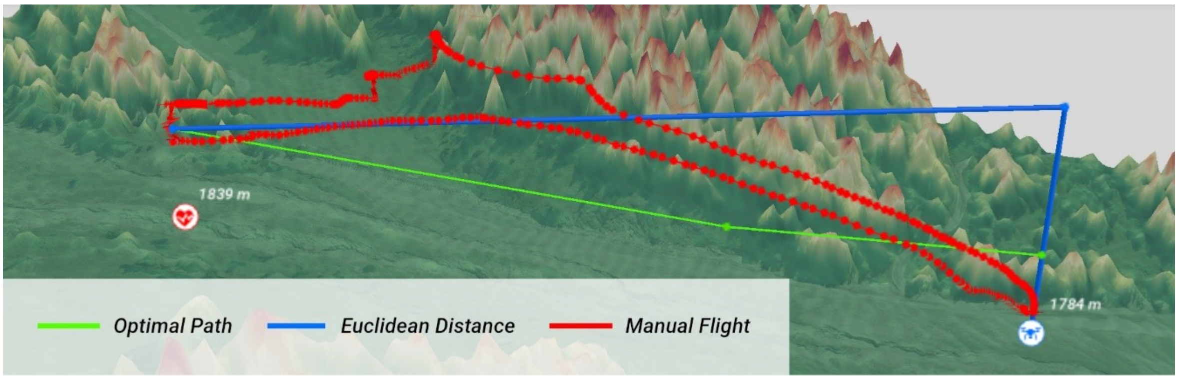

Figure 66: Corvara Flights Comparison

The resulting times and distances of the manual flight, were compared against estimations (E) made based on an optimal route planned with the proposed method (Table 4), and the approach that considers a direct straight-line flight keeping the same elevation, taking advantage of the Euclidean distance (Wankmüller et al., 2020).

Table 4: Corvara Flight Tests Results

Flight	Total Distance	Delivery Time	Return Time	Total Time	Max. Speed
Optimal (E)	602.00 m	00:01:19	00:01:19	00:02:38	4.2 m/s
Euclidean (E)	763.89 m	00:01:32	00:01:32	00:03:04	4.2 m/s
Manual	718.72 m	00:02:30	00:01:40	00:04:10	10.2 m/s

In this test, are observed the common challenges that rescuers face when manually flying to reach an emergency site. During a manual flight uphill, the perception of the remote pilot over the aircraft was distorted by the distance, requiring multiple trajectory adjustments and resulting in a longer time to effectively deliver the AED (Figure 66). In this flight, the defibrillator was dropped after 02:30 minutes of flight, while the estimated delivery using the optimal path, with a safety altitude threshold of 20 meters, was 01:19 minutes. In case of a flight that requires to adjust the altitude prior moving in a straight-line, the estimated delivery was 01:32 minutes, due to the time this needs to perform a gradual altitude climb.

Regarding the second practical case, was simulated the delivery of an AED during a mountain trail running competition in Ritten (South Tyrol, Italy) (4.4. Experimental Setup). In this was evaluated the performance of the drone following a route generated with the proposed method, over a challenging mountain terrain. During this test were considered different settings to return the drone back to the initial point, helping compare the three different approaches mentioned before, and were also implemented different altitude thresholds to follow the slopes variations in an Alpine scenario. Using the predefined waypoints as an altitude reference, was also possible to analyse the overall accuracy that the drone had while arriving to these locations, following the elevation differences of the surface underneath.

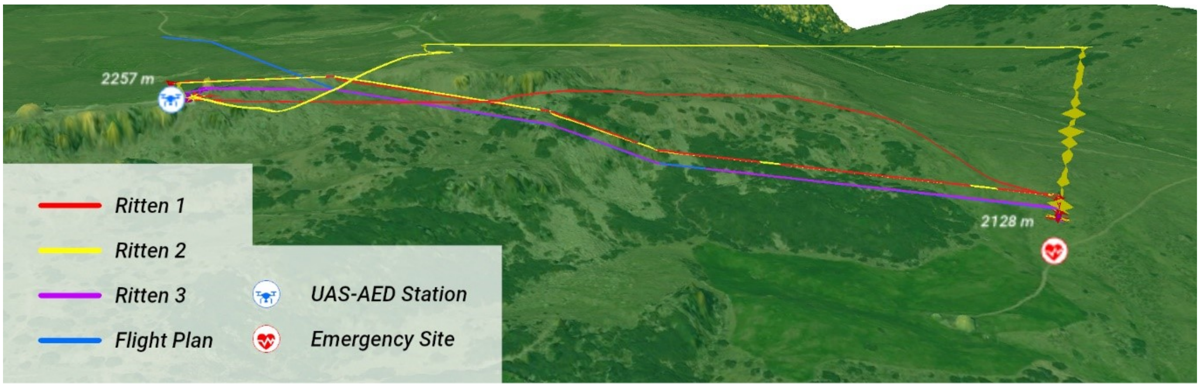

Figure 67: Ritten Flights Comparison

In this test were achieved three successful flights, following the predefined optimal path generated with the map-driven proposed workflow (Figure 67). The initial safety threshold was set to 40 meters above the surface level, but this was reduced to 30 meters after the positive outcomes of the first two missions. In the three flights the delivery time of the AED was perform in the desired location in around 3 minutes (Table 5).

Table 5: Ritten Flight Tests Results

Flight	Total Distance	Delivery Time	Return Time	Total Time	Max Speed
Optimal (E)	1,582.88 m	00:03:11	00:03:11	00:06:21	4.2 m/s
Ritten 1	1,638.50 m	00:03:36	00:06:35	00:10:11	6.2 m/s
Ritten 2	1,736.63 m	00:03:06	00:03:39	00:06:45	7.3 m/s
Ritten 3	1,532.17 m	00:02:59	00:02:30	00:05:29	7.2 m/s

Considerable differences between the flights, can be seen while comparing the three different approaches used to return to the base point. In the flight Ritten 1 was used a manual return, which considered multiple adjustments in the trajectory concluding the entire mission in 10:11 minutes (Table 5). The return of the Ritten 2 follows the Euclidean distance at a fixed elevation, using the Return To Home (RTH) function, to conclude the entire mission in 06:45 minutes. The flight Ritten 3 followed the optimal path in both directions, making a full flight adapted to the surface variations, this flight concluded the entire mission in 05:29 minutes, improving the estimated time that was 06:21 minutes. Based on these tests, it can be concluded that a drone following the optimal path calculated with the proposed workflow could perform automatic AED missions more efficiently than using other approaches implemented by first responders.

However, has to be consider that during these flights, was required to perform the take-off and landing manoeuvres manually, due to the close proximity with a ski lift and a radio antenna. Which would require to validate the overall improvement showed by the proposed workflow, by running fully automatic tests scenarios, prior implementing this as a feasible solution to deliver AED to assist cardiac arrest in mountain environments.

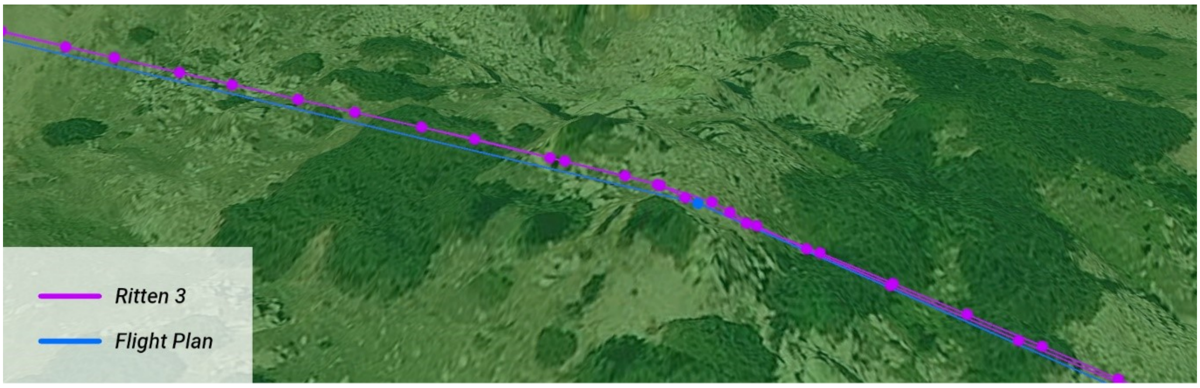

Figure 68: Ritten 3 Route, Waypoints Altitude Comparison

Comparing the estimated altitude of the optimal path waypoints, with the results of the flight Ritten 3, which followed these points towards the emergency and back to the initial point (Figure 68), overall altitude differences below 0.5 meters were observed (Table 6).

Table 6: Ritten 3 Route, Waypoints Altitude Accuracy

Route	Waypoint 1	Waypoint 2	Waypoint 3	Waypoint 4
Planned	2,264.68 m	2,235.61 m	2,201.24 m	2,165.50 m
Forward	2,264.97 m	2,235.82 m	2,201.44 m	2,165.98 m
Backward	2,264.92 m	2,235.72 m	2,201.15 m	2,165.67 m
Difference	**0.29 m**	**0.21 m**	**0.29 m**	**0.49 m**

This demonstrates the feasibility of planning complex drone routes in mountain environments based on detailed elevation models, which can then be successfully followed by drones equipped with highly precise location capabilities.

6. Conclusions

To summarize the key findings of this research that aim designing a map-driven distributed emergency drone service network, enabled to localize suitable areas and suggesting time-effective strategies for delivering AED in Alpine Regions.

During the study of the emergency drone service network distribution and coverage, were successfully identified the suitable areas for providing emergency drone services in South Tyrol (Italy), based on the weighted spatial analysis of the UAS regulations and the land use. Zones with high levels of suitability were found in vast mountainous rural areas, offering an opportunity to optimize the coverage of Emergency Medical Services (EMS) using drones towards them. As the base of the emergency drone service network, were proposed 542 potential locations for UAS-AED stations in South Tyrol, conformed mainly by fire rescue stations and Alpine huts. Even though, to exploit the full potential this would require to obtain the authorization to operate over protected areas and invest in adapting those facilities to deploy the drones.

Regarding the map-driven UAS-AED mission routing in mountain environments, is proposed a workflow to generate optimal flight paths for drones to navigate over challenging terrain in Alpine environments. This workflow is based entirely in cartographic methods, using geographic information management and geoprocessing techniques, designed to adapt to different types of terrains and altitudes, providing versatility for route planning. However, this would require further automation for real-time route generation and integration with rescue operations.

In relation to the performance of the UAS-AED missions following terrain variations, were conducted field test to evaluate the delivery of AED in Alpine environments. The flight paths generated based on the proposed workflow, showed significant improvements for the delivery of medical supplies, in comparison to other approaches commonly used by first responders in rescue operations. Demonstrating the potential of considering detailed geographic information and cartographic methods to generate strategic solutions to support first responders towards life-threatening emergencies.

Bibliography

Ahlqvist, O. (2009). Overlay (in GIS). In *International Encyclopedia of Human Geography* (pp. 48–55). Elsevier. https://doi.org/10.1016/B978-008044910-4.00487-9

Arunachalam, P. L., Krishna, P., Vignesh, M., & Thomas, T. S. (2021). Ambulance Booking Application. *2021 6th International Conference on Signal Processing, Computing and Control (ISPCC)*, 146–149. https://doi.org/10.1109/ISPCC53510.2021.9609423

ASTAT. (2021). *South Tyrol in figures*.

Ayamga, M., Akaba, S., & Nyaaba, A. A. (2021). Multifaceted applicability of drones: A review. *Technological Forecasting and Social Change*, *167*, 120677. https://doi.org/10.1016/j.techfore.2021.120677

Ball, S., Morgan, A., Simmonds, S., Bray, J., Bailey, P., & Finn, J. (2022). Strategic placement of automated external defibrillators (AEDs) for cardiac arrests in public locations and private residences. *Resuscitation Plus*, *10*, 100237. https://doi.org/10.1016/j.resplu.2022.100237

Baumgarten, M. C., Röper, J., Hahnenkamp, K., & Thies, K.-C. (2022). Drones delivering automated external defibrillators—Integrating unmanned aerial systems into the chain of survival: A simulation study in rural Germany. *Resuscitation*, *172*, 139–145. https://doi.org/10.1016/j.resuscitation.2021.12.025

Bauranov, A., & Rakas, J. (2021). Designing airspace for urban air mobility: A review of concepts and approaches. *Progress in Aerospace Sciences*, *125*, 100726. https://doi.org/10.1016/j.paerosci.2021.100726

Bennett, L. R., & Calkins, J. (2013). *The Language of Spatial Analysis*.

Bereg, S., Díaz-Báñez, J. M., Haghpanah, M., Horn, P., Lopez, M. A., Marín, N., Ramírez-Vigueras, A., Rodríguez, F., Solé-Pi, O., Stevens, A., & Urrutia, J. (2022). Optimal placement of base stations in border surveillance using limited capacity drones.

Theoretical Computer Science, *928*, 183–196. https://doi.org/10.1016/j.tcs.2022.06.024

Boutilier, J. J., Brooks, S. C., Janmohamed, A., Byers, A., Buick, J. E., Zhan, C., Schoellig, A. P., Cheskes, S., Morrison, L. J., & Chan, T. C. Y. (2017). Optimizing a Drone Network to Deliver Automated External Defibrillators. *Circulation*, *135*(25), 2454–2465. https://doi.org/10.1161/CIRCULATIONAHA.116.026318

Brugger, H., Zafren, K., Festi, L., Paal, P., & Strapazzon, G. (2021). *Mountain Emergency Medicine*. Edra.

By, R. A. de, & Huisman, O. (2009). *Principles of geographic information systems: An introductory textbook* (4th ed). The International Institute for Geo-Information Science and Earth Observation (ITC).

Caballero, E., Sainidis, D., Daras, P., Madridano, A., Konstantoudakis, K., & Flores, P. (2021). *An automated UAV-assisted 2D mapping system for First Responders*.

Carel Viljoen, Dina C (Christa) Janse van Rensburg, Willem van Mechelen, Evert Verhagen, Bruno Silva, Volker Scheer, Manuela Besomi, Rubén Gajardo-Burgos, Sérgio Matos, Marlene Schoeman, Audrey Jansen van Rensburg, Nicol van Dyk, Susan Scheepers, & Tanita Botha. (2022). Trail running injury risk factors: A living systematic review. *British Journal of Sports Medicine*, *56*(10), 577. https://doi.org/10.1136/bjsports-2021-104858

Cheskes, S., McLeod, S. L., Nolan, M., Snobelen, P., Vaillancourt, C., Brooks, S. C., Dainty, K. N., Chan, T. C. Y., & Drennan, I. R. (2020). Improving Access to Automated External Defibrillators in Rural and Remote Settings: A Drone Delivery Feasibility Study. *Journal of the American Heart Association*, *9*(14), e016687. https://doi.org/10.1161/JAHA.120.016687

Danser, R. A. (2018). *Applying Least Cost Path Analysis to Search and Rescue Data: A Case Study in Yosemite National Park*.

de Smith, M. J., Goodchild, M. F., & Longley, P. A. (2021). *Geospatial Analysis: A Comprehensive Guide to Principles Techniques and Software Tools* (6th ed.). The Winchelsea Press. https://spatialanalysisonline.com/HTML/?shortest_network_path_problems.htm

d-flight. (2023). *D-flight*. D-Flight. https://www.d-flight.it/new_portal/

Dolomiti Superski. (2023). Dolomiti Superski. https://www.dolomitisuperski.com/en/Experience/Ski-areas/Alta-Badia/Towns#Corvara

EASA. (2022). *Easy Access Rules for Unmanned Aircraft Systems*. EASA.

Elmi, M. (Ed.). (2018). *The Alps in 25 maps*. Permanent Secretariat of the Alpine Convention.

Elsensohn, F., Agazzi, G., Syme, D., Swangard, M., Facchetti, G., & Brugger, H. (2006). The Use of Automated External Defibrillators and Public Access Defibrillators in the Mountains: Official Guidelines of the International Commission for Mountain Emergency Medicine ICAR-MEDCOM☆. *Wilderness & Environmental Medicine*, *17*(1), 64–66. https://doi.org/10.1580/1080-6032(2006)17[64:TUOAED]2.0.CO;2

ENAC. (2021). *ATM-09A. UAS-IT: CRIT ERI D'IMPLEMENTAZIONE E PROCEDURE PER ZONE GEOGRAFICHE*. ENAC.

ENAC. (2022). *ENV-002—Aree protette della Provincia di Bolzano*.

Esri. (2023a). *Connect locations with optimal paths*. https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/connect-locations-with-optimal-paths.htm

Esri. (2023b). *Distance Accumulation Algorithm*. https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/distance-accumulation-algorithm.htm

Esri. (2023c). *Find Point Clusters (GeoAnalytics Desktop)*. https://pro.arcgis.com/en/pro-app/latest/tool-reference/geoanalytics-desktop/find-point-clusters.htm

Esri. (2023d). *How distance accumulation works*. https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/how-distance-accumulation-works.htm

Esri. (2023e). *Interpolate Shape (3D Analyst)*. https://pro.arcgis.com/en/pro-app/latest/tool-reference/3d-analyst/interpolate-shape.htm

Esri. (2023f). *Use ModelBuilder*. https://pro.arcgis.com/en/pro-app/latest/help/analysis/geoprocessing/modelbuilder/modelbuilder-quick-tour.htm

Esri. (2023g). *Weighted Overlay (Spatial Analyst)*. https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/weighted-overlay.htm

Fischer, M. M., & Getis, A. (Eds.). (2010). *Handbook of Applied Spatial Analysis: Software Tools, Methods and Applications*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-03647-7

Fischer, P., Rohrer, U., Nürnberger, P., Manninger, M., Scherr, D., Von Lewinski, D., Zirlik, A., Wankmüller, C., & Kolesnik, E. (2023). Automated external defibrillator delivery by drone in mountainous regions to support basic life support – A simulation study. *Resuscitation Plus*, *14*, 100384. https://doi.org/10.1016/j.resplu.2023.100384

Gamberini, L., Del Giudice, D., Saltalamacchia, S., Taylor, B., Sala, I., Allegri, D., Pastori, A., Coniglio, C., Gordini, G., & Semeraro, F. (2023). Factors associated with the arrival of smartphone-activated first responders before the emergency medical services in Out-of-Hospital cardiac arrest dispatch. *Resuscitation*, *185*, 109746. https://doi.org/10.1016/j.resuscitation.2023.109746

Gonzalez, R. C., & Woods, R. E. (2018). *Digital image processing*. Pearson.

Griffin, J. (2023, May 15). Italian tourism hotspot caps visitor numbers and restricts access to famed lake. *Independent.Ie*. https://m.independent.ie/life/travel/travel-news/italian-tourism-hotspot-caps-visitor-numbers-and-restricts-access-to-famed-lake/a1823672443.html

Habib, S. M., El-Raie Emam Suliman, A., Al Nahry, A. H., & Abd El Rahman, E. N. (2020). Spatial modeling for the optimum site selection of solar photovoltaics power plant in the northwest coast of Egypt. *Remote Sensing Applications: Society and Environment*, *18*, 100313. https://doi.org/10.1016/j.rsase.2020.100313

He, X., He, F., Li, L., Zhang, L., & Xiao, G. (2022). A route network planning method for urban air delivery. *Transportation Research Part E: Logistics and Transportation Review*, *166*, 102872. https://doi.org/10.1016/j.tre.2022.102872

Hildemann, M., & de Campolide, C. (2019). *An adaptable and scalable least cost network for air-taxis in urban areas Study area: Manhattan, New York*.

Hildemann, M., & Verstegen, J. A. (2023). 3D-flight route optimization for air-taxis in urban areas with Evolutionary Algorithms and GIS. *Journal of Air Transport Management*, *107*, 102356. https://doi.org/10.1016/j.jairtraman.2022.102356

Hong, I., Kuby, M., & Murray, A. T. (2018). A range-restricted recharging station coverage model for drone delivery service planning. *Transportation Research Part C: Emerging Technologies*, *90*, 198–212. https://doi.org/10.1016/j.trc.2018.02.017

Hubbard, S., & MacLaughlin, K. (2006). *A STUDY OF THE GIS TOOLS AVAILABLE DURING TORNADO EVENTS AND THEIR EFFECTIVENESS FOR METEROLOGISTS, FIRST RESPONDERS AND EMERGENCY MANAGERS*.

IDM Südtirol. (2023). *Südtirol*. https://www.suedtirol.info/

Italian Alpine Club. (2023, July 10). GeoResQ, the mountain rescue app becomes free for everyone. *Italian Alpine Club*. https://www.cai.it/georesq-lapp-per-il-soccorso-in-montagna-diventa-gratuita-per-tutti/

Jung, H., & Kim, J. (2022). Drone scheduling model for delivering small parcels to remote islands considering wind direction and speed. *Computers & Industrial Engineering*, *163*, 107784. https://doi.org/10.1016/j.cie.2021.107784

Lifeng Liu & Shuqing Zhang. (2009). Voronoi diagram and GIS-based 3D path planning. *2009 17th International Conference on Geoinformatics*, 1–5. https://doi.org/10.1109/GEOINFORMATICS.2009.5293350

Lim, J. C. L., Loh, N., Lam, H. H., Lee, J. W., Liu, N., Yeo, J. W., & Ho, A. F. W. (2022a). The Role of Drones in Out-of-Hospital Cardiac Arrest: A Scoping Review. *Journal of Clinical Medicine*, *11*(19), 5744. https://doi.org/10.3390/jcm11195744

Lim, J. C. L., Loh, N., Lam, H. H., Lee, J. W., Liu, N., Yeo, J. W., & Ho, A. F. W. (2022b). The Role of Drones in Out-of-Hospital Cardiac Arrest: A Scoping Review. *Journal of Clinical Medicine*, *11*(19), 5744. https://doi.org/10.3390/jcm11195744

Liu, C.-H., Sung, C.-W., Fan, C.-Y., Lin, H.-Y., Chen, C.-H., Chiang, W.-C., Ma, M. H.-M., & Huang, E. P.-C. (2021). Strategies on locations of public access defibrillator: A systematic review. *The American Journal of Emergency Medicine*, *47*, 52–57. https://doi.org/10.1016/j.ajem.2021.02.033

Mangiameli, M., Muscato, G., Mussumeci, G., & Milazzo, C. (2013). A GIS application for UAV flight planning. *IFAC Proceedings Volumes*, *46*(30), 147–151. https://doi.org/10.3182/20131120-3-FR-4045.00025

Martiny, J. (2023, May 9). *South Tyrol grapples with mass tourism*. Deutsche Welle. dw.com/en/south-tyrol-grapples-with-mass-tourism/a-65531663

Meng, L. (2021, March 18). *Douglas–Peucker Algorithm*. Cartography Playground. https://cartography-playground.gitlab.io/playgrounds/douglas-peucker-algorithm/

Mermiri, M. I., Mavrovounis, G. A., & Pantazopoulos, I. N. (2020). Drones for Automated External Defibrillator Delivery: Where Do We Stand? *The Journal of Emergency Medicine*, *59*(5), 660–667. https://doi.org/10.1016/j.jemermed.2020.07.027

Metzler, B. (2022, August 24). A UTMB Participant Died on Course. Is the Race Too Dangerous? [Outside]. *Outside*. https://www.outsideonline.com/health/running/racing/utmb-runner-death-2022/

Mitterer, S. (2023, April 5). *Alpinunfälle in Österreich 2022 – ein Jahresrückblick*. Österreichisches Kuratorium für Alpine Sicherheit. https://alpinesicherheit.at/alpinunfaelle-in-oesterreich-2022-ein-jahresrueckblick/

Mohd Daud, S. M. S., Mohd Yusof, M. Y. P., Heo, C. C., Khoo, L. S., Chainchel Singh, M. K., Mahmood, M. S., & Nawawi, H. (2022). Applications of drone in disaster management: A scoping review. *Science & Justice*, *62*(1), 30–42. https://doi.org/10.1016/j.scijus.2021.11.002

Murekatete, R. M., & Shirabe, T. (2021). An experimental analysis of least-cost path models on ordinal-scaled raster surfaces. *International Journal of Geographical Information Science*, *35*(8), 1545–1569. https://doi.org/10.1080/13658816.2020.1753204

OpenStreetMap. (2023). *OpenStreetMap*. https://www.openstreetmap.org/

Paal, P., & Elsensohn, F. (2021). Automated External Defibrillators. In *Mountain Emergency Medicine*. Edra.

Raivi, A. M., Huda, S. M. A., Alam, M. M., & Moh, S. (2023). Drone Routing for Drone-Based Delivery Systems: A Review of Trajectory Planning, Charging, and Security. *Sensors*, *23*(3), 1463. https://doi.org/10.3390/s23031463

Robakowska, M., Ślęzak, D., Żuratyński, P., Tyrańska-Fobke, A., Robakowski, P., Prędkiewicz, P., & Zorena, K. (2022). Possibilities of Using UAVs in Pre-Hospital Security for Medical Emergencies. *International Journal of Environmental Research and Public Health*, *19*(17), 10754. https://doi.org/10.3390/ijerph191710754

Roberts, N. B., Ager, E., Leith, T., Lott, I., Mason-Maready, M., Nix, T., Gottula, A., Hunt, N., & Brent, C. (2023). Current summary of the evidence in drone-based emergency medical services care. *Resuscitation Plus*, *13*, 100347. https://doi.org/10.1016/j.resplu.2022.100347

Roca-Riu, M., & Menendez, M. (2019). *Logistic deliveries with Drones. State of the art of practice and research*.

Romeo, R., Russo, L., Parisi, F., Notarianni, M., Manuelli, S., & Carvao, S. (2021). Mountain tourism – Towards a more sustainable path. *UNWTO*. https://doi.org/10.4060/cb7884en

Sabino, H., Almeida, R. V. S., Moraes, L. B. D., Silva, W. P. D., Guerra, R., Malcher, C., Passos, D., & Passos, F. G. O. (2022). A systematic literature review on the main factors for public acceptance of drones. *Technology in Society*, *71*, 102097. https://doi.org/10.1016/j.techsoc.2022.102097

Sato, H. P., & Sekiguchi, T. (2014). *MAPPING OF TOPOGRAPHY AND VEGETATION IN SHIRAKAMI MOUNTAINS "WORLD HERITAGE NATURAL RESOURCES" IN JAPAN*.

Schierbeck, S., Hollenberg, J., Nord, A., Svensson, L., Nordberg, P., Ringh, M., Forsberg, S., Lundgren, P., Axelsson, C., & Claesson, A. (2022). *Automated external defibrillators delivered by drones to patients with suspected out-of-hospital cardiac arrest*.

Schierbeck, S., Svensson, L., & Claesson, A. (2022). Use of a Drone-Delivered Automated External Defibrillator in an Out-of-Hospital Cardiac Arrest. *New England Journal of Medicine*, *386*(20), 1953–1954. https://doi.org/10.1056/NEJMc2200833

Schwartz, K. (2013). *Ski Slopes Demographics Change As More Senior Skiers Suit Up*. CBS Colorado. https://www.cbsnews.com/colorado/news/ski-slopes-demographics-change-as-more-senior-skiers-suit-up/

Scuttari, A., Ferraretto, V., Dibiasi, A., Isetti, G., & Erschbamer, G. (2023). *The Sustainable Turism Observatory of South Tyrol: First Anual Progress Report*.

Südtirol Ultra Skyrace. (2023). *Südtirol Ultra Skyrace*. Südtirol Ultra Skyrace. https://www.suedtirol-ultrarace.it/en.html

Südtiroler Bürgernetz. (2023). *GeoCatalog*. Südtiroler Bürgernetz. http://geokatalog.buergernetz.bz.it/geokatalog/#!

Szczepanek, A. (2023). *Bilinear Interpolation Calculator*. https://www.omnicalculator.com/math/bilinear-interpolation

TenBrink, J. (2019). Doing more with Euclidean Distance: Barriers and Paths. *ArcGIS Spatial Analyst*. https://www.esri.com/arcgis-blog/products/spatial-analyst/analytics/doing-more-with-euclidean-distance-barriers-and-paths/

Tourist Office Pragser Tal Valley. (2023). *Pragser Wildsee Lake*. https://www.prags.bz/en

UN. (2023). *Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development*. United Nations.

Van Veelen, M., Mendicino, R., Mejia-Aguilar, A., & Vinetti, G. (2023). *DRONE-AED Project*. https://noi.dexanet.biz/it/drone-aed-consegna-tramite-drone-di-un-defibrillatore-automatico-esterno-aed-aree-montane

Van Veelen, M., Roveri, G., Voegele, A., Cappello, T. D., Masè, M., Falla, M., Regli, I. B., Mejia-Aguilar, A., Mayrgündter, S., & Strapazzon, G. (2023). Drones reduce the treatment-free interval in search and rescue operations with telemedical support – A randomized controlled trial. *The American Journal of Emergency Medicine*, *66*, 40–44. https://doi.org/10.1016/j.ajem.2023.01.020

Vanat, L. (2021). *2021 International Report on Snow & Mountain Tourism*. https://www.vanat.ch/RM-world-report-2021.pdf

Vigili del Fuoco. (2023). *Corpo Nazionale del Vigili del Fuoco*. https://www.vigilfuoco.it/aspx/Home.aspx

Vögele, A., Ströhle, M., Paal, P., Rauch, S., & Brugger, H. (2020). Can drones improve survival rates in mountain areas, providing automated external defibrillators? *Resuscitation*, *146*, 277–278. https://doi.org/10.1016/j.resuscitation.2019.11.017

Wankmüller, C., Kunovjanek, M., & Mayrgündter, S. (2021). Drones in emergency response – evidence from cross-border, multi-disciplinary usability tests. *International Journal of Disaster Risk Reduction*, *65*, 102567. https://doi.org/10.1016/j.ijdrr.2021.102567

Wankmüller, C., Truden, C., Korzen, C., Hungerländer, P., Kolesnik, E., & Reiner, G. (2020). Optimal allocation of defibrillator drones in mountainous regions. *OR Spectrum*, *42*(3), 785–814. https://doi.org/10.1007/s00291-020-00575-z

Xu, C., Liao, X., Tan, J., Ye, H., & Lu, H. (2020). Recent Research Progress of Unmanned Aerial Vehicle Regulation Policies and Technologies in Urban Low Altitude. *IEEE Access*, *8*, 74175–74194. https://doi.org/10.1109/ACCESS.2020.2987622

YesAlps. (2023). *Rifugio Capanna Nera*. YesAlps. https://www.yesalps.com/it/rifugi/alta-badia/capanna-nera-2c9270690e5.html

Younes, A., Kotb, K. M., Abu Ghazala, M. O., & Elkadeem, M. R. (2022). Spatial suitability analysis for site selection of refugee camps using hybrid GIS and fuzzy AHP approach: The case of Kenya. *International Journal of Disaster Risk Reduction*, *77*, 103062. https://doi.org/10.1016/j.ijdrr.2022.103062

Yukun, J., Yanmang, S., Yan, W., Bei, W., & Shurui, F. (2023). Improved immune algorithm for sudden cardiac death first aid drones site selection. *International Journal of Medical Informatics*, *173*, 105025. https://doi.org/10.1016/j.ijmedinf.2023.105025

Zupan, R., Franges, S., Kljajic, I., & Stanic, M. (2022). *CRISIS MANAGEMENT AND CARTOGRAPHY*. 535–542. https://doi.org/10.5593/sgem2022V/6.2/s27.68

Appendices

Appendix 1: Tested UAS

Figure 69: Soleon Octagon of Eurac Researh in Corvara

Figure 70: MAvTech Q4X of MavTech in Ritten

Table 7: Tested UAS Characteristics

Provider	Eurac Reseach	MavTech
Brand	Soleon	MavTech
Model	Octagon	Q4X
Configuration	Octacopter	Quadcopter
Battery	2 x 6s1p - Li-Po	LiPo 6s
Length	1260 mm	1200 mm
Weight without Payload	4300 g	4250g
Maximum Take-off Mass	7500 g	9000 g
Autonomy	25 min	32 min