Integrating High-Volume Unmanned Autonomous Vehicle Operations in Civil Airspace

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Preface

First, I want to extend my gratitude to my supervisors at Delft University of Technology, Bart van Arem and Frank Guldenmund. Their diverse expertise allowed me to employ a range of methods while feeling fully supported at every step. Your guidance and insightful feedback have continuously challenged and motivated me to elevate my work. Our engaging discussions, fueled by genuine interest in the intersections of the innovation and safety, inspired me to explore into topics and methodologies beyond my initial comprehension of the challenges of addressing risks in innovation.

I would also like to thank Ilja Heitlager and Laurens Eversmann for the opportunity to conduct my research in such an inspiring environment as Schuberg Philis. Their unwavering support and guidance throughout the project were incredibly valuable. Our weekly conversations offered me a glimpse into their work and how they strive to push the boundaries of innovation. Through their guidance, I was able to grasp the critical connection between research and practical application, and why this link is so vital.

Additionally, I am grateful to everyone I interviewed. The insights provided a fascinating perspective on the practical relevance and complexities of integrating UAV operations in the Netherlands. These conversations revealed how various stakeholders perceive and tackle these challenges, highlighting the importance of understanding their diverse motivations. The cooperation and genuine interest in the subject encouraged me throughout my research.

Executive Summary

Unmanned Autonomous Vehicles (UAVs) have transformed numerous sectors with their versatility and efficiency. From the lifesaving delivery of medical supplies by the Zipline project into the potential for urban parcel delivery and agricultural monitoring, the applications of UAVs are extensive and promising. Despite these successes, the widespread adoption of UAV technology in Europe remains stalled. This research investigates the intricate interplay between regulatory frameworks, airspace management, and technological challenges that hinder UAV integration. Policymakers, aviation authorities, and private companies are actively contemplating the future of UAV operations, envisioning a well-organised airspace where UAVs can safely coexist with manned aircraft. However, achieving this vision is complex and fraught with challenges.

This study offers a thorough analysis of the current state and risks associated with UAVs in European airspace, focusing on the necessary infrastructure and regulatory frameworks. It seeks to address the pressing need for a structured approach to UAV integration. The findings aim to provide valuable insights for stakeholders to navigate the complexities of UAV operations, ensuring safety and efficiency as UAV technology continues to evolve. Central to this investigation is the primary research question**:**

'How can risks of high-volume UAV operations regarding public safety be mitigated through UAV infrastructure management?'

The European Union Aviation Safety Agency (EASA) is responsible on behalf of the European Commission for the safety of air traffic in Europe and provides guidelines for unmanned air traffic to all Member States of the European Union. In a legislative review conducted for this research these guidelines have been analysed. The regulation distinguishes three categories of UAV operations based on the risk and complexity of the operation. As the 'Open' and 'Specific' category are most common, the EASA is focussing on developing guidelines for those categories. The 'Open' category does not require operational authorisation of the national competent authority, making it the simplest and most accessible category. The 'Specific' category requires the conduction of a risk assessment and authorisation from the national competent authority, to allow these more complex and higher-risk operations. This category includes beyond visual line of sight (BVLOS) operations.

There are four risk assessments that are currently being conducted to receive authorisation for UAV operations in the 'Specific' category. The standard scenarios and pre-defined risk assessments both make use of pre-defined characteristics of UAV operations, contributing to a simplified approval process for these common UAV operations. A specific operational risk assessment (SORA) allows the UAV operator to determine the characteristics of the UAV operation and conduct a risk assessment accordingly. The Light UAV Operating Certificate provides an organization with long-term permission to conduct UAV operations that have been previously included in an STS, PDRA or SORA.

To enable high-volume UAV operations, the concept of U-space airspace has been introduced. In this airspace, U-space services are provided to enable efficient BVLOS UAV operations in a high-volume.

A literature review has been conducted to identify the risks associated with high-volume UAV operations regarding public safety. The most significant risks associated with high-volume UAV operations can be categorised into operational risks and risks related to supporting facilities. Operational risks include the loss of control of the UAV, collisions in the air with manned aircraft, other UAVs, or birds, and collisions on the ground with people, animals, or objects. An air collision can also lead to subsequent ground collisions, compounding the risk. Risks related to supporting facilities primarily involve issues with the communication network. Loss of control can occur due to connection loss within the communication network, and latencies in the network can further exacerbate control

issues, leading to potential operational failures. Addressing these risks is crucial for the safe and efficient integration of UAVs into the airspace.

SORA involves extensive documentation and the establishment of tailored risk reduction measures to mitigate ground and air risk. The SORA plays a crucial role in identifying and mitigating ground and air risks specific to singular UAV operations. In the context of SORA, air risk specifically refers to the risk of a collision between a UAV and a manned aircraft. However, this is risk does not incorporate the risk of collision between two UAVs. The risk of collision between UAVs is increased due to the high-density of unmanned air traffic.

U-space provides services for managing air traffic, introducing functionalities such as Network Identification, Geo-Awareness, Traffic Information, and Conformance Monitoring. U-space airspace is the designation of a certain volume in airspace for UAV operations, however it is not a risk assessment. Therefore, high-volume UAV operations in the concept of U-space still impose risks that need to be identified, managed and mitigated. The current SORA framework is limited in its ability to incorporate U-space services as mitigations or to address the simultaneous operation of multiple UAVs in the same airspace. This limitation presents a significant challenge for high-volume UAV operations, which inherently carry a higher risk of collisions between UAVs.

Connectivity to a robust communication network plays a crucial role in real-time data exchange between UAVs and control centres. At the moment, this is included neither in the SORA nor in the U-space services. Furthermore, to facilitate high-volume UAV operations, take-off and landing sites need to be arranged. Therefore, besides the designation of U-space airspace to enable high-volume UAVs, additional infrastructure elements need to be provided on the ground to ensure safe UAV operations.

In the research, four different design concepts for the arrangement of U-space airspace were identified along with four different strategies to determine flight plans. Unstructured and layered airspace allow for UAV operations between two variable locations or between a fixed starting point and a variable destination. The latter would require the UAV to fly back to the beginning point after delivering the parcel. The zones and tubes concept allow for the designation of fixed corridors in U-space airspace and strategically located vertiports along these corridors.

The flexibility of unstructured or layered airspace with dynamic routes allows operators significant freedom in path planning but has an increased risk of collision, especially when the traffic densities increase. Dynamic routes offer greater flexibility and adaptability; however, they require a more extensive and resilient connectivity network infrastructure. This is because they necessitate a commination network infrastructure with a wider coverage. Additionally, variable take-off and landing sites require an analysis of the selected location for each operation.

The tubes and zones concept reduce the risk of collision between UAVs in high-density airspace. By designating specific flight paths and segregating air traffic into structured corridors, these concepts reduce the potential for in-air separation conflicts and streamline the management of UAV operations. This structured approach allows for more predictable traffic patterns and easier monitoring, significantly enhancing the overall safety of UAV operations in high-traffic areas. Designating specific air pathways, allows for more focused and efficient network coverage, reducing the complexity ensuring robust connectivity for UAV operations. Additionally, the designation of vertiports, contributes significantly to operational safety by providing controlled environments that mitigate the risk of uncontrolled descents and enhance traffic management. Municipalities are responsible for selecting appropriate sites and ensuring compliance with safety standards. Contrary to dynamic routes, designating corridors for UAV operations allows for the strategic placement of vertiports, providing safe take-off and landing environments.

However, a significant gap in the current system is the lack of a designated stakeholder or institution to facilitate and manage this structured airspace. Despite the benefits of a structured U-space airspace, there is currently no dedicated institution or stakeholder responsible for the implementation and management of these corridors. The current lack of a designated institution to facilitate structured U-space airspace is a significant gap that hinders the development and safe integration of UAV operations. By addressing this gap and establishing a robust institutional framework, the benefits of structured airspace can be realised, paving the way for safer, more efficient, and scalable UAV operations.

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Chapter 1

Introduction

Unmanned Autonomous Vehicles have revolutionised various sectors with their versatility and efficiency. From the rapid delivery of medical supplies by the Zipline project in Ghana, which has saved countless lives in remote areas (De León, 2019), to the potential for urban parcel delivery and agricultural monitoring (Tsouros et al., 2019), the applications of UAVs are vast and promising. However, despite these success stories, the widespread adoption of UAV technology in Europe appears to be at a standstill. This research investigates the complex interplay of regulatory frameworks, airspace management, and technological challenges. Various stakeholders, including policymakers, aviation authorities, and private companies, are contemplating the future of UAV integration. They envision a meticulously organised airspace where a high-volume of UAVs can operate safely alongside manned aircraft. Yet, the realisation of this vision remains elusive. This research aims to offer a thorough analysis of the current state and risks for UAVs in European airspace.

In this chapter the problem description will be provided (section 1.1). This will be followed by the research questions (section 1.2). Subsequently, the scientific and practical relevance of the research will be discussed in section 1.3 and 1.4 respectively.

1.1 Problem Description

In recent years, growing interest from both the industry and research communities have resulted in rapid advancements in the field of Unmanned Aerial Vehicles (Habibi et al., 2023). Unmanned Autonomous Vehicles (UAVs) are aircrafts without an onboard pilot (Wang et al., 2024). UAVs can operate autonomously in dynamic and operational environments. Using UAVs for parcel delivery can reduce road traffic congestions and pollutant emissions in comparison to using trucks (Di Puglia Pugliese et al., 2020). Due to both the logistic and sustainability benefits of UAV flights, forecasts of the EASA and NASA show intensive growth of UAV flights in the near future (Rumba & Ņikitenko, 2020). Originally, UAVs were used solely for military operations. Recently, commercial and civil applications of UAVs are getting more attention, for example in industries such as agriculture, transportation and carrying payloads (figure 1) (Černý et al., 2023; Yang et al., 2020). Moreover, future applications of using UAVs for carrying payloads can improve the accessibility to healthcare, as they can deliver items such as blood samples, medications, vaccines, and organs, between healthcare institutions and directly to patients' homes (Hiebert et al., 2020; Rosser et al., 2018). High volumes of UAV operations are expected for delivering payloads with UAVs. An airspace density of one UAV in every 3,4 square kilometre is considered high-volume (Xue et al., 2019).

Figure 1: UAVs for Parcel Delivery (Bloch, 2020)

Widespread usage of UAVs in the civil and commercial sectors is expected in the future, therefore guidelines and regulations are already being developed by aeronautics authorities for insertion of high volumes of UAVs in civil airspace in Europe (Doherty & Rudol, 2007). There is still an ongoing growth in the size, speed and manoeuvrability of UAVs (Habibi et al., 2023). The development of UAV regulations should keep pace with the rapid emergence of UAVs, which significantly contributes to the integration of UAV into national and international aviation systems. The research of Fotouhi et al. (2019) discusses how rules might be out-of-date due to the rapid development of emerging technologies. Thus, even though the technology is already available and ready to be used, the technology is not in use yet, as the technology advances much faster than the laws and regulations.

The technological advances and the increased demand, as well as the increased efficiency for UAV operations, give rise to the need for regulations that allow high volumes of beyond visual line of sight (BVLOS) operations (Politi et al., 2021). BVLOS flights are expected to be the standard way of operating for many future commercial UAV activities, such as parcel delivery (Barrado et al., 2020). This requires wider autonomy of the UAVs and minimal interaction with the ground control. Regulators and organisations are currently working towards updating (inter)national policies to enable BVLOS, with some predictions estimating BVLOS operation within the year 2035 (Saunders et al., 2023). Regulations are restricting certain uses of UAVs as it introduces risks for the air safety of manned aviation and for the safety of public on the ground. Additionally, the risk of collision between UAVs is introduced due to the high-volume of the UAV operations. By gradually analysing the risks and knowing the modes of operation, restrictions can slowly disappear, and operating laws can come into place (DeBusk, 2010). Currently, the focus of risk assessments is to evaluate and mitigate safety risks, consisting of both air and ground risks. Nevertheless, addressing risks associated with security, privacy, and environmental concerns may also necessitate the implementation of suitable risk mitigation measures (Hullah et al., 2023). The risks associated with security, privacy and environmental issues are outside the scope of this research.

Organisations are hesitant to provide guidance on regulations and standards until a common understanding can be reached. There are increasing concerns regarding public safety from national and international aviation authorities. Standard procedures of the aviation industry, such as safety management systems and standard operating procedures, still need to be adapted to UAVs used for delivery (Saunders et al., 2023). However, the research of Rumba and Nikitenko (2020) mentions that some modern methods of air traffic control may be found ineffective to cope with the expected density of vehicles. Although UAVs have been in operation for several decades, there is still little experience with UAVs in public spaces, as most operational experience comes from war zones and humanitarian contexts (Cawthorne & Wynsberghe, 2020). In the research of Vanderhorst et al. (2024) it is argued that there is a lack of understanding from the policy makers concerning the risk dimensions of the commercial UAV applications. Moreover, to be able to develop UAV regulations, socio-technical concerns of UAVs need to be analysed and understood. Airspace developed without regulations and infrastructure to accommodate the autonomy, are restricting any testing and trials of such systems. The research of Saunders et al. (2023), describes that currently UAVs present a severe risk for manned aviation as well as people on the ground and, therefore, are not allowed to fly in controlled airspace or within the proximity of people. In most countries, no-fly zones, are in effect to reduce safety risks for manned aviation and people on the ground. This includes a safe distance away from people, other vehicles and properties, such as airports and government buildings. The different applications for UAVs along with policy priorities and regulatory environments impose different challenges. The challenges will attract players with different interests, and partnerships into the UAV system. All these factors can in turn generate and support diverse ideas and approaches to the integration of this new technology within delivery systems for BVLOS UAVs (Hiebert et al., 2020).

A system must be provided for controlling unmanned vehicles as the number of UAVs grows every year. Questions about how countries may integrate UAV heliports, noise problems, social adaptation, and legal scenarios of liabilities are still under evaluation (VanderHorst et al., 2024). This integration also presents complex challenges that must be addressed to ensure safe and efficient UAV operations.

While extensive research has been conducted on specific aspects of UAV integration, a comprehensive analysis of the system as a whole remains lacking. These studies contribute to enhancing certain aspects of UAV integration, they often do so in isolation, without considering the broader implications for the airspace system as a whole. An infrastructure should be established connecting different components needed for the integration of high-volume UAV operations in civil airspace, such as communication between UAVs, algorithms for path planning and sites for take-off and landing. In the research of Tomić et al. (2012) it is argued that currently, outdoor environments lack clear structure. Parcel delivery by UAVs is both impeded by design constraints and strict flight restrictions. Research that connects all different components for a high-volume infrastructure is lacking.

This research aims to bridge the gap between different research by providing an exhaustive analysis of the integration of UAVs into civil airspace. It seeks to evaluate the current risk mitigation strategies and technological solutions within the context of the entire airspace system, identifying potential shortcomings and proposing integrated solutions. By adopting a systems perspective, this study aims to enhance the safety and efficiency of UAV operations, ensuring their successful integration into the increasingly complex airspace environment.

1.2 Research Questions

As outlined above, a comprehensive analysis for an infrastructure for integrating UAVs in airspace is lacking. The main research question leading this research is:

'How can risks of high-volume BVLOS UAV operations regarding public safety be managed and mitigated through UAV infrastructure management?'

For this main question, the following sub questions can be derived:

1. *What are the current regulatory frameworks for operating UAVs BVLOS?*
2. *What are the risks regarding public safety of incorporating high-volume UAV operations in civil airspace?*
3. *How do existing regulatory frameworks incorporate and manage risks of high-volume UAV BVLOS operations regarding public safety?*
4. *How can the risks of high-volume UAV operations regarding public safety be managed and mitigated?*
5. *What are the roles and responsibilities of different public and private stakeholders in a high-volume UAV infrastructure to enhance public safety?*

1.3 Scientific relevance

This research intends to reduce the knowledge gap in the current knowledge of integrating high-volume BVLOS UAV operations in civil airspace. This study will integrate various aspects of the infrastructure, including technological, regulatory, and operational components, to offer a comprehensive perspective. This approach will help identify how these individual elements interact and function together within the larger system of airspace infrastructure management. The study will contribute to the identification of risks associated with the integration of UAVs into civil airspace and existing aviation systems. These include the risk of collision between UAVs, risks caused by external factors such as weather circumstances, and risks imposed by different vertiport designs. Addressing these varied risks will provide a more nuanced understanding of the safety challenges inherent in high-volume UAV operations.

This research aims to bridge the gap between existing studies by adopting a holistic approach, analysing how individual elements function within the larger context of airspace management. By synthesising various research findings, this study seeks to provide a comprehensive understanding of the challenges and potential solutions for integrating UAVs into civil airspace.

1.4 Practical relevance

This research will be conducted for Schuberg Philis. Schuberg Philis has created a vision together with KPN to contribute to a UAV delivery system for high-volume BVLOS UAV operations. KPN is seeking to play a role in providing a communication network for communication between UAVs as a network provider. Schuberg Philis wants to support the IT services needed for the high-volume UAV operations. In order to be aware of the opportunities and limitations for a high-volume UAV system, this research is conducted.

The research will provide a detailed analysis of current regulatory frameworks, examining their scope, strengths, and limitations. Understanding these regulatory landscapes is crucial for identifying areas that require enhancement to accommodate the unique challenges posed by high-volume UAV operations. By highlighting gaps in the present regulatory framework, this study will suggest improvements to better manage and mitigate the risks associated with integrating UAVs into civil airspace. These insights will be invaluable for policymakers and regulatory bodies aiming to develop more robust and adaptive regulations for UAV operations.

Additionally, this research aims to outline possible public and private stakeholder roles in ensuring a secure process for the integration of BVLOS UAVs in the civil airspace. The results will offer valuable insights to policymakers, industry professionals, and regulatory bodies engaged in shaping the landscape of UAV integration in civil airspace and the unmanned traffic management.

1.5 Thesis Outline

The thesis is outlined as follows. Chapter 2 illustrates the research design used to conduct research. In chapter 3 the state-of-the-art regulatory frameworks for flying UAVs BVLOS will be described. Subsequently, in chapter 4 the risks of operating high volumes of UAVs BVLOS will be provided. Moreover, chapter 4 will discuss the risks of the regulatory frameworks. Additionally, it will identify risks that are not covered by the frameworks. Chapter 5 introduced different design concepts for UAV infrastructures to address the risks identified in the previous chapter. The infrastructures will be analysed by evaluating the safety imposed by the different design concepts. Chapter 6 discusses different management models for the implementation of high volumes of UAV operations. Chapter 7 includes the discussion and limitations of the research. Finally, chapter 8 presents the conclusions and recommendations.

Chapter 2

Research Design

This section gives an overview of the methodology used for the research. Figure 2 illustrates the research design used to conduct the research.

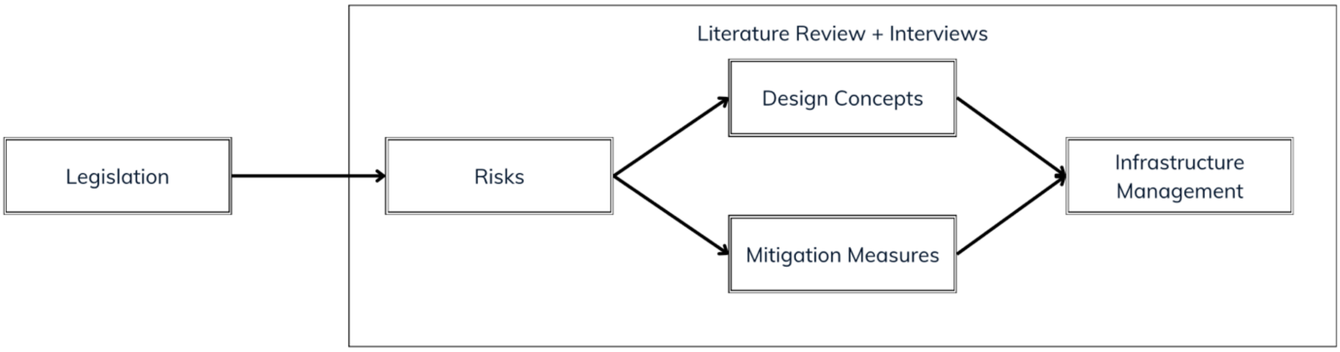

Figure 2: Research Design (Author's Image)

2.1 Legislative Review

The first sub question: '*What are the current regulatory frameworks for flying UAVs BVLOS?*' has been answered by reviewing the current rules and legislation. This has been done in order to get an understanding of the possibilities and limitations of current regulatory frameworks to enable high-volume UAV operations. The European legislation, as well as the Dutch legislation have been analysed.

2.2 Literature Review

The method used for the gathering of data is a literature review. Webster & Watson (2002) argue that an effective and well-conducted literature review creates a firm foundation for advancing knowledge and facilitating theory developments. Snyder (2019) states that a literature review can identify knowledge gaps within the literature. Moreover, the paper states that a literature review can address research questions with a power that no single study has as it integrates findings and perspectives from many empirical findings.

A literature review has been conducted to investigate risks regarding public safety that are included by integrating UAV operations in civil airspace. This involved analysing qualitative studies that discuss specific risks and the effectiveness of various mitigation strategies. This answered sub question 2: '*What are the risks regarding public safety of incorporating high-volume UAV operations in civil airspace?*'

The frameworks identified in sub question 1 have been analysed to determine how the risks of high-volume UAV operations are managed and mitigated by those frameworks. By comparing the identified risks with the current regulatory frameworks, the third sub question has been answered: '*How do existing regulatory frameworks incorporate and manage risks of high-volume UAV BVLOS operations regarding public safety?*'

The research investigates how the infrastructures both in the air and on the ground can be designed to reduce risks of high-density UAV operations regarding public safety. By conducting a literature, the possible structures for both air and ground for high-volume UAV operations have been identified. Additionally, it has been evaluated how risks associated with high-density UAV traffic can be controlled and mitigated through infrastructure design. The study also explored how high-volume UAV traffic can be integrated into airspace while managing and mitigating risks for public safety. This answers sub question 4: '*How can the risks of high-volume UAV operations regarding public safety be managed and mitigated?'.*

The research also included a stakeholder analysis to identify the roles of different public and private stakeholders involved in UAV operations, such as UAV operators, regulatory authorities, and governmental entities. Based on the legislation and investigated mitigation measures, different public and private stakeholder roles were identified. Different management strategies have been evaluated to answer question 5: '*What are the roles and responsibilities of different public and private stakeholders in a high-volume UAV infrastructure to enhance public safety?*'.

The analysis identified gaps in current practices and propose recommendations for improving UAV safety and efficiency. This answers the main research question: *'How can risks of high-volume BVLOS UAV operations regarding public safety be managed and mitigated through UAV infrastructure management?'.*

The data obtained during the research needs to meet certain quality standards. Scopus has been used to retrieve literature for the literature review. Scopus is a search engine that holds publications that have been peer reviewed by academics. This ensures a high level of quality and integrity when comparing with for example Google Scholar. The literature review focussed on articles that addressed both risks and mitigating measures. This approach helped scope the research. The search yielded a significant number of hits, from which relevant risks were retrieved for different system components. The interrelation of these risks was then analysed in the context of the entire system.

2.3 Semi-Structured Interviews

Throughout the research, interviews will be conducted to validate gathered insights. This approach allows for the incorporation of supplementary literature reviews as necessary during the study. When interviewees provide new information, it can be further investigated to enhance the research. Additionally, by distributing the interviews over an extended period, various elements such as risks, and risk mitigation measures can be validated. This iterative process ensures that the research becomes more complete.

Young et al. (2018) mention that interviews allow an in-depth analysis from a relatively small sample size and place the focus of research on the views of participants. The interviews will be of a semi-structured form as this gives the opportunity to expand the interviewee's responses (Rubin & Rubin, 2005).

The interviews will be conducted with different relevant stakeholders. Stakeholders such as governments, municipalities, and current managers of the (inter)national aviation systems will be approached for the interviews. For the interviews, contacts of Schuberg Philis will be used. The interviews were recorded and transcribed by Microsoft Teams, to make sure all information from the interviews would be available throughout the duration of the research. An overview of the participants can be found in table 1.

Table 1: List of Interview Participants

Interview	Company/Institution	Function	Date of Interview	Duration of Interview
1	Network Provider	Innovation Manager	27th of February	1 h 19 min
2	Developer	CEO	19th of March	1 h 11 min
3	Ministry of Infrastructure and Water Management	Project Manager U-Space	27th of March	1 h 17 min
4	Municipality	Team Leader Entrepreneurs Desk	11th of April	2 h 06 min
5	Software Engineer	Software Engineer	22nd of April	54 min
6	Airport	Airport Manager	24th of April	43 min
7	Developer	CEO	6th of May	46 min
8	UTM Provider	Business Development Manager	10th of May	1 h 08 min
9	UAV integration	UAS consultant	10th of May	1 h 20 min
10	Police Department	Operational Specialist	16th of May	1 h 02 min

2.4 Data Gathering

Initially, the focus of the research was identifying suitable mitigation measures for risks associated with high-volume UAV operations. The methodology to do this was by establishing a risk assessment. Two risk assessments were found to be suitable for risks in aviation: Hazard and Operability Analysis (HAZOP) and Bow Tie Diagrams. HAZOP and Bow Tie Diagrams are common risk assessment methods used in aviation (Denney et al., 2019; Downes & Chung, 2011). Hence, the search terms used in Scopus were "bow tie" OR "HAZOP" AND "UAV". An overview of the search terms in Scopus can be found in table 2. This led to the retreival of 25 documents, of which 10 were usable for this research. This was not considered as sufficient.

Table 2: Search Terms Scopus

	Search Terms in Scopus	Documents Found	Documents useful for research	Documents not suitable for research
1	"bow tie" OR "HAZOP" AND "UAV”	25	10	15
2	“STPA” AND “drone” OR “UAV” OR “UAS”	24	8	16
3	“risk management" AND "uav" AND "delivery"	10	6	4
4	"risk management" AND "UTM"	10	7	3
5	"SORA" AND "UTM" OR "UAV" OR "UAM" OR "UAS" OR "u$space"	49	9	5
6	"UAV" OR "drone" AND "high$volume"	61	8	53

To identify more risks, articles about UAVs and STPA were analysed, retreiving 24 documents. To expand the research, a new strategy was applied to identify articles concerning delivery risks. Scopus was used to look for documents containing the words “risk management" AND "uav" AND "delivery". This led to the identificatoin of 10 documents of which 6 were usefull for this research. Again, the research was expanded by looking for articles with the words "risk management" AND "UTM". This approach included the identification of research where the unmanned traffic management (UTM) was analysed. UTM can enable high-volumes of UAV operations. This led to the identification of 10 documents, of which 7 were useful for this research.

To elaborate the research, the terms "SORA" AND "UTM" OR "UAV" OR "UAM" OR "UAS" OR "u$space" were used to look for documents. This led to the retreival of 49 documents. The first 15 documents were analysed, and 9 were identified as useful. However, no new risks were identified in these documents. Hence, the analysis of the documents was stopped.

To focus more on the risks for high-volume UAV operations, this was used as a search term in Scopus. This led to the retreival of 61 documents. Nevertheless, the articles found were mainly about the application of UAV for inspections and agriculture. The UAVs used for these applications make use of cameras, thus the high-volume referred to in these articles consists of articles addressing risks of the high-volumes of data generated by these cameras.

Chapter 3

Regulatory Frameworks

The European Union Aviation Safety Agency (EASA) is responsible on behalf of the European Commission for the safety of air traffic in Europe. The guidelines formulated by the EASA provide the overall framework regarding UAV traffic management in the Member States, including the Netherlands. The regulation distinguishes three categories of UAV operations based on the risk and complexity of the operation (EASA, 2018). These categories are designed to ensure that UAV operations are conducted safely while balancing the regulatory burden on operators. The categories are 'Open', 'Specific' and 'Certified', where the 'Open' category contains the least risks for safety in the air and on the ground, and the 'Certified' category contains flights with the most risks. The categories will be briefly discussed below. An elaborate description of the categories in included in Appendix A.

The 'Open' category includes in visual line of sight (VLOS) operations. This category does not require operational authorisation of the National Competent Authority, making it the simplest and most accessible category for hobbyists and small-scale commercial operators. The 'Specific' category allows for more complex and higher-risk operations but imposes stricter requirements to ensure safety and compliance. This category includes beyond visual line of sight (BVLOS) operations. Operators must obtain an operational authorisation from the National Competent Authority before conducting 'Specific' category operations. This involves submitting an operational plan and a risk assessment that demonstrates how the operator will mitigate identified risks. Currently, the procedure to receive authorisation for operations this category is complex due to this risk assessment. An overview of the different risk assessments will be provided in the next section. Operations in the 'Certified' require an operator that has been licensed by the national competent authority to guarantee an acceptable level of safety. Again, the UAV operator must complete a risk assessment to receive operational approval, which will identify the conditions needed for the UAVs operation (EASA, 2024). The 'Certified' category ensures the highest level of safety and regulatory compliance, akin to manned aviation, and is necessary for UAV operations that carry substantial risks. As the 'Open' and 'Specific' category are most common, the EASA is focussing on developing guidelines for those categories. The development of the guidelines for the 'Certified' category are still under development.

3.1 Risk Assessments

In this section, the risk assessments will be described that need to be conducted prior to flying a UAV in the Netherlands. As mentioned in the previous section, there is not authorisation required for flying a UAV in the 'Open' category. There are four different risk assessment procedures that can be conducted to request authorisation for an UAV operation in the 'Specific' category. These will be briefly described below. A more elaborate description of the risk assessments can be found in appendix B.

3.1.1 STS

The first procedure to request a UAV flight authorisation is to apply for a Standard Scenario (STS). The STS framework is designed to streamline the approval process for common UAV operations by providing clear operational conditions and safety measures. In this procedure, the UAV operation is described and the risk assessment for these operations is already conducted. Therefore, by applying for an STS there is no need for the operator to conduct the assessment. The request consists of a declaration of the operator that the characteristics of the UAV operation are as described in the STS. An operator can apply for an STS by submitting a declaration to the competent authority of that

Member State. There are two standard scenarios: STS-01 and STS-02. STS-01 includes flights that are conducted in visual line of sight. These operations are intended for use cases such as inspections, surveillance, and monitoring. STS-02 allows for operating beyond visual line of sight. It involves using visual observers to assist in maintaining airspace awareness and safety over larger areas, typically not exceeding two kilometres from the remote pilot when visual observers are used.

3.1.2 PDRA

The second risk assessment is a pre-defined risk assessment (PDRA). This procedure also includes a description of characteristics of the operation. PDRAs are established by EASA to streamline the authorisation process for specific types of UAV operations. These assessments provide standardised risk evaluations and mitigation measures for common UAV operations, allowing operators to comply with predefined conditions. Similarly to the STS, the operator has to declare that the operation is as described in the PDRA. The declaration should again be submitted to the competent authority. There are five pre-defined operations, these include agriculture works, infrastructure inspections and surveillance.

3.1.3 SORA

The third procedure is a specific operations risk assessment (SORA). This assessment includes operations that have not been pre-defined, and therefore leave more freedom to the operator. The operator has to define the characteristics of the UAV operation. A risk assessment needs to be conducted to determine the required risk mitigation measures for that operation. The mitigation measures need to reduce the ground risk and air risk of the operation to acceptable levels. In the context of SORA, air risk specifically refers to the risk of a collision between a UAV and a manned aircraft. The risks that come forward in the assessment should be reported along with suitable mitigation measures. Instead of conducting the risk assessment for a single UAV operation, the assessment can also be conducted to receive a long-term operating permit for a certain area. Hence, a permit could be obtained to operate a UAV for a longer period of time.

The primary objective of SORA is to ensure that UAV operations are conducted safely and that all potential risks are systematically identified, assessed, and mitigated. By combining detailed risk assessments with safety measures, SORA ensures that UAV operations can be conducted safely and effectively, even in more complex and higher-risk environments.

The SORA consists of ten steps, a more detailed overview is included in appendix C for reference. The four most important requirements of the SORA will be discussed below, these are: Ground Risk, Air Risk, Specific Assurance and Integrity Level (SAIL), and Operational Safety Objectives (OSO).

Ground risk refers to the risk of the operation harming people and property on the ground. The SORA framework determines the intrinsic and final Ground Risk Class (GRC) based on the frequency and severity of potential incidents. After determining the initial GRC, suitable mitigation measures are identified and evaluated. Mitigation measures are required to reduce the ground risk to an acceptable level. There are three categories of mitigation measures. Category M1 includes measures that aim at reducing the number of people that are at risk on the ground. Measures in category M2 reduce the effects of the ground impact once the control of the operation is lost. For the mitigations in the third category (M3) an emergency response plan (ERP) needs to be established to address and limit the effect of an operation out of control. Additionally, the UAV operator is required to have completed ERP training. The robustness of the measures is determined by three levels: low, medium and high. The robustness level depends on the degree in which the effectiveness of the mitigation measure has been verified and validated.

Air risk focuses on the potential for UAVs to encounter manned aircraft. The SORA requires the designation of an operational volume to each UAV. The operational volume consists of the flight geography and the contingency volume (Salma & Schmehl, 2023). The operational volume is a representation of the volume where the UAV intends to be at that moment in time. The flight geography represents a three-dimensional volume around the UAV with a temporal component representing the time and duration that the volume will be occupied by that UAV (Capitán et al., 2022). The volume will move in time, along with the movements of the UAV, as the operation continues. In case of an abnormal situation where the UAV leaves the flight geography, it enters the contingency volume. In the contingency volume, procedures are triggered to make the UAV fly back into the flight geography (Bertrand et al., 2023). The SORA framework establishes an initial Air Risk Class (ARC) for the operational volume, which can be modified through strategic and tactical mitigations. Strategic mitigations are pre-planned and are generally implemented during the mission planning phase. They aim to reduce the inherent risk before the UAV operation begins by considering factors such as the operational environment, airspace usage, and procedural controls. Tactical mitigations are real-time actions taken during the UAV operation to manage and respond to dynamic changes and unexpected situations. These mitigations are designed to address immediate risks that arise while the UAV is in flight. The goal is to ensure that the air risk is within acceptable limits, allowing safe UAV operations across different airspace environments.

The SAIL represents the level of confidence that the UAV operation will stay under control. The SAIL category is determined based on the final GRC and final ARC.

Operational Safety Objectives (OSOs) ensure the safety of UAV operations. For the assigned SAIL, the operator will be required to show compliance with each of the 24 OSOs. Each OSO shall be met with the required level of robustness, depending on the SAIL. The level of robustness for UAV operations correspond to the combined levels of integrity and assurance needed for safety measures. The robustness can be at a low, medium or high level. A low level of robustness includes a declaration from the UAV operator that the required integrity level has been achieved. By providing supporting evidence through testing or proof of experience, a medium level of robustness can be achieved. A high level of robustness can be received by the validation of a competent third party.

3.1.4 LUC

The last risk assessment has a different approach. The Light UAV Operator Certificate (LUC) enables an organisation to get an authorisation the authorise operations by itself when a description of the operation is included in the LUC. A LUC is a certification issued by the EASA that allows UAV operators to self-authorise certain types of operations within the ‘Specific’ category without requiring individual operational authorisations from the competent authority each time. The organisation has to describe UAV operations that it wants to conduct and perform risk assessments for these operations. The risk assessments can be the STS, PDRA or SORA. By including different operations and risk assessments accordingly, in the LUC, the organisation can therefore receive authorisation to conduct those operations. The authorisation is a long-term operating permit for that organisation.

This certification is aimed at operators who demonstrate a high level of safety, compliance, and organisational maturity in their UAV operations. The LUC is designed to streamline the regulatory process for UAV operators who have established robust safety management systems and demonstrated consistent adherence to aviation safety standards.

3.2 U-space airspace

There is a demand for a scalable autonomous unmanned traffic management solution for BVLOS and fully autonomous flight control in developed airspace (Rumba & Ņikitenko, 2020). To create a safe environment for this high volume of UAV flights, Unmanned Traffic Management, or the U-space has been introduced (Boronat et al., 2023). A U-space airspace includes advanced rules for all potential participants in the operation of unmanned systems. The designation of a U-space airspace enables operations in high volumes of unmanned aircraft (EASA, 2020). In this airspace, it will be possible to operate UAVs BVLOS by providing services that will support operations and make them more efficient (figure 3). The U-space airspace includes services and procedures that are necessary to operate UAVs safely (Commission Implementing Regulation (EU) 2019/947, 2019). Member States have the authority to designate a geographical zone as U-space airspace where UAV operations can take place. U-space airspace aims at mitigating UAV encounters with manned aircraft and other UAVs. Legislation regarding U-space airspace has been implemented in 2023 for all Member States of the European Union (Eurocontrol, 2024). Nevertheless, no U-space airspace has been designated yet in any Member State of the European Union.

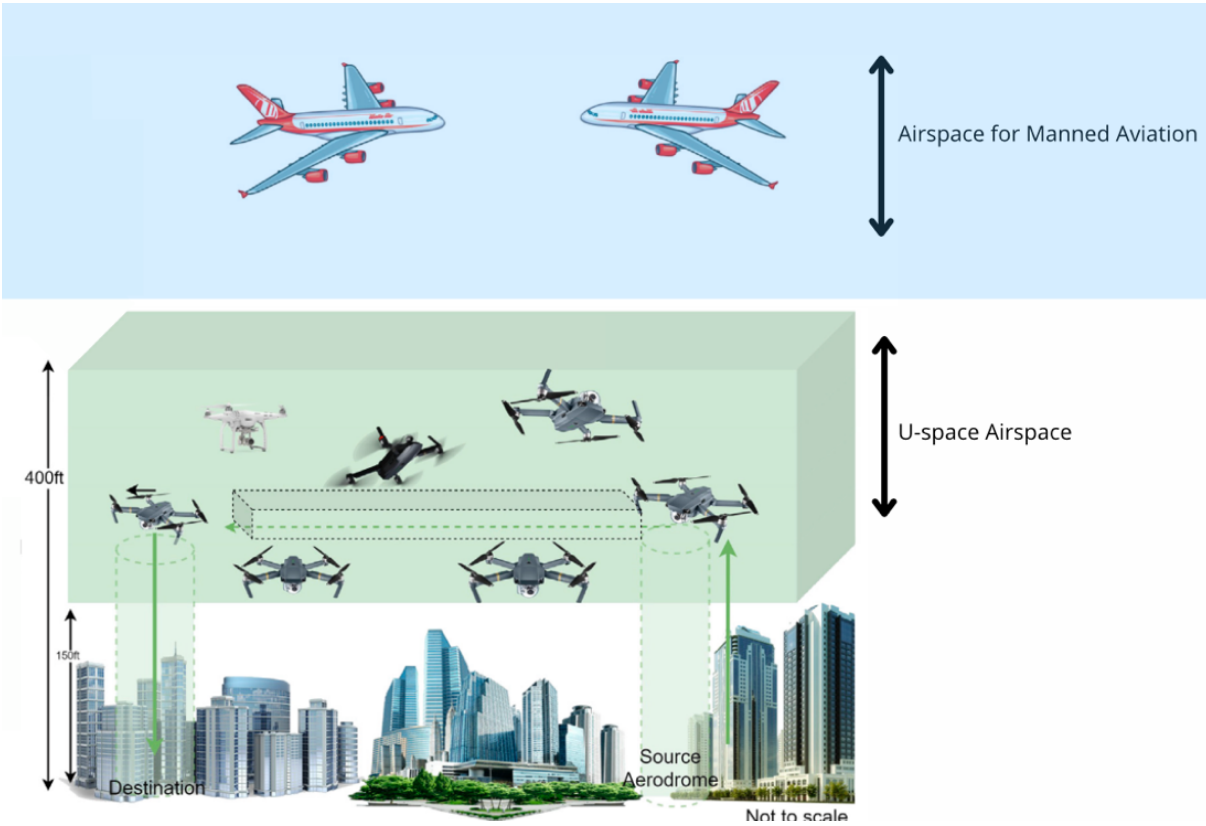

Figure 3: U-space Airspace (Shrestha et al., 2021)

3.2.1 U-Space Services

In the U-space airspace, the UAV operations require support by U-space services that have been determined by the EASA, to ensure high-volume and efficient operations in U-space airspace (EASA, 2020). These services consist of highly automated digital services designed to enable the UAV operations (Eurocontrol, 2023). There are four mandatory U-space services that must be provided in U-space airspace (Commission Implementing Regulation (EU) 2021/664, 2021). They will be shortly described below.

1. Network Identification Service: This service ensures that UAVs can be identified and tracked in real-time. It provides information about the UAV, its operator, and the geographical position, altitude, route, take-off point and the emergency status of the UAV.
2. Geo-Awareness Service: This service provides UAVs with up-to-date information about geographical zones, including restricted areas, no-fly zones, and areas with temporary flight restrictions. This helps prevent UAVs from entering unsafe or unauthorised areas.
3. Traffic Information Service: This service provides the UAV operator with information on any other conspicuous air traffic, that may be in proximity to the position or intended route of the UAV flight. Upon receiving the traffic information services, the UAV operator should take the relevant action to avoid any collision hazard.
4. Flight Authorisation Service: The UAV operators should be provided with the terms and conditions for each individual flight, through a UAV flight authorisation service. This service manages flight authorisations for UAV operations, ensuring that UAVs can only operate within approved areas and under specified conditions. It helps manage airspace usage and prevents conflicts between different airspace users.

In addition, the U-space services can be expanded to six services when considered necessary by the Member State to ensure safe and efficient UAV operations. A description of these services has also been published in Commission Implementing Regulation (EU) 2021/664 (2021). These additional services are:

5. Weather Information Services: Weather data, provided by trusted sources, should be provided to UAV operators to maintain safety and support operational decisions of other U-space airspace.
6. Conformance Monitoring Services: This service detects any deviation from the authorised flight and notifies the UAV operator.

3.2.2 Introduction of stakeholders

The implementation of the U-space guidelines introduces new roles for both public and private stakeholders. A description of the roles will be given below. An overview of the stakeholders is provided in figure 4. The boxes represent an organisation in the system, the arrows represent information that is exchanged between the organisations.

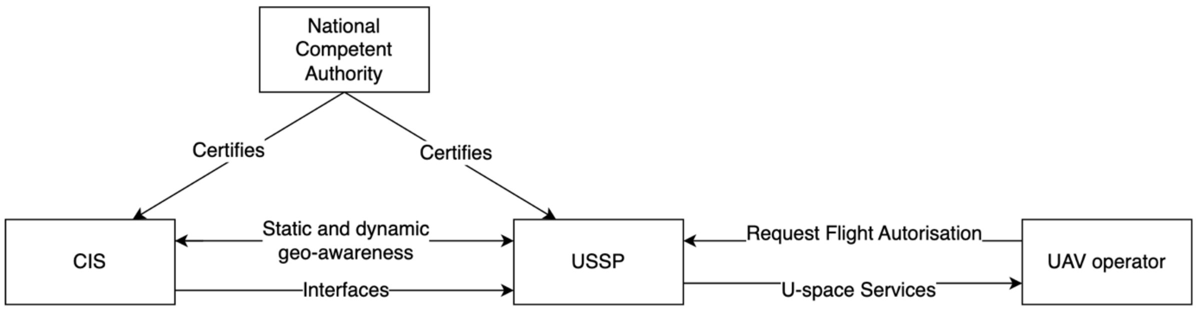

Figure 4: Stakeholder Map (Author's Image)

U-space Service Provider

The U-space services should be provided by a U-space service provider. A U-space service provider (USSP) should therefore provide at least the four mandatory U-space services, and when deemed necessary by the Member State, it should be able to provide all six services. Any USSP should get certified by the national competent authority of that Member State. The USSP provides the U-space services to the UAV operators that request flight authorisation. The USSP has to use information provided by the Common Information Service Provider (CIS) to evaluate the flight authorisation request. The guidelines stipulate that there should be at least one USSP per U-space airspace.

Common Information Service Provider

A Common Information Service Provider (CIS) is the heart of the U-space system (EASA, 2020). The regulation of the EASA states that there needs to be one CIS provider per U-space airspace. Hence, there can be as many CIS providers as there are U-space airspace in that Member State. The CIS provider ensures that all the information can be exchanged between the various organisations to fulfil their obligations. The CIS will have to make available to the relevant and authorised actors at all times on a non-discriminatory basis, ensuring data quality and security. The CIS should establish identical interfaces between different airspaces. The EU is developing standardised procedures for these interfaces (Römers, n.d.). The information to be exchanged includes both static and dynamic data such as geographical limits, applicable operational requirements, and the list of certified USSPs offering U-space services in that airspace (Eurocontrol, 2023). When designating a single CIS provider, the provider must meet the certification requirements specified by the EASA.

UAV operators

Any individual or organisation that owns or hires a UAV is considered a UAV operator. UAV operators apply for a flight authorisation at the USSP. Hence, the UAV operator should establish a contract with the certified USSP of the U-space airspace. In order to receive the flight authorisation, certain requirements need to be met by the UAV operator. The flight authorisation request should comply with the terms and conditions as described by the USSP. After the approval of the flight authorisation request, the UAV receives the U-space services by the USSP of that U-space airspace.

National Competent Authority

The role of the national competent authority includes several aspects, including the certification of the CIS and USSPs in the Netherlands. Moreover, their duties include issuing operational authorisations, conducting inspections, and enforcing safety standards to prevent accidents and incidents. Contrary to authorising UAV operations requested by conducting a risk assessment, the competent authority does not have to authorise requested UAV operations in U-space airspace.

Chapter 4

Risks of High-Volume UAV Operations

Integrating high volumes of UAV operations in airspace imposes certain risks. A literature review has been conducted to identify risks of high-volume UAV operations. The identification of risks is important in the aviation industry as aviation authorities utilise a risk-based approach when developing new standards, such as the development of standards for unmanned airspace (Bijjahalli et al., 2022).

The risks of high-volume UAV operations can be distinguished in risks during the operation on the one hand and risks regarding the support of the operations on the other hand. The support of UAV operations consists of, among other things, take-off and landing facilities and the utilisation of a communication network. Firstly, the risks during UAV operations in high-density airspace will be discussed. Secondly, the risks regarding the supporting facilities of the UAV operations will be discussed. This answers sub-question 2*: 'What are the risks of incorporating high-volume UAV operations in civil airspace?'* Initially, around 200 risks were identified based on a literature review. After a thorough analysis, which included the removal of duplicates and the consolidation of similar risks, this number was reduced to approximately 100.

Subsequently, the degree in which the current regulatory frameworks take the identified risks into account will be evaluated. The four risk assessments as described in the previous chapter will be discussed in this context, followed by the evaluation of the U-space airspace. This answers sub question 3: '*How do existing regulatory frameworks incorporate and manage risks of high-volume UAV BVLOS operations?'*

This chapter is structured as follows. First the risks of high-volume UAV operations will be discussed in section 4.1. In section 4.2 the risk assessments and the concept U-space airspace will be discussed, by evaluating how these incorporate the risks of high-volume UAV operations.

4.1 Risks of High-Volume UAV Operations

The primary focus of this research is on evaluating the risks associated with high-volume Beyond Visual Line of Sight (BVLOS) UAV operations, concerning public safety. Safety in this context consists of both safety in the airspace where UAV operate and safety on the ground below these operations. In the context of airspace safety, the research examines potential hazards that could arise from UAVs interacting with other aircraft, whether they are manned or unmanned, and airspace users. On the ground, the safety risks involve the potential for UAVs to cause harm to people, property, and infrastructure should they malfunction, lose control, or otherwise deviate from their intended flight paths. By focusing on both airspace and ground safety, this research aims to provide a thorough analysis of the safety challenges posed by high-volume BVLOS UAV operations.

4.1.1 Risks during the operations

The degree of safety in an airspace is primarily assessed by the number of separation violations (Sunil et al., 2015). If a separation violation is not resolved, it can lead to a collision. In manned aircraft collisions can be prevented by the pilot, as the pilot is able to see an object and avoid it. This mechanism is called 'see and avoid'. As there is no pilot on board of an unmanned aircraft, there is no 'see and avoid' mechanism. Therefore, in unmanned aircraft this is replaced by detect and avoid. The most significant consequence of an unresolved conflict is a collision, which can occur either on the ground or in the air (Denney et al., 2018). Collisions in the air can occur between a UAV and other airspace users such as manned aircraft and other UAVs and a UAV and a bird (Dasu et al., 2018). Denney et al. (2019) emphasise on the risk of a non-cooperative aircraft entering the airspace that has been designated to UAV operations. Their research mentions the risk of manned aircraft heading into the U-space airspace, both aware and unaware of UAV operations. Similarly, Edwards et al. (2021) describe the risk of an aircraft without communication systems entering U-space airspace, such as skydivers and uncertified UAVs.

The risk of a separation violation increases when other airspace users enter the airspace designated to UAV operations. In case there are active UAV operations nearby, the risk of collision increases (Denney et al., 2019). The risk for an intrusion is larger when the boundaries of the designated airspace are less clear, as ambiguity in airspace boundaries can lead to unauthorised entries (Milerová et al., 2022). Collisions in the air can occur at various phases of UAV operations, including take-off, landing, and en-route. Simulations by Sunil et al. (2018) highlight that climbing and descending traffic causes the majority of separation conflicts, underscoring the importance of including all aircraft flight phases in a comprehensive safety analysis. An increase in the amount of traffic, leads to an increase in the likelihood of a collision (Mandapaka et al., 2023; Pérez-Castán et al., 2020).

If a collision occurs in the air, it can lead to an descend to the ground of the UAV. In that case, the UAV exits its designated airspace, or its operational volume. This causes a deviation from the authorised operation route. A descend of a UAV to the ground can be controlled or uncontrolled (Clothier et al., 2015). A controlled descend can be a safety control in case the UAV detects any possible error. For example, if a UAV has been involved in a collision and is damaged, a control action can be activated that leads the UAV to a safe spot to land (Plioutsias et al., 2017). An uncontrolled descend can happen after a collision if the UAV is severely damaged, and therefore the control of the UAV is lost (Bertrand et al., 2023; Plioutsias et al., 2017). The descend of the UAV could result in a collision on the ground between a UAV and a third party such as a person, vehicle or building (Pang et al., 2022). The consequences are ranging from negligible to severe injury, damage, or even fatality (Petritoli et al., 2018).

Instead of the UAV leaving its designated airspace as a consequence of a collision, the UAV could also exit its designated airspace, and therefore deviate from its authorised operation route, and cause the risk of a separation violation. The UAV then enters airspace that is not designated to unmanned air traffic. The airspace could be designated for manned air traffic or be free of air traffic because of the ground risks of that area. This can be the consequence of a proposed operation route of the UAV being falsely verified as feasible or authorised when they should have been denied (Habibi et al., 2023). As a result of this, the operation of the UAV can occur outside of the designated area. Additionally, the risk of collision increases if a UAV exits its designated airspace. This situation can arise due to a variety of factors, including a loss of control of the UAV or an authorised request that did not meet the necessary requirements. Such deviations from the assigned route are particularly hazardous because the characteristics of the actual conducted operation route are unknown, further increasing the risk of collision (Besada et al., 2019). In scenarios where the original route is no longer feasible, an alternative flight plan can be activated to ensure continued operation risks (Capitán et al., 2022).

A deviation from the authorised route increases the risk of insufficient terrain knowledge or even terrain unawareness (Clothier et al., 2015). A UAV could (unintentionally) be operated in the approximation of an area that increases the risk of the operation. This includes operations in an environment with an airport or heliport (Salma & Schmehl, 2023), in an area with a higher population density (D'Amato et al., 2023), within a small distance to restricted airspace such as military bases (Chowdhury & Lipsett, 2023), near an aerodrome (Denney et al., 2019), near bird migration routes during migration season (Dasu et al., 2018).

Environmental factors such as weather conditions also influence UAV operations (Alharbi et al., 2022). Adverse weather can affect both flight paths and final positioning (Stádník et al., 2022), necessitating robust systems to manage these variables. Adverse weather conditions pose significant risks to the safe operation of UAVs, potentially leading to collisions or crashes (Reiche et al., 2021). Inclement weather such as strong winds, heavy rain, fog, or snow can severely impact the flight capabilities of UAVs, compromising their stability, navigation, and overall performance. Weather conditions are also a risk during take-off and landing, as the motions of the UAV can be influenced by extreme weather conditions (Chowdhury & Lipsett, 2023). The impact of adverse weather conditions on high-density UAV operations is an important factor that requires real-time monitoring and dynamic response.

4.1.2 Risks of Supporting High-Volume UAV Operations

A crucial aspect of the support of UAV operations is establishing the ground infrastructure, as it plays a significant role in ensuring the safety and efficiency of UAV operations. Ground infrastructure supports UAV operations, ensuring robust communication networks, and providing safe and efficient facilities for take-off and landing. Firstly, the communication network infrastructure is fundamental to the success of UAV operations. This includes the deployment of reliable and resilient communication systems that facilitate data exchange between UAVs and control centres. These systems must be capable of handling high data volumes and maintaining uninterrupted connectivity. Effective communication networks ensure that UAVs can be monitored, controlled, and navigated safely, thereby reducing the risk of collisions and operational failures. The ground infrastructure for these networks includes the provision of supplies, such as masts, to secure connectivity to the network that UAVs utilise when operating within the system.

Secondly, the facilities for take-off and landing are integral to the ground infrastructure. This analysis will examine the current state and challenges of ground infrastructure. By understanding and improving the ground infrastructure, safety of high-volume UAV operations can be enhanced.

Communication Network

UAVs rely on communication networks to be connected to the air traffic system. The network should provide wide area coverage, ensuring UAVs can operate in diverse environments, including urban, rural, and remote areas (figure 5). Strong and consistent signal strength is required to maintain connectivity. The increasing volume of UAV operations increase the demand on these communication networks. High uptime of the communication network is essential to ensure UAVs remain connected at all times, which is important for maintaining control.

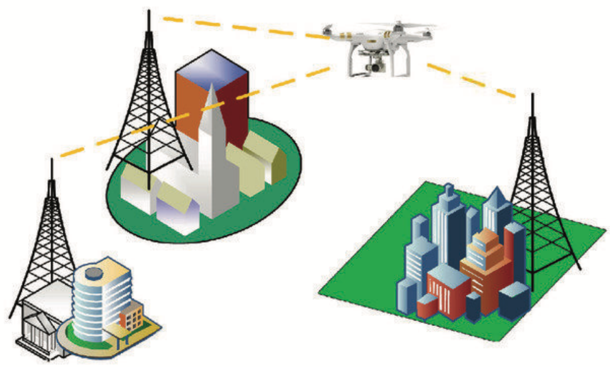

Figure 5: Connecting with Network (Zhao et al., 2019)

Besides the network being unavailable, the UAVs can be disconnected from a network due to connection loss, without the network being down. Causes of connection loss include the sensitivity of satellite links to environmental and terrain factors, and damage to antennas (Chowdhury & Lipsett, 2023; Clothier et al., 2015). Resilience to interference is vital for maintaining reliable communication. However, the research of Colpaert et al. (2022) states that cellular networks have low coverage of only eighty percent, which poses a risk to UAV operations. With proper site location and antenna orientation, this risk can be reduced. If the connection is lost, the UAV might not be able to complete the operation and could land in an inappropriate spot. Loss of connection might also lead to loss of control of the UAV, which can either continue flying or descend to the ground (Bertrand et al., 2023). Interview data suggests that UAVs typically descend in case of loss of connection. A descend to the ground can pose significant risks to both airspace users and people on the ground.

Supporting real-time communication is necessary to enable timely control and monitoring of UAVs. Efficient communication protocols that minimise delay in data transmission are necessary to maintain the responsiveness needed for collision avoidance systems and other time-sensitive operations. Communication latencies pose substantial risks. Increased latency in UAV response times compared to manned aviation can cause significant delays in communication (Edwards et al., 2021). These latencies, along with potential damages to antennas and communication outages, can result in delays in UAV manoeuvres. Delays in manoeuvres can in turn result in a mid-air-collision. Research of Xue (2019) concludes that risks caused by communication latencies increase as the density of airspace increases. Therefore, low latency of the communication network is an important requirement for high-volume UAV operations. This is because cellular networks are sensitive to environmental factors and terrain, leading to risks of interrupted communication caused by unexpected interference, such as obstacles in the communication pathway (Edwards et al., 2021). Therefore, without an established terminal distribution network, large-scale free operations cannot meet the safety and efficiency requirements of high-density airspace traffic, thereby compromising the safety of the UAV system network (Zhang et al., 2023).

Moreover, a network is used by UAVs to utilise navigation systems (Dasu et al., 2018). Unmanned air traffic relies heavily on advanced technologies to support its navigation services, as it is autonomous. These technologies enable the seamless integration of UAVs into the airspace, ensuring that they can be monitored and managed effectively. Ensuring accurate and reliable navigation for a high number of UAVs, particularly in complex urban environments, is critical to avoid collisions and maintain orderly traffic flow. The high volumes of UAV operations generate a high volume of data, which can exceed the capacity of current systems (Moore et al., 2020). UAVs commonly use GPS (Global Positioning System) for navigation. GPS receivers are used to determine the location, altitude, and velocity of UAVs, allowing them to navigate along predetermined flight paths or follow waypoints, also known as geofencing. Geofencing is widely used practice for UAV flights, involving the creation of virtual boundaries within which the UAV must operate (Capitán et al., 2022; Dasu et al., 2018). UAVs using GPS combined with autopilot software, can interact with a geofence and avoid restricted areas (Lykou et al., 2020). Geofencing can also be used to guide the UAVs through the authorised operation route.

Regular maintenance of the ground infrastructure, including antennae, will reduce the risk of damage to antennae (Edwards et al., 2021). Furthermore, the risk of loss of connection can be decreased by health-monitoring the systems. This also increases the probability of a recovery in case there is a loss of connection.

In conclusion, a communication network for UAVs must be highly reliable, secure, and capable of supporting real-time, low-latency communication. It must offer extensive coverage, be resilient to interference, and ensure seamless interoperability of navigation systems.

Take-Off and Landing Sites

The support of UAV operations also consists of take-off and landing sites. The UAV infrastructure must achieve an acceptable level of safety, which includes safe take-off and landing. Whilst take-off and landing sites are essential for some UAV operations, they may not be necessary for others. UAVs used for parcel delivery require a proper landing spot to deliver the parcel (Seo et al., 2016). Such sites could range from open spaces with level surfaces (figure 6) to fixed vertiports (Chowdhury & Lipsett, 2023).

Figure 6: Level Surface Take-Off and Landing Site (Naval Technology, 2022)

Guidelines regarding vertiports have been developed by the EASA. Figure 7 shows the possible design of a vertiport. These guidelines, outlined in the Prototype Technical Design Specifications for, offer guidance to urban planners, local decision-makers, and industry stakeholders, ensuring the safe design of vertiports that support the operations of UAVs and other vertical take-off and landing aircraft (EASA, 2022). The integration of vertiports as take-off and landing hubs for UAVs necessitates the adherence to specific requirements to ensure safe and efficient operations. The guidelines of the EASA include that there should be at least two landing options available to accommodate UAVs in various operational scenarios. However, according to Mullan (2020) there are gaps in the regulations regarding the safety and efficiency of the guidelines. The gaps include the absence of protocols for different risks such as fires and the absence of charging facilities for the UAVs. Furthermore, the vertiports guidelines do not address autonomous vehicles. The research of Jang et al. (2017) mention that additional space can be reserved around take-off and landing sites, to enhance safety.

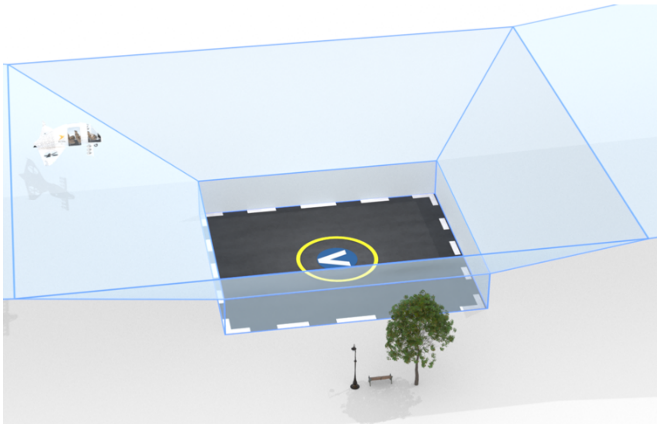

Figure 7: Vertiports as Proposed by EASA (EASA, 2022)

Additionally, securing take-off and landing sites against physical capture and damage of UAVs is an important aspect of risk mitigation. Seo et al. (2016) recommend the implementation of physical barriers to prevent unauthorised access to UAVs. Additionally, the availability of fast and accurate weather information enhances safe take-off and landing. Accurate weather forecasts are essential for safe UAV operations, but inaccuracies in weather conditions can pose significant risks (Stádník et al., 2022). In abnormal situations, such as equipment failure or adverse weather conditions, it should be ensured that the UAV can continue its flight and land safely at a designated vertiport (EASA, 2023). This capability is crucial to prevent any harm to passengers and third parties on the ground. Therefore, obtaining reliable weather information can contribute to risk mitigation. A weather information service could be provided in the USSP services at the vertiports by including weather stations at the vertiports.

In conclusion, the integration of take-off and landing sites to support UAV operations introduce several risks. To mitigate these risks, the establishment of vertiports is suggested. The EASA has provided guidelines for the vertiports; however, these guidelines do not address all risks.

4.2 High-Volume Operations in Current Law

The increasing integration of UAVs into civil airspace necessitates robust frameworks to manage and mitigate associated risks, particularly as the volume of UAV operations increases. This section describes the risk mitigation that is currently incorporated in the risk assessments and the concept of U-space airspace. Subsequently, the limitations regarding the suitability of these risk assessments for assessing the risks in high-volume UAV operations and addressing risks in the concept of U-space will be determined.

4.2.1 High-Volume in Risk Assessments

In the previous chapter, four risk assessments were briefly described. The suitability of the risks assessments will be discussed in the light of assessing risks of high-volume UAV operations. Table 3 provides an overview of the evaluation of the risk assessments.

Table 3: Characteristics of Risk Assessments

	Characteristics of UAV operation	**Long-term operating permit**	**Suitable for**	**Ground risk**	**High-volume**
STS	Pre-determined	No	VLOS operations BVLOS operations within 2 kilometres from pilot	Yes	No
PDRA	Pre-determined	No	Agriculture Surveillance Short range cargo delivery	Yes	No
SORA	Unique description	Yes	Operations as described in the SORA	Yes	No
LUC	Pre-determined	Yes	Operations as described in the LUC	Yes	No

In case a UAV operator wishes to conduct a UAV operation in the 'Specific' category, a risk assessment should be conducted. The UAV operator can make use of risk assessments that are already conducted and provided by the competent authority. First, the requirements of the standard scenarios (STS) will be checked. If the descriptions as provided in the STS do not match the operation to be conducted, the pre-defined risk assessments (PDRA) will be compared with the operation. If the PDRA does not match the characteristics of the operation, a specific operation risk assessment is to be conducted by the operator. A flow-chart of this process is provided in figure 8.

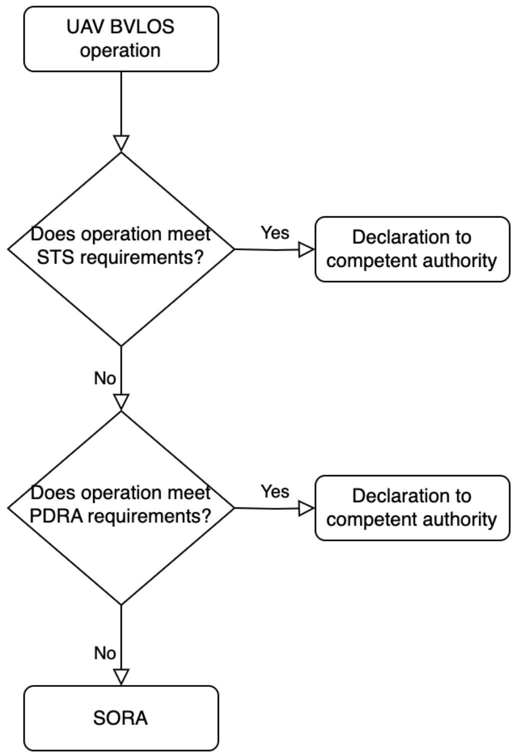

Figure 6: Flow-Chart of Risk Assessments (Author's Image)

The STS do not explicitly consider high-volume UAV operations. Instead, it focuses on ensuring safety through controlled environments and predefined operational parameters for individual or small numbers of UAVs. Pre-determined risk assessments are designed to cover a range of UAV operations, including those that might be conducted frequently or under specific conditions. PDRAs typically focus on individual or small-scale UAV operations and do not address the complexities associated with managing multiple UAVs in high-density airspace. The Light UAV Operator Certificate is designed to ensure that operators have robust safety management systems, comprehensive training programs, and effective compliance monitoring in place. However, the certification itself does not provide the detailed, traffic management and coordination capabilities required for managing high-density UAV operations.

The SORA gives freedom to characterise the UAV operations. A UAV operator can apply for a long-term operating permit for a certain area. The SORA addresses ground risk and allows for different risk mitigation measures to reduce this ground risk. Ground risk is reduced by integrating mitigation measures aimed at minimising the potential harm to individuals on the ground. Based on the identified hazards of the UAV operations, mitigation measures can be selected. In research, numerous mitigating strategies to reduce ground risk can be included in a SORA for UAV operations.

Part of the SORA is determining the characteristics of the ground area beneath the airspace where the operations are going to take place. The characteristics of the ground area include, among other things, the density of the population, the presence of roads, highways, and train tracks. Terrain awareness as included by SORA contributes to safety by allowing for improved site selection. Terrain awareness also allows for keeping a safe distance to restricted airspace such as military bases (Chowdhury & Lipsett, 2023). This is an example of strategic terrain avoidance to increase the safety of UAV operations (Clothier et al., 2015). Furthermore, the designated airspace can be located close to an urban environment, or in a more rural environment to increase the level of safety to an acceptable level (Salma & Schmehl, 2023).

Additionally, the adjacent area should be considered as proposed by Habibi et al. (2023). This determines the imposed risk of a deviation of the UAV from the flight geography. Certified maps can be used to map these areas and establish ground risk buffers to prevent impacts with people in the event of an uncontrolled descent after a loss of control of the UAV (Bertrand et al., 2023). The width of the buffer is determined based on the acceptable of the level of safety (Salma & Schmehl, 2023. The research of Bertrand et al. (2023) also describe that an underestimation may lead to excessive risks and an overestimation may impose too restrictive constraints on the mission. Hence, the width of the buffer should be design cautiously. The ground risk buffer can be arranged in several ways, for example by notifying people that there is a corridor located near them, or by ensuring a controlled ground area, where no third parties are present. A risk that comes along with the validation procedures of maps is the use of incorrect maps, an unsuitable procedure to check the maps or not conducting the procedure the right way.

In case of an uncontrolled descent, deploying a parachute can serve as an effective mitigation measure to significantly reduce the risk of damage and injury. When a UAV experiences a failure, due to connection loss or collision, the automatic deployment of a parachute can slow its descent, minimising the impact force upon landing. This mitigation measure is particularly valuable in densely populated areas or regions with high ground risk, as it helps to protect both people and property on the ground. Nevertheless, the use of parachutes is not without its challenges. The deployment must be reliable under various conditions, and the parachute itself must be robust enough to handle the weight and speed of the descending UAV. Moreover, the integration of parachute systems adds complexity to UAV design and maintenance. Despite these challenges, the benefits of incorporating parachutes as a safety feature make them a vital component in mitigating the risks associated with uncontrolled descents, enhancing the overall safety framework for UAV operations.

SORA also considers air risk and allows for the implementation of different risk mitigation measures. However, these measures are aimed at minimising the risk of collision between the UAV and manned aircraft. SORA fails to assess to consider the high-density of air traffic, caused by the high-volume of UAV operations (Castro & Garcia, 2021). Therefore, it does not take into account the risk of collision between UAVs. The SORA approach is focused on single-mission risk assessment (Barrado et al., 2020). Hence, the assessment is not suitable for high-volume UAV operations.

SORA can be used to evaluate potential risks and propose mitigation actions before starting to fly. However, while UAS are flying, unexpected events or threats might still occur, leading to dangerous situations (Capitan et al., 2019). In conclusion, the current risk assessments are not suitable to address risks regarding high-volume UAV operations.

4.2.2 High-Volumes in U-space Airspace

U-space airspace aims at integrating high-volume UAV operations in civil airspace. The U-space services have been briefly introduced in the previous chapter. In this section a description of the services will be provided and how the U-space services enable high-volume operations.

The Network Identification Service provides essential data used by all other services to ensure accurate and up-to-date information about the UAV, the geographical position, altitude, route. The network identification service provides relevant and timely information about geographical zones necessary for the geo-awareness service. The geo-awareness service provides the UAV with geographical zones that are relevant to U-space airspace. This service makes use of geofence provided by the communication network.

The Network Identification Service also provides relevant and timely information about other traffic enabling the traffic information service. Manned aircraft is usually equipped with a transponder that provides the aircraft's identification, altitude and position. Automatic Dependent Surveillance–Broadcast (ADS-B) is a surveillance technology used in aviation to enhance situational awareness, safety, and air traffic management. ADS-B is used to detect the aircraft to be avoided (Lin & Saripalli, 2015). It allows aircraft to broadcast their positional information to other aircraft and ground stations in real-time. In most parts in Europe, ADS-B is mandatory. With ADS-B, it is possible for aircraft to receive ADS-B signals from other aircraft. UAVs are provided with both unmanned and manned traffic information as part of the traffic information service, this enhances safety. However, as previously mentioned, not all airspace users are provided with this service. Hence, detect-and-avoid systems (DAA) still need to mitigate the risk of collision with aircraft without ADS-B or other airspace users such as birds. DAA use sensors and algorithms to detect potential obstacles and take evasive actions automatically. The DAA aims to enhance the UAVs ability to autonomously detect and avoid other aircraft, providing an additional layer of safety (Edwards et al., 2021). However, existing DAA systems have drawbacks when applied to high-density UAS traffic (Karch et al., 2024). The research of Mandapaka et al. (2023) mentions that collision avoidance systems, such as DAA, are not capable of handling the high volume of UAV operations. It also mentions that DAA systems use a high volume of data which cannot be processed at the speed of UAVs. Therefore, other systems should be put into place. In the research, Vehicle-to-Vehicle communication systems are proposed as a suitable solution for high-volume UAV operations. Through this system, UAV can communicate their position, travel direction and velocity to nearby UAVs.

UAV Flight Authorisation service sets the terms and conditions for each flight, ensuring that UAV operations are conducted safely and in compliance with all relevant regulations. This also includes the compliance of alternative routes, ensuring backup plans are in place (Besada et al., 2019; Capitán et al., 2022). Information from the network identification service and geo-awareness service are used to ensure that both the UAV and its operator are properly registered and authorised to conduct operations. This helps in preventing unauthorised UAVs from accessing U-space airspace. Besides, the information is used to validate the planned route and ensure that it does not conflict with other authorised flights or restricted areas. Thus, it considers traffic density. Lastly, it helps to maintain awareness of the UAVs current location and flight status, which is important for dynamic airspace management.

Weather Information Services supports UAV Flight Authorisation Services by providing weather data that influences flight safety and authorisation decisions, both during take-off and landing and the en-route operation. The USSP should be provided with weather information by a 'trusted source'. The EASA is working on the guidelines for a 'trusted source' in this context.

Conformance Monitoring Services continuously checks the UAV adherence to the authorised flight path. Real-time data regarding the geographical position, altitude and route information from the Network Identification Service is used to detect and report deviations of the path, ensuring compliance and enhancing safety. The service ensures that UAVs operate within the parameters set by their flight authorisations, maintaining orderly and predictable traffic flow in high-density airspace. To contain UAVs within flight regions, a containment system using waypoints is introduced, ensuring UAVs follow prescribed routes. If a deviation from the authorised path occurs, Conformance Monitoring Services uses the pre-approved backup routes established during the flight authorisation process to guide the UAV safely. Misalignments in location and time, can disrupt scheduled airspace operations, creating congestion and elevating the potential for accidents. These risks underscore the necessity for rigorous monitoring and real-time adjustments through Conformance Monitoring Services, which rely on accurate data from Network Identification and Geo-Awareness Services to ensure UAVs adhere to their authorised flight paths and schedules, thereby maintaining the overall safety and efficiency of high-density airspace.

The exchange of data generated by the U-space services requires a reliable and robust communication between UAVs, USSPs, CIS and air traffic management is important. The communication network utilised by unmanned air traffic should be able to process all this data.

4.3 Limitations of Current Frameworks

The SORA is used to identify risks and suitable mitigation measures. To illustrate the limitations of SORA the bow-tie model will be used (figure 9). An undesired event is the centre of the bowtie. The left side of the bowtie illustrates the contributing threats of the undesirable event (Lee, Grosh, Tillman & Lie, 1985). Conversely, the right side of the bowtie illustrates the potential consequences that may arise after the undesired event occurs (Andrews & Dunnett, 2000). Hence, the left side of the bowtie contains measures to prevent the undesired event from happening. The right side of the bowtie contains recovery measures. These measures are focused on reducing the impact of the undesired event.

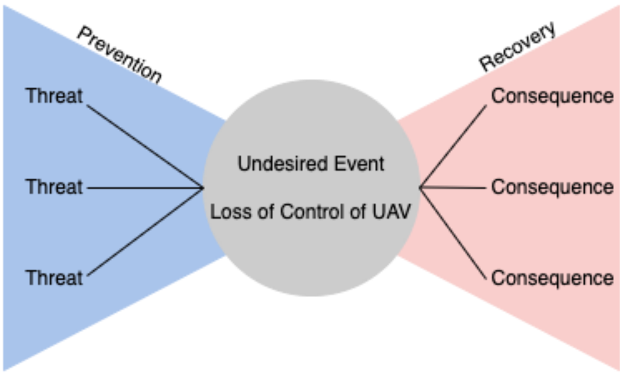

Figure 7: Bow-Tie Model (Author's Image)

In the context of UAV operations, a common undesired event is loss of control of the UAV. This has been discussed in the beginning of this chapter. There are several scenarios that lead to a loss of control of the UAV, and several possible scenarios that can occur after a loss of control. The risk for loss of control can be controlled or mitigated. Controlling the risk aims at preventing the loss of control. Mitigating the risk of loss and control aims at reducing the impact of the loss of control. The measures as identified in the SORA are primarily focused on mitigating the risks. Hence, they are focused on controlling the consequences of a loss of control of the UAV. The impact of ground risk is reduced by reducing the number of people at risk, reducing the impact and establishing an emergency response plan in case of the occurrence of the risk. The air risk is focused on procedures that can be activated after an undesired event occurs.

The integration of high-volume BVLOS UAV operations into civil airspace presents significant challenges and risks that must be carefully managed to ensure safety and efficiency. The SORA is designed to evaluate operational risks, including both ground and air risks, and propose mitigation measures to ensure the safety of UAV operations. It is particularly effective in addressing ground risks through the establishment of ground risk buffers and implementing robust risk mitigation strategies. While the SORA provides a robust framework for assessing and mitigating risks associated with UAV operations, it does not incorporate the concept of U-space airspace. Instead, SORA focuses primarily on risk assessment for individual UAV operations and does not integrate the elements required for managing high-density UAV operations. Hence, SORA cannot include the U-space services as risk mitigations or consider high volumes of UAVs operating in the airspace at the same time (Volf et al., 2024). To support this statement, a SORA has been conducted. In this SORA, it has been attempted to include U-space and the U-space services. Step 1 to step 3 can be performed without many difficulties. These steps include the determination of the ground risk of the UAV operations. Nevertheless, in step 4 it becomes evident that the SORA is not able to incorporate U-space airspace, as step 4 to 10 include the determination of air risk. As a result, step 4 to step 10 cannot be performed in a sufficient manner. An overview of the conducted SORA can be found in appendix D. This drawback poses a significant challenge to the determination of air risk classifications as proposed by SORA.

U-space is a set of services and procedures developed to support high-volume and efficient UAV operations in European airspace. While U-space provides essential services and procedures for the integration of UAVs into airspace, it does not function as a risk assessment tool. It remains to be tested in the context of further U-space service interactions involving high-density traffic operations (Büddefeld et al., 2023). To determine whether U-space airspace can handle high-volume UAV operations, it is necessary to conduct a detailed risk assessment. This ensures that high-density operations can be safely managed within the U-space framework. High-volume UAV operations in the concept of U-space still impose risks regarding loss of control of the operation, connectivity risk and risk during the take-off and landing phases.

By designating certain airspace as U-space airspace, the overall air risk classification within that designated area may be effectively lowered due to the presence of advanced technological solutions and regulatory measures aimed at mitigating risks. These measures include U-space services, among others. As a result, the traditional criteria used by SORA to determine air risk classes may no longer accurately reflect the actual level of risk within U-space airspace. This discrepancy highlights the need for greater alignment and integration between a risk assessment method and U-space frameworks to ensure a comprehensive and harmonised approach to risk assessment and management in UAV operations. As a result of this, the risks of a high volume of UAV operations cannot be mitigated to an acceptable level.

To address these risks an additional layer of safety should be implemented. Vetyia et al. (2022) investigate the how safety can be improved by different airspace designs. Conflicts between UAVs can be prevented by implementing different airspace designs. The following section discusses how different designs for the infrastructure of airspace enhance safety levels by reducing the probability of certain risks.

Chapter 5

Design Concepts

In the previous chapter, it is concluded that the current regulatory frameworks are not suitable to address all risks regarding public safety of high-volume UAV operations. The risk assessments and the concept of U-space did not address the risk of loss of control and collision of the UAV with another object. Therefore, an additional safety layer should be added to integrate high-volume UAV operations in airspace. Moreover, the facilities to support the high volumes of UAV operations were not included in the concept of U-space, such as the communication network and take-off and landing sites. This chapter answers sub question 4: '*How can the risks high-volume UAV operations regarding public safety be reduced?*'

The integration of UAV operations in a high volume necessitates the development of robust infrastructure to ensure safe and efficient integration of U-space airspace. This section discusses different design concepts for an infrastructure to enable high volumes of UAV operations. This infrastructure includes both a structure for the infrastructure in the air, and the infrastructure of the ground to support the UAV operations. First, the design concepts for the arrangement for air infrastructure will be discussed, followed by the description of the possibilities to establish the ground infrastructure accordingly.

5.1 Infrastructure in the Air

The infrastructure in the air consists of both the arrangement of the structure of airspace, as well as the strategy to determine flight plans. First, the different arrangement of U-space airspace will be provided. These will be elaborated by introducing different strategies to determine the routes to be conducted by UAVs.

5.1.1 Arranging Civil Airspace

The U-space concept that is being developed by the EASA, determines the guidelines for each Member State. The guidelines are therefore the minimum requirements for the arrangement of civil airspace. Hence, the simplest design concept for the arrangement of civil airspace is designating a U-space airspace. Sunil et al. (2017) propose four different design concepts for arranging airspace, these are visualised in the figure below (figure 10).

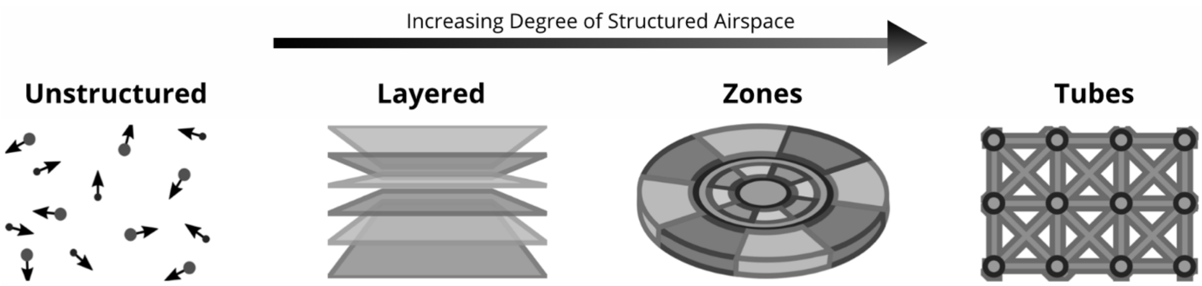

Figure 8: Design Concepts for Structuring U-space Airspace (Sunil et al., 2017)

The first design concept has the lowest degree of structured airspace, the fourth concept has the highest degree of structure of airspace. The four design concepts for structuring airspace will be described below. The research of Shrestha et al. (2021) uses similar concepts, nevertheless, their research is based on an urban area, and therefore has a high population density. The figures retrieved from their research do illustrate this urban area (figure 11, 12 and 16). This is not necessarily the setting of this research, as it is exploring the risks of different characteristics of UAV operations, including the risks of the ground area below the operations. The airspace structure of these figures should be taken into account.

5.1.1.1 Unstructured

The first design concept is an unstructured design, where operations are determined by the physical constraints (Sunil et al., 2015). The foundation for the arrangement of civil airspace is the U-space airspace, as introduced by EASA. Here, a U-space would be designated where U-space services are provided, however, the airspace would have no structure. Unstructured airspace refers to airspace designs that offer operators complete freedom in path planning in that U-space airspace (Sunil et al, 2018). In this concept, it is of important to separate UAVs from other UAVs, aircraft and objects (Alharbi et al., 2022; Clothier et al., 2015; Edwards et al., 2021).

Figure 9: Unstructured Airspace (Shrestha et al., 2021)

5.1.1.2 Layers

The second design concept implements layers in U-space airspace. Based on the travel direction of the operations, the UAVs are assigned to a certain layer in airspace. Therefore, the UAVs in a layer have the same travel direction. Similarly, Salma & Schmehl (2023) describe a concept where UAVs are separated by assigning different altitudes to UAVs based on their travel direction. This is similar to the one-way streets concept as described by Doole et al. (2021). Results of different research shows that vertical segmentation of the airspace leads to fewer separation conflicts and losses of minimum separation distance between UAVs (Badea et al., 2021). This way collisions are prevented as the operational paths of the UAVs do not intersect. Figure 12 visualised this concept. The different colours in the figure represent different travel directions of the UAVs.

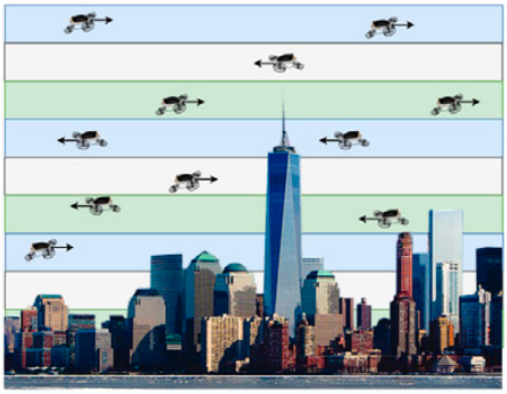

Figure 10: Layered Airspace (Shrestha et al., 2021)

In order to be able to reach different destinations it is important to include all possible travel directions in the layers. Sunil et al. (2017) do this by implementing layers in airspace for every travel direction in an angle of 45 degrees (figure 13), resulting in eight layers in airspace. A UAV must travel through layers to reach the layer with the suitable travel direction, except when the desired travel direction is the first layer. When the UAV has reached its destination, it has to descend back through these layers.

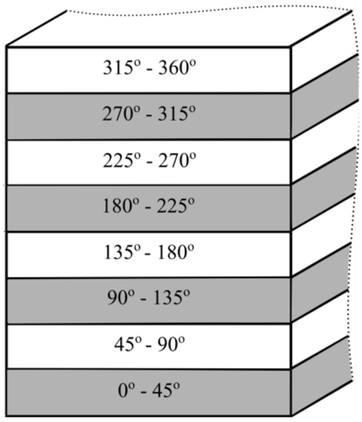

Figure 11: Layers in Airspace (Sunil et al., 2017)

Figure 12: Separation of Manned Aircraft (Prabhakaran, 2023)

This design concept structures airspace in a similar way as the airspace utilised by manned aviation. To prevent collisions, aircraft in manned aviation are typically kept at different altitudes. For instance, aircraft flying eastward may be assigned odd thousand feet (e.g., 31.000 feet, 33.000 feet), while those flying westward may be assigned even thousand feet (e.g., 32.000 feet, 34. 000 feet). Hence, for every 1000 feet increase in altitude, the travel direction of aircraft changes. Figure 14 illustrates how manned aircraft is vertically structured.

5.1.1.3 Zones

The third concept as proposed in the paper, also makes use of separation of UAVs based on travel direction. The travel directions are towards or away from a central point. This separation is therefore not based on vertical segmentation but on horizontal segmentation. A visualisation of this concept is included in figure 15. As can be seen in the figure, there are lines and rings in the model. The lines allow for the UAVs to travel towards or away from the central point. The lines are alternating in travel direction. The rings allow for UAVs to change directions. UAVs can travel between two points by using a combination of the lines and rings. The zones arrangement can be expanded by including more central points. The lines and rings in this concept are similar to the corridor concept that is described by Bijjahalli et al. (2022). The corridor concept is also used in manned aviation, where aircraft fly though these designated corridors. The research of Shrestha et al. (2020) does not include a visualisation of this design concept.

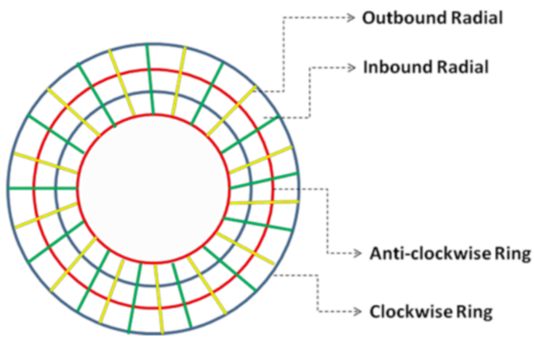

Figure 13: Zones Concept (Sunil et al., 2015)

5.1.1.4 Tubes

In its most structured form, the final concept introduces three-dimensional tubes that create a fixed route structure in the air (figure 16). This approach also establishes corridors in U-space airspace where UAV operations can be conducted. This concept includes both horizontal and vertical segmentation, aiming to increase predictability of traffic flows by means of pre-planned conflict free routes. New flights are only allowed to select routes that are not predicted to conflict with existing aircraft in the network. Thus, tubes at the same horizontal level never intersect (figure 17). UAVs in the same horizontal layer have the same velocity, ensuring separation. The higher the layer, the higher the prescribed speed of UAV operations conducted in that layer.

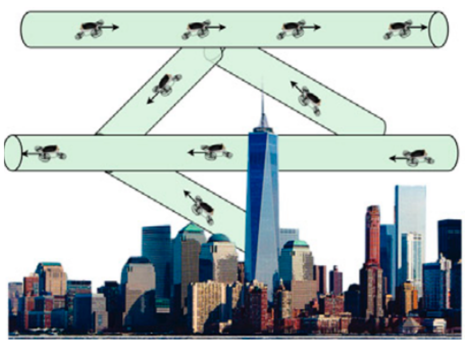
Figure 16: Tubes Concept in Airspace (Shrestha et al., 2021)

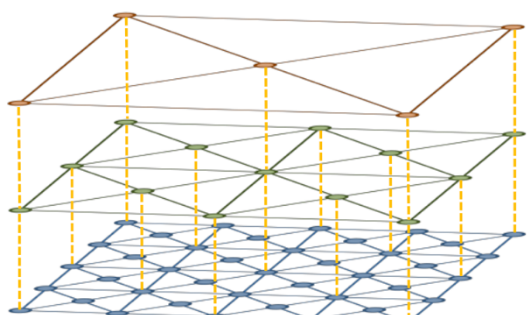
Figure 17: Tubes Concept in Airspace (Sunil et al., 2015)

5.1.2 Determining Flight Plans

Flight plans are evaluated based on the risk they impose both on the ground and in the air. In this section, four different alternatives for the determination of flight plans will be discussed. The Dutch Knowledge Institute for Mobility conducted research for the Ministry of Infrastructure and Climate where they distinguish three different variants for parcel delivery with UAVs (Kennisinstituut voor Mobiliteit, 2017). These include parcel delivery between variable locations, parcel delivery from a fixed location to a variable location and delivery between two fixed locations. In addition to the three alternatives, a fourth alternative will be introduced, where there is a fixed route with several take-off and landing sites. The arrangements for U-space airspace, as proposed in the previous section are applicable to different strategies for the determination of flight plans. Delivery between variable locations or to a variable destination allow for an unstructured and layered arrangement of airspace. Deliveries between two or more fixed locations allow for the zones and tube arrangement of U-space airspace.

For the different design concepts, there are different rules and legislation, spacial implications and risks. These will be analysed in section 5.3.

5.1.2.1 Dynamic Flight Routes

In the first two alternatives, parcels are delivered to variable locations. In case of the first alternative, the beginning point also varies. Whereas, in the second alternative the beginning point of the operation is fixed and only the destination varies. Path planning techniques commonly used for UAV applications are based on unstructured configurations (Causa & Fasano, 2023). This freedom of path planning can be implemented in an unstructured as well as a layered U-space airspace as described by Sunil et al. (2018).

In an unstructured airspace, UAVs are allowed to ascend and descend everywhere, resulting in a strong variation in operations. This allows the operations to have variable landing spots. Therefore, designation of vertiports is not possible for this alternative. UAVs are permitted to use the most direct path between origin and destination, as well as optimum flight altitudes and velocities. As a result of this, the characteristics of operations vary strongly. This often results in the need to request for authorisation for the operation, and a risk assessment might need to be conducted to ensure that each flight is operated under an acceptable level of safety. Currently, UAV flights in the Netherlands are operated between variable locations.

Delivery between two variable locations also allows for layered arrangement of airspace. Here again, the UAVs are allowed to take-off and land anywhere, making it impossible to designate fixed landing points. The UAVs have to ascend and descend to the right layer in airspace according to their travel direction. This results in an increase in duration of the operation, as ascending and descending is added to the operation, but still allows for the most direct path to the location.

Operations with a fixed beginning point and varying ending points require for the UAVs to fly back to the fixed beginning point after delivering the parcel. As the beginning point is fixed, this location can be prepared for the take-off and landing of UAVs. This alternative could be used for delivering emergency goods. An example is the delivery of a defibrillator in case of an emergency. The defibrillator will be located at a fixed point and will be delivered to the location of the emergency. Another application is the delivery of parcels from a warehouse or distribution centre to people's homes or another location where they wish to receive the parcel.

5.1.2.2 Fixed Flight Routes

The third and fourth alternatives involve predefined pathways within U-space airspace; hence, the requested flights must adhere to these designated paths. The third alternative is a fixed route between two fixed points, whereas the last alternative is a fixed route between multiple fixed locations. The corridors that are designated in both the zones as the tubes arrangement, allow for fixed flight routes. The zones arrangement allows for UAVs to operate between two or more fixed points. The tubes arrangement structures airspace with two or more fixed points for UAVs to take-off and land, the UAV then follows the designated corridors in airspace to reach its destination.

By implementing the corridors of the zones and tubes arrangement between fixed locations, the characteristics of the flight operations will be the same every time. This eliminates the necessity to conduct a risk assessment for each operation. Hence, a long-term operating permit could be granted for the operations in these corridors. A fixed take-off and landing point can be designated and arranged accordingly. Current examples of applications for this alternative are delivery between two hospitals in Switzerland (Keaten & O'brien, 2017) or from the inland to the Wadden Islands in the Netherlands (Gutker, 2022).

By increasing the number of take-off and landing locations of the zones and tubes concepts, several take-off and landing locations can be designated and arranged. This allows the route to be entered and left at several points during the route. An example of this application is a route between windmills in a wind farm. During the maintenance of a wind farm, a vessel leaves the harbour with several construction workers and tools on board. The vessel travels to all windmills and drops the workers off with the tools and supplies they need. Often, after the vessel has left the windmill, a certain tool is left on the vessel, or additional tools and supplies may be needed on the windmill. The vessel then has to travel back to the wind mill to deliver the tools, this is time consuming and inefficient. Ampelmann is investigating the opportunities of UAVs to increase efficiency and reducing down-time during operations. By providing a corridor between the windmills, tools can be delivered during the operation.

The implementation of corridors can be compared with the road and train track networks. The roads, highways and train tracks are the corridors. Only in airspace, the corridors are three-dimensional, instead of the two-dimensional layout of roads and train tracks. The fixed take-off and landing points can be compared with the entries and exits of the highways, or the stations along the train tracks.

5.3 Risks in the Design Concepts

Unstructured or layered airspace with dynamic routes offers operators freedom in path planning but poses higher collision risks at higher traffic densities. Therefore, this does to optimise safety levels. In the event of a possible conflict between two UAVs, the conflict can be resolved by altering the direction, speed, and altitude of the UAV (Sunil et al., 2015). Operations between a fixed and variable point require the UAV to fly back to the beginning point after conducting the operation. This requires an additional operation for the UAV to fly back to the beginning point.

Operation requests for varying routes and destinations, might require a risk assessment to determine the suitability of the proposed destination and the safety of the proposed flight. To ensure that each flight is operated at an acceptable level of safety, a flight plan assessment should consider several factors. These include providing a route that is navigable by the vehicle, respecting its kinematic restrictions and reducing ground risk by adjusting the route. As the operations vary more, this increases the risk of insufficient terrain knowledge or even terrain unawareness (Clothier et al., 2015). A UAV operation could be operated in the approximation of an area that increases the risk of the operation. This is an example of strategic terrain avoidance to increase the safety of UAV operations as discussed by Clothier et al. (2015).

Furthermore, dynamic routes in unstructured or layered airspace require more coordination efforts from the CIS and USSP to manage the varying operations. There is an increase of interface management and communication. Free-planned routes cannot meet the safety and efficiency requirements of urban airspace mobility. To address this issue, a public air route network for low-altitude logistics UAVs needs to be established (Zhang et al., 2023).

The research by Doole et al. (2021) indicates that an effective way to structure UAV traffic is to have vertically segmented altitude layers with respect to travel direction. The research concludes that a one-way concept has a lower number of conflicts than the two-way concept. The research of Sunil et al. (2017) has demonstrated that vertically segmenting the airspace to separate cruising traffic with respect to travel directions at different altitudes leads to high levels of safety. Segmentation of traffic occurs in the design concepts layers, zones and tubes. By structuring UAV traffic, the risk of a conflict is reduced. However, conflict resolution based on altitude alteration may create new conflicts with traffic in adjacent layers. Hence, conflict resolutions are limited to altering the direction and speed of the UAV.

U-space airspace structure is used to reduce either the number of conflicts and possibly improve conflict geometries, which is the aim of the zones concepts, or to provide full protection by preventing conflicts altogether, the aim of the tubes concept (Sunil et al., 2015).

As unmanned air traffic grows, there will be a growing need to avoid UAV collisions. This can be done by introducing physical constraints to flight in the form of corridors (Besada et al., 2019). The study of Hoekstra et al. (2016) revealed that segmentation of traffic contributes to lowering the conflict probability and, thus, an increase in airspace safety. In the design concepts zones and tubes, path planning is introduced by designating corridors. Predefined corridors guide UAV operations, ensuring that flights adhere to designated paths. This design minimises risks by harmonising UAV operations with other airspace users and optimising airspace management. Malekpour (2021) emphasises the need for designated flight corridors, a concept included in zones and tubes, to ensure safety., To enhance safety, the corridors can be located close to a rural environment rather than an urban environment (Salma & Schmehl, 2023). The designation of corridors allows evaluating both the adjacent area on the ground and in the air (Habibi et al., 2023). This determines the imposed risk of a deviation of the UAV from the flight geography. Evaluating both ground and air areas for corridor selection based on safety is critical (Clothier et al., 2018). As the zones and tubes concepts involve predefined pathways within U-space airspace, the requested flights must adhere to these designated paths. Hence, the structured approach ensures that all flights are conducted within established safety parameters, minimising risks and optimising airspace management. The zones and tubes concepts simplify the management of routes and therefore enhance safety. By strictly following these predefined paths, UAV operations can be harmonised with other airspace users, ensuring a safe and efficient integration of unmanned flights into the broader aviation ecosystem.

5.4 Ground Infrastructure in Design Concepts

In this section, the risks associated with the ground infrastructure of high-volume UAV operations across various design concepts are analysed. Each design concept presents unique challenges and risks that must be addressed to ensure operational safety and reliability. The risks in dynamic flight operations within unstructured or layered airspace associated with the ground infrastructure will be discussed, as well as the risks for the fixed corridors as proposed in the zones and tube concepts. Firstly, the risks regarding the communication network will be discussed, followed by the risks associated with the take-off and landing sites.

5.4.1 Communication Network

To establish a robust communication network for UAV operations, the ground infrastructure must incorporate several components to ensure reliable and high-speed communication necessary for safe and efficient UAV management.

Cellular networks are an ideal candidate as they provide wide coverage and remove the need for the USSP to deploy expensive dedicated infrastructure (Colpaert et al., 2022). Academic researchers and people in the field envision the 5G-network for UAV connectivity, as it provides robust connectivity, high data rates, low latency, essential for real-time communication between UAVs and ground control systems (Dasu et al., 2018). Moreover, it supports precise positioning and provides much more accurate location estimation than existing networks. The 5G-network holds the potential to enable safe control and information retrieval from UAVs (Besada et al., 2019). Furthermore, a reliable and high-volume throughput ensures that a high number of UAVs can exchange information to collaborate and cooperate under different mission allocations (Wang et al., 2021). The ability of 5G to handle a high volume of simultaneous connections is vital for the scalability of UAV operations. The infrastructure includes traditional cell towers and a denser network of small cells, particularly important for 5G's high-speed, low-latency requirements. 5G-networks support positioning and provide more precise and accurate location estimation than existing networks, improving navigation of UAVs (Dasu et al., 2018).

The network must exhibit high reliability and availability. This can be achieved through redundancy, ensuring there are multiple pathways to prevent single points of failure, thereby guaranteeing continuous operation even if one part of the network fails. In terms of connectivity risks, connecting UAVs to different providers' networks improves coverage probability to 98%, compared to 80% with a single network (Colpaert et al., 2022). Network diversity increases the coverage of the network. With proper site location and antenna orientation, coverage can be further enhanced. Additionally, research indicates that relying on a single cellular network for UAV connectivity is unreliable due to low coverage probability, with one network ensuring only eighty percent coverage (Colpaert et al., 2022).

For dynamic routes as described in alternatives with variable destinations and unstructured airspace, securing network coverage across the entire country presents significant challenges. This is due to the variability and unpredictability of UAV flight paths. Unlike fixed routes, dynamic routes necessitate a broader and more flexible network infrastructure, requiring extensive deployment of cell towers and small cells to ensure consistent connectivity in various, sometimes remote, locations. The risk of losing communication with the UAV due to distance being out of range is greater with dynamic routes and unstructured airspace (Chen & Mo, 2016). Furthermore, support facilities such as power supply must be widely available to ensure uninterrupted service.

Designating specific air pathways or corridors, as proposed in alternatives with zones and tubes, and fixed routes, allows for concentrated network coverage around these predetermined routes. This simplifies infrastructure requirements, enabling efficient placement of communication towers and small cells along designated corridors, thus reducing the risk of losing connectivity and improving overall safety. Additionally, in case of communication network outages, vehicle-to-vehicle communication can be provided in corridors. Inter-aircraft cooperative communication protocols are expected to maintain orderly flow and avoid conflicts within corridors (Bijjahalli et al., 2022).

Altitude Angel, a large player in the UAV market in the UK, has implemented a UAV pilot program, utilising a network of masts spaced approximately 4 kilometres apart to guarantee connectivity for UAV operations. In the Netherlands, KPN has been actively involved in providing 5G connectivity for UAV operations (KPN, 2020). To establish robust connectivity for UAV operations, the ground infrastructure must incorporate several components to ensure reliable and high-speed communication necessary for safe and efficient UAV management. This infrastructure includes traditional cell towers and a denser network of small cell towers.

Overall, while dynamic routes offer greater flexibility and adaptability, they require a more extensive and resilient connectivity network infrastructure. Designating specific air pathways, on the other hand, allows for more focused and efficient network coverage, reducing the complexity and cost associated with ensuring comprehensive connectivity for UAV operations.

5.4.2 Take-Off and Landing Sites

Take-off and landing sites, serving as critical infrastructure for UAV operations, introduce various risks that must be carefully managed to ensure safety and efficiency. Depending on whether the destination of the operation is fixed or not, the take-off and landing sites can be designated. Significant risks arise from the variable take-off and landing points, as proposed in the design concepts where the destination of the UAV operations vary for every operation. This increases the risk of selecting an insufficient location for the landing of the UAV (Chowdhury & Lipsett, 2023). In scenarios where UAVs utilise variable take-off and landing sites, third parties may not always be aware of UAV activity occurring nearby. This lack of awareness increases the risk of potential collisions or incidents involving bystanders or other aircraft operating nearby. Moreover, adverse weather conditions pose a more substantial risk when there are variable take-off and landing sites, as the unpredictability of weather patterns can disrupt UAV operations and compromise safety.

Fixed landing points provide greater predictability and awareness of UAV activity for third parties. Implementing specific hubs for UAV take-off and landing can significantly enhance safety. The correct and thorough selection of these sites is important, as inadequate choices can introduce substantial risks to UAV operations. Conducting a desktop assessment followed by an in-person inspection ensures the suitability of these sites for safe operations. Chowdhury & Lipsett (2023) emphasise that the risk of incorrect or insufficient site selection is magnified when take-off and landing spots vary. Incorporating proper selection of take-off and landing sites avoids hazards. By addressing these factors, UAV operators can mitigate risks and enhance the safety and efficiency of their operations. Adverse weather conditions can still pose a threat to operations at fixed landing points, albeit to a lesser extent compared to variable sites.

In conclusion, variable take-off and landing sites necessitate an extensive and resilient vertiport infrastructure. Alternatively, take-off and landing sites along the corridors for UAV operations provide increased levels of safety, as vertiports can be implemented.

5.5 Conclusion

While dynamic routes offer flexibility, they also necessitate extensive and resilient network infrastructure to ensure seamless and safe UAV operations. To address this, the design concepts of zones and tubes provide a structured approach to managing U-space airspace. By implementing corridors as proposed by these concepts, the safety of high-volume UAV operations can be significantly enhanced. The use of designated corridors allows for improved network connectivity, ensuring that UAVs maintain reliable communication links throughout the operation.

Designating specific air pathways not only simplifies the ground infrastructure requirements but also enhances safety through better network coverage and management. For instance, with clearly defined corridors, UAVs can be monitored and controlled more effectively, reducing the risk of mid-air collisions and ensuring smooth traffic flow. Moreover, the establishment of vertiports along these corridors further bolsters safety. Vertiports serve as dedicated take-off, landing, and maintenance hubs for UAVs, providing critical infrastructure support and facilitating efficient operations. The strategic placement of vertiports ensures that UAVs have access to essential services and can quickly respond to any operational contingencies.

However, the implementation of a structured infrastructure for U-space airspace necessitates an entity responsible for managing this infrastructure. Current regulatory frameworks do not adequately address this requirement, leaving a gap in the overall management and coordination of UAV operations. A dedicated managing entity would be essential for overseeing the establishment and maintenance of corridors, ensuring compliance with safety standards, and coordinating with various stakeholders, including aviation authorities, UAV operators, and U-space service providers. Such an entity would also play a crucial role in continuously assessing and adapting the infrastructure to evolving technological advancements and operational demands. By doing so, it would ensure that the infrastructure remains robust and capable of supporting the growing volume of UAV operations. This proactive management approach would help mitigate risks associated with high-volume UAV operations, ultimately contributing to a safer and more efficient U-space airspace. The next chapter will further investigate different stakeholder roles in a U-space airspace.

Chapter 6

Managing U-space Airspace

The implementation of U-space airspace introduces several new stakeholders to establish U-space airspace. As mentioned in chapter 3, the implementation of U-space airspace introduces the role of a U-space service provider, a common information service provider and UAV operators. The previous chapter also highlighted the necessity to assign an entity to be responsible for the implementation of the U-space infrastructure. The possible roles for different public and private stakeholders in a U-space airspace will be described in this chapter. To enhance this analysis, different strategies to manage U-space airspace will be discussed. This answers sub question 5: *What are the roles and responsibilities of different public and private stakeholders in a high-volume UAV infrastructure to enhance public safety?*

A primary challenge in the establishment of U-space airspace is the lack of significant movement due to mutual dependency, where parties are waiting for others to take the initiative. Private parties seem to be waiting for public institutions to make the first step, whilst public institutions are primarily focussing on establishing the legislation for an UAV infrastructure. Large investments are needed, particularly for ground infrastructure, which present a barrier to progress in the development. However, this is not necessarily a direct risk to public safety for UAV flights but highlights the economic and logistical hurdles that must be overcome to advance UAV integration. By evaluating different management strategies, stakeholders can make informed decisions about the most suitable model for the management strategy for a U-space airspace.

6.1 Management Models

Three strategies for managing unmanned air traffic have been identified by Dasu et al (2018). Firstly, centralised management where there is one central entity that authorises and allocates spaces to UAVs, for the time of the flight. Upon request, the UAV operator receives a flight trajectory from this central entity. The opposite strategy is decentralised, where several entities have the authority to authorise requested UAV operations. Lastly, hybrid management is described, where parts of the airspace will be controlled by a central entity, whilst other parts of airspace will be available to the public.

An important aspect of the management of civil airspace is the role of the government. Adecs Airinfra conducted research initiated by the Ministry Infrastructure and Water Management to investigate the possible roles for the government in the implementation of U-space airspace (Adecs Airinfra, 2021). The report describes four possible models with different roles for the government in U-space: regime model, open market model, participation model and the integration of manned and unmanned air traffic.

The regime model presumes that the development of a UAV system will not effectively take off without the proactive involvement of the state, necessitating strong central management as described by Dasu et al. (2018). Therefore, this model envisions an active and stimulating role for the central government. The government would oversee U-space airspace designation, manage operations, establish an oversight and enforcement framework, and create a financial structure, aligning with a centralised management approach. The government's investment can lower entry costs for private organisations, which stimulates innovation. However, support of the general public may be lower compared to an open market or participation model. Nonetheless, the research of Dasu et al. (2018) mentions, it may not be ideal to give all control to a single entity as it can generate a lot of work load. This is the current situation in the Netherlands where UAV operation requests in the 'Specific' category require authorisation by the competent authority. This process might take up to several months. The competent authority is not able to process al requests in a timely manner.

Conversely, the open market model adopts a more passive role for the national government. It presumes that if there is a societal demand for U-space airspace, the market will take the lead. This model therefore receives more support from the general public than the regime model. In this model, responsibilities will be taken on by market participants, infrastructure managers, or local authorities as needed. Hence, the CIS and USSP(s) should invest in the infrastructure, and therefore, are responsible for the business model. The high investment costs for private parties could impede progress, given the immature state of the UAV market. As there is not necessarily only one provider for USSP services, this model corresponds with decentralised management. This decentralised approach faces coordination challenges between operations, as multiple organisations are involved in the authorisation of UAV operation requests.

The participation model promotes equal collaboration between the state, local authorities, existing operational organisations, and market participants. Together, they ensure the establishment and maintenance of the U-space ecosystem, this supports a hybrid management approach. The principle of the participation model is to allow for an open market, and in case the open market is not sufficient, the government can interfere. This corresponds to a hybrid management as described by Dasu et al. (2018). This approach does not present significant risks as described for other models, as the government support mitigates many challenges that are posed by the involvement of private organisations. The participation model allows the government to subsidise investments when private organisations cannot fully cover costs. Different (private) organisations are involved in the authorisation process for requested operations, however, the government is able to intervene to assure a universal U-space airspace.

The integration model seeks to integrate unmanned traffic management (UTM) as closely as possible with the current air traffic management (ATM) system. This model aims to minimise the transitional phase with separate systems for unmanned and manned airspace. This model can be adapted to the centralised, decentralised, and hybrid management strategy. This approach risks rigidity, as adhering too closely to the current ATM system can reduce stakeholder input and support. It also limits market accessibility due to the current ATM system's responsibilities, leaving little room for innovation.

In summary, the regime model offers centralised control and innovation stimulation, while an open market model encourages market-driven development despite coordination challenges. The participation model balances government support and private investment, and the integration model leverages existing ATM systems with potential limitations on innovation.

6.2 Management of U-space airspace in the Netherlands

The effective management of the unmanned air traffic system in the Netherlands requires a clear understanding of the roles and responsibilities of various stakeholders, as well as the implementation of robust management strategies. This section explores the probable management strategies and delineates the roles of different stakeholders in U-space in the Netherlands. An overview of all public and private stakeholder roles identified in this research, is provided in figure 18 and appendix E. The boxes represent different roles for public and private stakeholders. The stakeholder that will (probably) fulfill the role is also included in the box. The dotted arrows represent a regulating relation between two stakeholders. The solid arrows reperesent streams of data. Roles that are already designed to a certain takeholders are in the green boxes. Roles that are probably going to be assigned to a certain stakeholder are in the yellow boxes. The roles that are yet to be assigned to a stakeholder are coloured in orange. The blue box represents a role that has been identified in this research. The different public and private roles will be discussed below. If possible, the organisation that is going to fulfill the role will be introduced.

The roles of the EU, EASA, national competent authority, CIS, USSPs and UAV operators have already been described in chapter 3. The stakeholder map provided in chapter 3 (figure 4), will be elaborated based on the knowledge gained throughout this research.

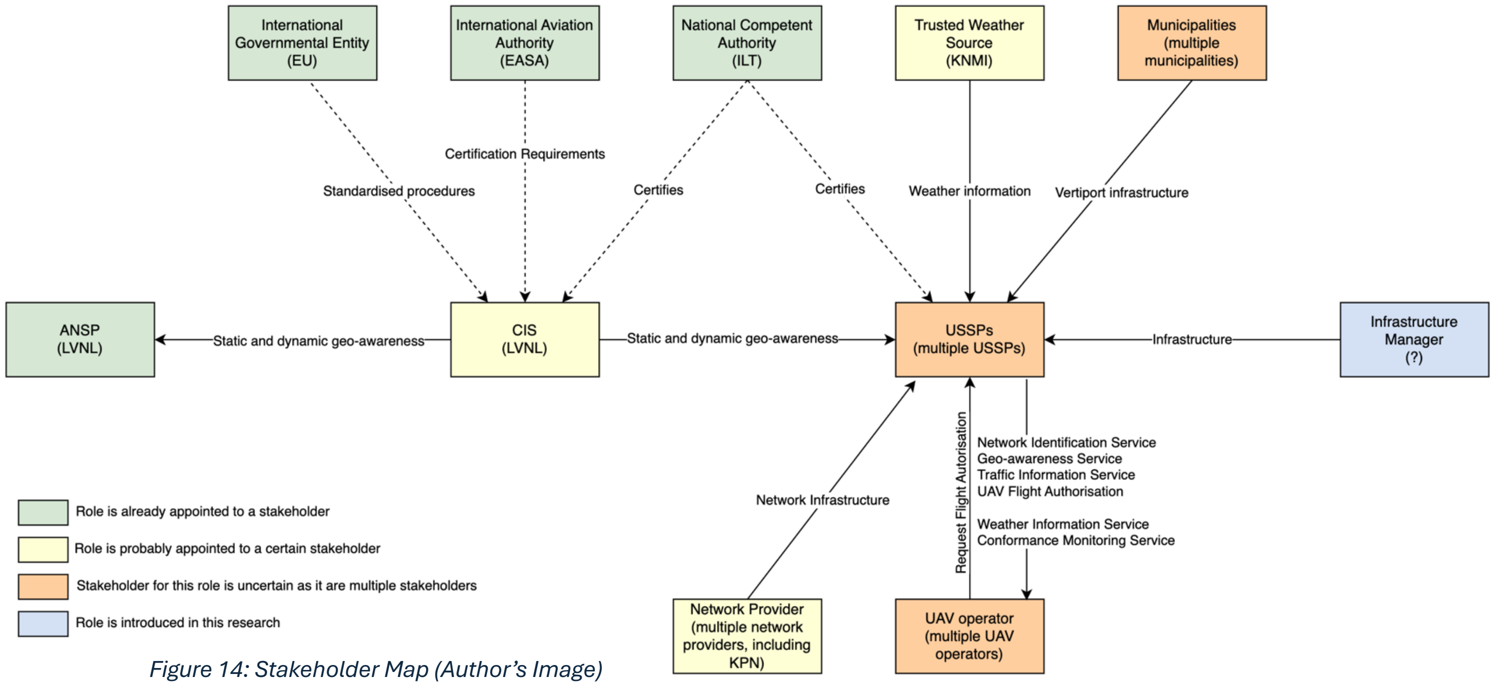

Figure 14: Stakeholder Map (Author's Image)

6.2.1 CIS

The guidelines of the EASA state that there should be at least one CIS provider per U-space airspace. This allows for multiple CIS providers within a Member State, allowing for all three management strategies as introduced by Dasu et al. (2018): centralised, hybrid, and decentralised. Research was conducted by Airhub, on behalf of the Ministry of Infrastructure and Water Management, investigating the possibilities for assigning one or multiple CIS provider in the Netherlands. The research concludes that a centralised architecture for a CIS is preferred over a decentralised model (AirHub, 2023). By establishing only one CIS, there is one single point of contact that exchanges all the necessary information to all relevant stakeholders for the functioning of U-space airspace. Additionally, considerations include the need for a CIS to be viewed as a national service requiring a single source of information. A public task managed by the government is seen as logical to provide basic needs and information. Ensuring the quality and reliability of data is crucial in this centralised form to minimise the risk of a 'single point of failure'. Due to these considerations, several Member States have already made the decisions to designate their national Air Navigation Service Provider (ANSP) as the single CIS. Therefore, it is assumable that the Netherlands will also chose for this approach. The ANSP in the Netherlands is Luchtverkeersleiding Nederland (LVNL).

LVNL is already working on a test trail to be a CIS. A collaboration has been initiated in the Netherlands to demonstrate the possibilities of a CIS provider. LVNL along with Altitude Angel, Airhub and Senhive will demonstrate the capabilities of a CIS provider (Altitude Angel, 2024). For the trial, Altitude Angel has developed an open and interoperable interface for USSPs to receive geo-awareness data from LVNL and share flight information with other U-space stakeholders. However, the trail is conducted with low volumes of UAV operations, as it is still difficult to receive authorisation for a UAV operation.

6.2.2 USSP

The guidelines of the EASA also mention that there should be at least one USSP per U-space airspace, again allowing for all three management strategies. Contrary to the approach for CIS, the Ministry of Infrastructure and Water Management supports a competitive market with multiple USSPs, corresponding to a decentralised management strategy. Furthermore, it is essential that the USSP and CIS are two distinct entities to prevent any conflict of interest.

Currently, there is only one organisation in the world who is licensed as a USSP; Airwayz (De Jager, 2023). Airwayz has been certified by the Isreali Civil Aviation Authority as a USSP in the U-space in Israeli (Airwayz, 2023). Besides Airwayz, there are no organisations that are capable of providing all four, or even six, U-space services. Some organisations are able to provide part of the services. It is unclear if it will be possible for different organisations to collaborate as one USSP.

To enhance U-space services, both during take-off and landing and en-route, a trusted weather source could provide the Weather Information Service to the USSP. This way, the USSP does not have to provide this service by itself, but the service is provided to the USSP, and the USSP provides it to the UAV operators as part of its services. The Weather Information Service in the Netherlands could be provided by the Royal Netherlands Meteorological Institute (KNMI) (De Jager, 2021).

6.2.3 National Competent Authority

The role of the national competent authority includes several aspects, including the certification of the CIS and USSPs in the Netherlands. Moreover, their duties include issuing operational authorisations, conducting inspections, and enforcing safety standards to prevent accidents and incidents.

The national competent authority in the Netherlands is The Human Environment and Transport Inspectorate (ILT). The ILT should ensure that UAV operations do not negatively impact public safety and the environment (Ministerie van Infrastructuur en Waterstaat, n.d.). Furthermore, the ILT collaborates with other stakeholders to integrate UAVs safely into the Dutch airspace, promoting innovation while maintaining strict oversight to safeguard the public interest.

At the moment, the ILT has to authorise the requested UAV operations in the 'Specific' category. The ILT has a separate department for integrating unmanned airspace and the authorisation of UAV operation requests. As the process to grant authorisation is still very complex and time consuming, the ILT is not able to authorise the requests in a timely manner.

6.2.4 Municipalities

The Ministry of Infrastructure and Water Management envisions municipalities taking on a significant role in vertiport management. The municipalities are responsible for the arrangement of the vertiports according to the guidelines as stated in the Prototype Technical Design Specifications. Nevertheless, it is yet unclear what a responsibility in this context embodies. Additionally, it is to be determined where the UAV operations would take place, and therefore what municipalities would benefit from establishing vertiports. Once a U-space or corridor has been designated in airspace, it can be determined what would be strategic locations for take-off and landing sites. According to the strategic designation of take-off and landing sites, municipalities can start to establish vertiports.

The Weather Information Service as proposed by the U-space services could enhance safety during take-off and landing by providing accurate weather information. The trusted weather source is a U-space service that can be provided by another organisation than the municipality itself, such as the KNMI as previously suggested.

6.2.5 UAV Operators

UAVs have diverse applications, each with different UAV operators depending on the specific use case. This section explores various UAV applications and the corresponding operators.

UAV Operators for Parcel Delivery

Figure 15: Medical UAV (ANWB, 2023)

UAV operators in the context of parcel delivery are likely to include logistics companies and healthcare institutions. PostNL is collaborating with ANWB in the Medical Drone Service Project, where they want to establish a digital corridor between two hospitals (ANWB, 2023). The corridor will be utilised to deliver, amongst other things, blood and medicines between the hospitals. Moreover, logistics company DHL also recognises the possible high impact that UAVs can have on logistics, but they remark that the regulatory developments are withholding the applications of UAVs (DHL, n.d.). In the United States of America, several logistics companies are already delivering parcels by UAV. For example, UPS conducts BVLOS UAV operations (Vasani, 2023), as well as Amazon (Amazon, 2024). Additionally, a supermarket chain, Walmart, also delivers groceries by UAV, in collaboration with Zipline (Walmart, 2024).

UAV Operators for Other Applications

In agriculture, UAV operators are often farmers who utilise UAVs. The application of UAVs in agriculture can boost productivity and contribute to more sustainable farming practices by minimising waste and operational costs (Delavarpour et al., 2021). For the inspection of bridges, buildings, highways and other objects, Rijkswaterstaat also uses UAV operations (Rijkswaterstaat, n.d.). There are already multiple companies in the market that provide such inspection services with UAVs. Police, fire, and ambulance services can greatly benefit from UAV operations. In emergency situations, UAVs can be rapidly sent to the incident site, providing real-time camera footage to help emergency responders assess the severity of the situation before arriving. The police department in Enschede have received a long-term operating permit for UAV use after conducting a SORA in collaboration with the ILT. This process, which took over a year, highlights the rigorous evaluation required to ensure UAV operations meet safety standards (NOS, 2024).


Figure 16: Farmer as UAV Operator (WUR, n.d.)


Figure 17: Inspector as UAV Operation (Stork, n.d.)

6.2.6 Network Providers

The communication network envisioned to enable UAV operations is the 5G-network. In the Netherlands, KPN is working on the realisation of the 5G-network to support UAV operations (KPN, 2024). KPN uses a 'coverage checker' to determine the coverage at a certain location in airspace. According to the coverage, the optimised operation route can be calculated. This way, the UAV operation is supported by a sufficient communication network during the duration of the operation.

As previously mentioned, the coverage of the communication network can be improved by using different networks. It can be further investigated whether a combination of different cellular networks provide a better coverage of the communication network.

6.2.7 Infrastructure Provider

To enhance safety of UAV operations, it is suggested to establish an infrastructure both in air and on the ground. The infrastructure for high-volume UAV operations needs to be established. At present, this task and responsibility has not been assigned to a dedicated organisation. The UAV infrastructure should be managed and maintained by this entity. The role that a responsible entity would assume for managing this infrastructure is analogous to the responsibility that Rijkswaterstaat holds over the road network in the Netherlands and ProRail holds over the railway network.

The UAV infrastructure will need to be established in consultation with various stakeholders. The dedicated authority will collaborate with municipalities to determine the locations of vertiports along the corridors. By working closely with municipalities, the dedicated authority can ensure that vertiports are strategically placed. This will involve identifying optimal locations that balance operational efficiency with minimal disruption to existing activities.

Additionally, partnering with network providers is crucial for establishing a reliable communication network. Properly positioned antennas are necessary to maintain consistent connectivity across the UAV corridors, enabling real-time data exchange and effective traffic management. This ensures that UAVs can operate safely and efficiently, with continuous communication to prevent collisions and manage air traffic dynamically. By coordinating these efforts, the dedicated authority can build an integrated infrastructure that supports the safe and efficient integration of UAVs into the airspace.

Chapter 7

Discussion & Limitations

This research has analysed the risks associated with high-volume UAV operations regarding public safety. In addition, different concepts to structuring airspace were evaluated. Finally, the different roles for both public and private stakeholders were discussed. This section includes a reflection of the research, followed by the limitations of the research.

7.1 Discussion

The initial goal of this research was to conduct a risk assessment for high-volume UAV operations in The Netherlands. Most existing research focused identifying the risks associated with single UAV operations. It soon became evident that limited research had been conducted regarding risks of high-volume UAV operations. Therefore, the focus of the research was shifted from conducting a risk assessment to identifying the risks associated with high-volume UAV operations. This realisation shifted the focus of the research towards understanding how infrastructure can contribute to safety in high-volume UAV operations.

This outcome of this research is based on qualitative research on the risks of high-volume UAV operations, as quantitative research in this context is scarce (Sedov et al., 2021). Similarly, the research of Martin et al. (2018) mentions that research regarding air risks associated with UAVs has been largely qualitative. Additionally, the SORA is a qualitative method used for the risks assessment of UAV operations (Carbó et al., 2023). Asghari et al. (2023) also emphasise on this by mentioning that risk assessments for unmanned air traffic are mostly qualitative. They conclude their research by identifying a big gap between the risk assessments and the definition of quantitative requirements of UAV operations. Quantative research in the context of UAV operations is mainly focused on path planning algorithms (Charalampidou et al., 2020). While this aspect is an important enabler of UAV operations, it only covers a relatively small segment of UAV operations. Path planning is essential for ensuring that UAVs can navigate safely, but the techniques do not incorporate the broader infrastructural and systemic risks posed by high-density UAV traffic. The absence of quantitative data limits the depth of insights into certain aspects of the research topic and may constrain the ability to draw robust conclusions or make evidence-based recommendations.

The insights derived from qualitative research may not be easily generalisable to all contexts or regions (Ritchie & Lewis, 2003). Different regulatory environments, technological infrastructures, and operational practices can significantly influence the applicability of the findings. Moreover, it is discussed in literature whether or not it is possible to generalise research results from one research to another (Falk & Guenther, 2007). Therefore, it can be questioned if the outcomes from other research can be used as data in this research.

Moreover, data retrieved from interviews relies on the interpretations and perspectives of the participants involved. While interviews are valuable for capturing expert perspectives and insights, they are subject to limitations. Expert judgement may vary based on individual experiences, biases, or interpretations, potentially influencing the validity and reliability of the findings. Additionally, the subjective nature of interviews may introduce biases or inaccuracies into the data, challenging the objectivity and generalisability of the findings.

7.2 Limitations

While this research provides valuable insights into the infrastructure required for safe and efficient UAV operations within U-space airspace, it is important to acknowledge several limitations regarding the scope of the study.

As a consequence of the complexity of the main subject, the research was scoped. The primary focus of this research was on the risks to public safety associated with UAV operations. As a result, significant aspects such as security, privacy, and environmental considerations were not comprehensively addressed. The research of Young (2020) emphasis on the necessity of the incorporation of cybersecurity safeguards when developing an unmanned air traffic system. The research of Hu et al. (2020) also emphasises this by mentioning several risks regarding security of UAV operations. Moreover, the privacy of people should be respected (Geronel et al., 2022). Examples of environmental risks associated with UAV operations, include noise pollution and potential impacts on wildlife. These factors are crucial for assessing the overall impact of UAV integration into airspace (Hullah et al., 2023).

Furthermore, the economic effects of implementing a UAV infrastructure were not assessed. The research of Gordo et al. (2023) concludes that corridors are not efficient in terms of time. This is also emphasised in the research of Sunil et al. (2015) where they argue that any structuring of traffic flows decreases overall efficiency of the system. Therefore, establishing dedicated corridors and structured airspace might lead to less efficient flight paths for UAVs. Conversely, the research of Zhang et al. (2023) concludes that free-planned routes are less efficient. Inefficient path planning leads to increased fuel usage of the UAVs, potentially increasing operational costs and reducing the anticipated sustainability benefits (D'Amato et al., 2023).

Despite these limitations, the research contributes valuable qualitative insights into the possibilities for an infrastructure to enable high-volume UAV operations in civil airspace. The research offers a nuanced understanding of the risks regarding public safety and perspectives surrounding UAV operations and airspace management. Recognising and addressing these limitations can inform future research efforts and enhance the credibility and applicability of findings in the field.

Chapter 8

Conclusions & Recommendation

This research was conducted through a qualitative literature review. Moreover, different aspects of the integration of high volumes of UAV operations in civil airspace were connected through this research. In this section the conclusions of this research will be provided. Subsequently, recommendations for future research will be made.

8.1 Conclusions

Using UAVs for parcel delivery can reduce road traffic congestions and pollutant emissions in comparison to using trucks. Widespread usage of UAVs in the civil and commercial sectors is expected in the future, therefore guidelines and regulations are already developed by aeronautics authorities for insertion of UAVs in civil airspace in Europe. Regulators and organisations are currently working towards updating (inter)national policies to enable BVLOS. The challenges will attract players with different interests, and partnerships into the UAV system**.** All these factors can in turn generate and support diverse ideas and approaches to the integration of this new technology within delivery systems for BVLOS UAVs. A system must be provided for controlling unmanned vehicles as the number of UAVs grows every year. To achieve this, an infrastructure should be established connecting different components needed for the integration of a high-volume UAVs in airspace.

This research was conducted through a qualitative literature review. Moreover, different aspects of the integration of high volumes of UAV operations in civil airspace were connected through this research. To address this focus, it was crucial to examine the existing methods for identifying and assessing risks. The SORA methodology was initially considered, but it became clear that SORA is not entirely adequate for high-volume UAV operations. While SORA provides a structured approach to risk assessment, it is primarily designed for individual or small-scale UAV operations and does not fully address the complexities of high-density environments.

The most critical risks identified in this research can be categorised into operational risks and risks associated with supporting facilities. One significant risk during UAV operations is the loss of control of the UAV, which occurs when the UAV deviates from its intended path due to technical failures or environmental factors. This deviation can lead to unintended and potentially dangerous consequences. Another concern is the risk of collision in the air, which can be a result of loss of control of the UAV. A collision in the air can occur between a UAV and manned aircraft, other UAVs, or birds. Additionally, there is a considerable risk of a collision of the UAV on the ground, where there is a collision between a UAV and a person, animal, or other objects on the ground. An aerial collision often results in debris falling to the ground, causing further damage or injuries.

Supporting facilities play a crucial role in UAV operations, these include facilities to provide a communication network and facilities to support take-off and landing of the UAV. One primary risk associated with supporting facilities is the loss of control resulting from a failure in the communication network. This can lead to UAVs becoming unresponsive and potentially deviating from its original flight plan. Another significant risk is the latency in communication networks, where delays in communication between the UAV and the control systems can result in slow or incorrect responses to control inputs. These delays increase the likelihood of accidents, as real-time communication is vital for the safe operation of UAVs.

The four risk assessments as proposed by the EASA do not consider high volumes of UAVs. Therefore, the risk assessments cannot address the risks of high-volume UAV operations. The concept of U-space airspace enables high-volume UAV operations. Therefore, the ability of the concept of U-space to take high-volume UAV operations was explored. However, U-space is not a risk assessment tool, but a set of services and protocols aimed at enabling UAV traffic. Hence, it does not identify, control and mitigate risks.

To address the various risks associated with UAV operations, an additional layer of safety can be implemented. Conflicts between UAVs can be mitigated by adopting different airspace structure designs. High-volume UAV operations require robust infrastructure to ensure safe and efficient integration into U-space airspace. This infrastructure includes both the arrangement of airspace structure and the strategy for determining flight plans. Four distinct airspace structure designs and four strategies for flight plan determination have been evaluated.

Unstructured or layered airspace with dynamic routes offers operators flexibility in path planning but poses higher collision risks at increased traffic densities. Therefore, this approach does not optimise safety levels. Operation requests for varying routes and destinations may require a risk assessment to determine the suitability and safety of the proposed flights. Additionally, dynamic routes in unstructured or layered airspace demand more coordination from the Common Information Service (CIS) and U-space Service Providers (USSPs) to manage the varying operations, increasing interface management and communication complexity. Free-planned routes cannot meet the safety and efficiency requirements of airspace. Additionally, for dynamic routes with variable destinations in unstructured airspace, securing network coverage across the entire country presents significant challenges due to the unpredictability of UAV flight paths. Unlike fixed routes, dynamic routes require a broader and more flexible network infrastructure, necessitating extensive deployment of cell towers and small cells to ensure consistent connectivity in various, sometimes remote, locations. The risk of losing communication with UAVs due to being out of range is greater with dynamic routes and unstructured airspace. Additionally, support facilities such as power supply must be widely available to ensure uninterrupted service. Variable take-off and landing points increase the risk of selecting inappropriate locations for UAV landings.

Segmentation of traffic contributes to lowering conflict probability, thus enhancing airspace safety. In the design concepts of zones and tubes, path planning is achieved by designating corridors in U-space airspace. Predefined corridors guide UAV operations, ensuring flights adhere to designated paths. These corridors allow for fixed flight plans, minimising risks by harmonising UAV operations with other airspace users and optimising airspace management. The zones and tubes concepts simplify route management and enhance safety. Moreover, designating specific air pathways or corridors, as proposed in zones and tubes, allows for concentrated network coverage around these predetermined routes. This simplifies the development of the supporting infrastructure, enabling strategic placement of communication towers along designated corridors, reducing the risk of connectivity loss and improving overall safety. Implementing vertiports for UAV take-off and landing can significantly enhance safety. The Ministry of Infrastructure and Water Management envisions municipalities taking on a significant role in vertiport management.

While dynamic routes offer flexibility, they also necessitate extensive and resilient network infrastructure to ensure seamless and safe UAV operations. To address this, the design concepts of zones and tubes provide a structured approach to managing U-space airspace. By implementing corridors as proposed by these concepts, the safety of high-volume UAV operations can be significantly enhanced. However, the implementation of a structured infrastructure for U-space airspace necessitates an entity responsible for managing this infrastructure. Current regulatory frameworks do not adequately address this requirement, leaving a gap in the overall management and coordination of UAV operations. A dedicated managing entity would be essential for overseeing the establishment and maintenance of corridors, ensuring compliance with safety standards, and coordinating with various stakeholders, including aviation authorities, UAV operators, and U-space service providers.

In the Netherlands, a centralised architecture for a CIS is preferred over a decentralised or hybrid model. It is likely that the Air Navigation Service Provider of the Netherlands, Luchtverkeersleiding Nederland, will be assigned as the CIS, as several Member States have already decided to do so.

Contrary to the approach for CIS, the Ministry of Infrastructure and Water Management supports a competitive market with multiple USSPs, corresponding to a decentralised management strategy. Furthermore, it is essential that the USSP and CIS are two distinct entities to prevent any conflict of interest. Currently, there is only one USSP in the world, highlighting the necessity to support organisations in taking on this role.

8.2 Recommendations

Based on the limitations of this research, several recommendations can be made. Besides, based on the findings of this research recommendations can be made.

As mentioned before, by concentrating primarily on public safety risks, this research provides a foundational understanding of the necessary infrastructure for UAV operations. However, future studies should incorporate a broader range of factors, including security, privacy and environmental considerations. This will contribute to a more comprehensive evaluation of the challenges and opportunities associated with the integration of high volumes of UAV operations. Addressing these risks will contribute to a more holistic approach to developing UAV infrastructure, ensuring that all relevant aspects are considered in the pursuit of safe, efficient, and sustainable UAV operations.

Moreover, future research and infrastructure development should also consider the economic implications of UAV operations. Assessing the cost-effectiveness of implementing dedicated corridors and other infrastructural elements is essential for the development of the infrastructure. Additionally, the sustainable benefits such as the reduction of pollutant emissions in comparison to using trucks should be determined for corridors. The research conducted by the Dutch Knowledge Institute for Mobility highlights that different characteristics of UAV deliveries have different sustainability benefits (Kennisinstituut voor Mobiliteit, 2017). Nevertheless, some UAV operations do not have sustainability benefits when comparing with a delivery by truck. Balancing operational efficiency with sustainability benefits will help optimise the economic impact of UAV integration.

Future research should focus on developing integrated approaches that combine robust risk assessment tools with comprehensive infrastructural frameworks to manage the complexities of high-volume UAV operations effectively. A comprehensive risk assessment framework should be established to incorporate U-space airspace principles. The framework should incorporate at least all system components that are included in the SORA, to provide a comprehensive framework. This framework should identify and mitigate potential risks associated with UAV operations within U-space airspace, including collision risks, connectivity risks and risks associated with take-off and landing, but also security, privacy and environmental issues. This will require collaboration among regulatory bodies, technology providers, and industry stakeholders to establish a consensus on infrastructure standards and risk management practices. By integrating risk assessment with U-space airspace management, stakeholders can proactively address safety concerns and ensure the safe coexistence of UAVs with other airspace users.

Additionally, stakeholder engagement is essential to initiate the development of U-space service providers and possible organisations responsible for infrastructure management. Furthermore, municipalities should become involved in the development of the vertiports in the UAV infrastructure. Relevant stakeholders, including government agencies, aviation authorities, municipalities, and UAV operators, should be involved in collaborative efforts to establish the necessary infrastructure.

Lastly, it is essential to document the effectiveness of risk mitigation measures implemented within UAV operations. This will contribute to the quantitative research available regarding risks associated with high-volume UAV operations. This documentation should include comprehensive records detailing the design, implementation, and performance of each mitigation measure and the possible infrastructure designs. By documenting and validating the effectiveness of risk mitigation measures, stakeholders can provide transparency and accountability in U-space airspace. Third-party validation, as required by the SORA, ensures that the effectiveness and robustness of mitigation measures are independently verified, enhancing confidence in the safety and reliability of UAV operations within U-space airspace. In order to be able to validate the effectiveness and robustness of the mitigation measures by third parties, those parties should become certified to do so. Furthermore, transparent documentation enables continuous improvement and refinement of mitigation strategies based on empirical evidence and feedback from stakeholders, contributing to the long-term success and sustainability of U-space airspace management initiatives.

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Appendix A – Categories of UAV Operations

Open Category

The Open category is intended for low-risk UAV operations. It includes three subcategories (A1, A2, and A3), each with specific requirements and limitations:

A1 Subcategory:

- Operations are allowed over people but not over assemblies of people.
- The maximum take-off mass (MTOM) of the UAV must be less than 250 grams, or up to 500 grams if the UAV is compliant with specific safety requirements.
- The pilot must maintain visual line of sight (VLOS) and keep the UAV at a maximum altitude of 120 meters.

A2 Subcategory:

- Operations close to people but not over them.
- The MTOM of the UAV must be less than 2 kilograms.
- The pilot must maintain VLOS and keep a safe horizontal distance from people, typically a minimum of 30 meters, which can be reduced to 5 meters if the UAV has a low-speed mode.
- The pilot must have completed a specific training course and passed an exam.

A3 Subcategory:

- Operations are conducted far from people and away from residential, commercial, industrial, or recreational areas.
- The MTOM of the UAV must be less than 25 kilograms.
- The pilot must maintain VLOS and keep a safe distance from people and property, typically at least 150 meters.

Specific Category

Operations in this category include:

- Flying beyond visual line of sight (BVLOS)
- Operations over populated areas
- Flights in controlled airspace

Certified category

The Certified category is for the highest-risk UAV operations that are comparable to manned aviation activities. This category includes operations where:

- UAVs are used for transporting dangerous goods or passengers.
- UAVs have a significant weight (typically above 25 kilograms).
- Operations are conducted in highly populated areas or in environments where the failure of the UAV could pose a severe risk to people, property, or other airspace users.

Appendix B – Risk Assessments

STS

STS-01: VLOS Operations Over Controlled Ground Area

The Standard Scenario STS-01 pertains to Visual Line of Sight (VLOS) UAV operations intended for general purposes such as inspections, surveillance, and monitoring. These operations are conducted over a controlled ground area, ensuring no uninvolved persons are present within the operational zone. UAVs used in this scenario must weigh less than 25 kg and operate at speeds not exceeding 50 knots (approximately 92.6 km/h), with flight altitudes kept below 120 meters above ground level (AGL).

Operations are limited to uncontrolled airspace, away from aerodromes and restricted areas, and must be carried out during daylight hours under Visual Meteorological Conditions (VMC). Remote pilots must hold valid certification or proof of competency for VLOS operations and must maintain continuous visual contact with the UAV without the aid of visual enhancements (except corrective lenses).

To mitigate ground risks, a controlled area must be established to ensure the absence of uninvolved persons. Operators are required to have documented emergency procedures in place, including protocols for loss of control and emergency landings. Reliable communication links between the UAV and the remote pilot must be maintained at all times.

The duration of each flight should not exceed 30 minutes unless specific authorisation is granted. Operations must cease during adverse weather conditions such as strong winds, heavy rain, or poor visibility. Operators must maintain an operational manual that outlines procedures, safety measures, and emergency protocols, and a pre-flight checklist must be completed for each operation to ensure all systems are functional and compliant with the requirements of STS-01.

STS-02: BVLOS Operations with Observers

Standard Scenario STS-02 applies to Beyond Visual Line of Sight (BVLOS) UAV operations that utilise visual observers. This scenario is suitable for long-range inspections, surveying, and infrastructure monitoring. Operations must be conducted in predetermined and surveyed areas with established observer positions.

UAVs in this scenario must weigh less than 25 kg and operate at speeds not exceeding 50 knots (approximately 92.6 km/h), with flight altitudes kept below 120 meters AGL. Operations are limited to uncontrolled airspace, away from aerodromes and restricted areas, and must be conducted during daylight hours under VMC.

Remote pilots must hold valid certification or proof of competency for BVLOS operations. Visual observers must be strategically positioned along the flight path to maintain visual contact with the UAV and communicate with the remote pilot to ensure safe operations.

Ground risk mitigation involves ensuring that no uninvolved persons are present along the flight path. Operators are required to have documented emergency procedures, including loss of control and emergency landing protocols, and must maintain reliable communication links between the UAV, the remote pilot, and the visual observers.

The duration of each flight in this scenario should not exceed 60 minutes unless specific authorisation is granted. Operations must cease during adverse weather conditions such as strong winds, heavy rain, or poor visibility. Operators must maintain an operational manual that outlines procedures, safety measures, and emergency protocols, and a pre-flight checklist must be completed for each operation to ensure all systems are functional and compliant with the requirements of STS-02.

Standard Scenarios (STS) streamline the authorisation process for common UAV operations by providing predefined operational conditions and safety measures. STS-01 focuses on VLOS operations over controlled ground areas, ensuring safety through stringent visual contact and controlled environment protocols. STS-02 addresses BVLOS operations with the use of visual observers, incorporating additional measures to ensure safety over extended distances. Both scenarios require operator certification, strict adherence to operational limits, safety procedures, and thorough documentation to ensure safe and efficient UAV operations.

PDRA

A Predefined Risk Assessment (PDRA) is a concept introduced by the European Union Aviation Safety Agency (EASA) to streamline the process of authorising UAV operations within the specific category. The PDRA framework provides a set of standardised risk assessments for common types of UAV operations, thereby simplifying the approval process for operators who can demonstrate compliance with these predefined conditions and mitigations.

The primary objective of a PDRA is to offer a structured approach to managing and mitigating risks associated with UAV operations without requiring each operator to conduct a full, individualised Specific Operations Risk Assessment (SORA). This not only reduces the administrative burden on operators and regulatory bodies but also promotes consistency and safety in UAV operations across the EU.

Each PDRA outlines specific operational parameters and conditions under which UAV operations can be conducted. These parameters typically include limitations on operational altitude, airspace type, flight duration, UAV weight, and the type of environment (urban, rural, or controlled). By adhering to these predefined conditions, operators can ensure that their operations fall within an acceptable risk threshold as determined by EASA.

In addition to operational parameters, PDRAs also specify the necessary mitigations and safety measures that operators must implement. These measures often include requirements for UAV equipment, such as the presence of detect-and-avoid systems, redundant communication links, and fail-safe mechanisms for navigation and control. Operational mitigations may involve procedures for ensuring safe separation from other airspace users, protocols for emergency situations, and guidelines for maintaining continuous situational awareness.

To use a PDRA, an operator must demonstrate compliance with all the specified conditions and mitigations through a formal application process. This typically involves submitting documentation that details the operational concept, the UAVs to be used, and how the operator will meet the safety and mitigation requirements outlined in the PDRA. Once the application is reviewed and accepted, the operator is granted authorisation to conduct the specified operations without the need for a full SORA.

PDRAs are particularly beneficial for routine or repetitive UAV operations where risks and mitigations are well understood and can be consistently managed. Examples include infrastructure inspections, agricultural monitoring, and surveying operations. By leveraging PDRAs, operators can expedite the approval process and focus on conducting their missions safely and efficiently.

Overall, the PDRA framework represents a significant step towards the standardisation and simplification of UAV operations within the specific category. It enhances safety by ensuring that common risks are thoroughly assessed and mitigated while providing a more accessible pathway for operators to gain operational authorisations.

SORA

The first step in SORA is the development of a Concept of Operations (ConOps). The ConOps describes the specifics of the UAV operation. This is different than the other risk assessments, where the UAV operations are pre-defined. The ConOps include the type of UAV used, the operational environment, flight paths, and any other relevant operational details. This detailed description sets the stage for the subsequent risk assessment by providing a clear understanding of the operation's scope and context.

Once the ConOps is established, the next step is to determine the intrinsic Ground Risk Class (GRC). The GRC assesses the potential impact of the UAV operation on people and property on the ground. This involves evaluating factors such as population density, the potential severity of harm in the event of a crash, and the UAV's operational characteristics. The GRC is then used to classify the inherent risk level of the operation.

Following the GRC assessment, the Air Risk Class (ARC) is determined. The ARC evaluates the likelihood of a mid-air collision with manned aircraft. This assessment considers the airspace in which the UAV will operate and the expected traffic density, and the presence of other airspace users. The ARC classification helps identify the operational measures needed to mitigate air risks.

Combining the GRC and ARC results in the Specific Assurance and Integrity Level (SAIL). The SAIL provides a combined risk level that indicates the overall complexity and risk of the operation. Higher SAIL levels correspond to more complex operations that require more stringent safety and mitigation measures.

Operational Safety Objectives (OSOs) are then established based on the SAIL. OSOs are specific safety targets that must be achieved to mitigate the identified risks. These objectives cover various aspects of the operation, including UAV design, operator training, maintenance procedures, and emergency protocols.

To address the identified risks, both strategic and tactical mitigations are applied. Strategic mitigations involve planned measures such as geofencing, predefined flight routes, and coordination with air traffic control. Tactical mitigations include real-time measures like detect-and-avoid systems and emergency response procedures.

Residual risks are those that remain after all mitigations have been applied. These risks are further evaluated to ensure they are within acceptable levels. If necessary, additional safety measures are implemented to address any residual risks.

The final step in the SORA process involves continuous monitoring and review. This ensures that the UAV operation remains safe over time and that any changes in the operational environment or UAV performance are promptly addressed. Operators are required to maintain detailed records and regularly review their operations to ensure ongoing compliance with safety standards.

LUC

By holding an LUC, an operator gains a higher degree of operational flexibility and autonomy, significantly reducing the administrative burden associated with gaining approval for each individual flight operation.

To obtain an LUC, an operator must undergo a rigorous evaluation process by EASA or the national aviation authority of their respective EU member state. This evaluation assesses the operator's organisational structure, safety management system (SMS), compliance monitoring, training programs, and operational procedures. The foremost elements of this assessment include:

Once the operator has successfully demonstrated compliance with these requirements, they are issued an LUC, which grants them the authority to self-authorise specific types of UAV operations. The scope of the operations that can be self-authorised is defined by the terms of the LUC and may include various scenarios such as BVLOS flights, operations over populated areas, and flights in controlled airspace.

The LUC provides significant benefits to UAV operators by allowing them to conduct operations more efficiently and respond quickly to changing operational needs without waiting for individual approvals. However, it also places a considerable responsibility on the operator to maintain the highest standards of safety and compliance continuously.

Appendix C – Overview SORA

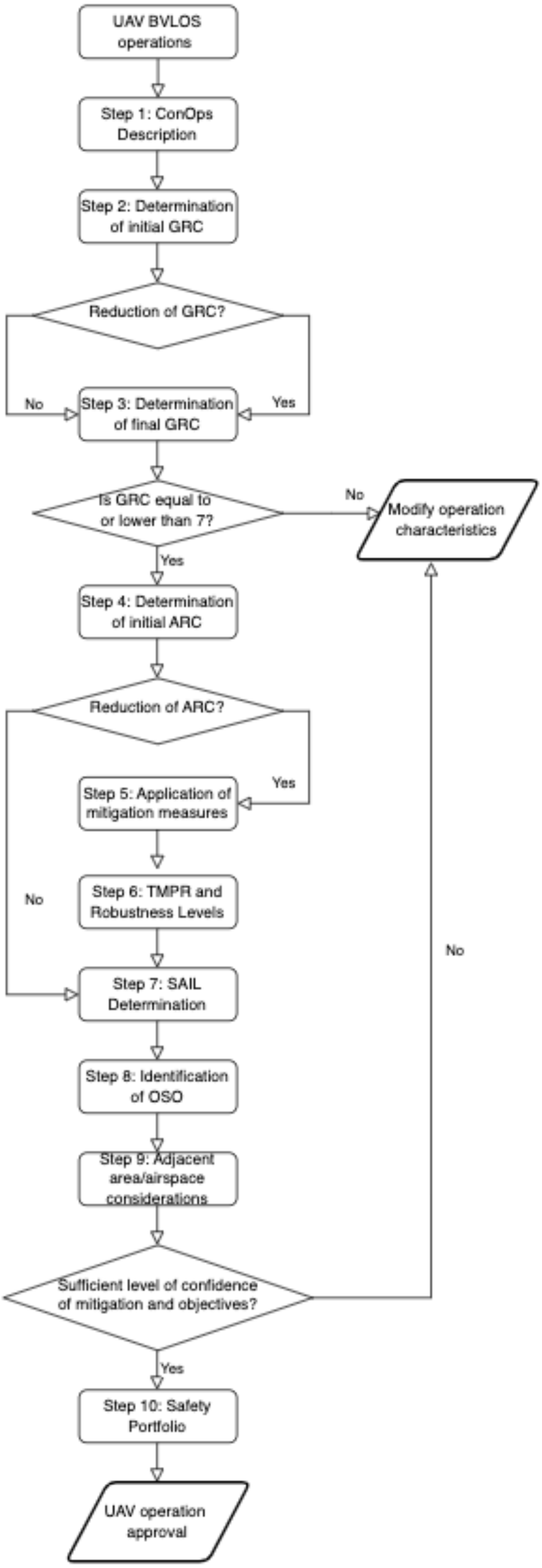

Figure 18: Overview SORA (Author's Image)

Appendix D – SORA for High-Volume UAV Operations

Specific Operations Risk Assessment (SORA) for a long-term operating permit for operations in U-space airspace in The Netherlands for high-volume UAV operations Beyond Visual Line of Sight (BVLOS) for commercial purposes.

Step 0: Pre-application Evaluation

Operations in the context of this research are not included in the category 'open' or 'certified', are not included in STS or PDRA, are not considered harmless for ground risk by the competent authority and are no subject to specific NO-GO from the competent authority. Therefore, a SORA should be applied.

Step 1: ConOps Description (Concept of Operations)

Description:

- Type of Operation: BVLOS for parcel delivery
- Airspace: U-space airspace in The Netherlands
- Operational Area: Urban and suburban areas with high UAV traffic
- Flight Altitude: Typically, between 50-150 meters above ground level
- Flight Frequency: High-volume, potentially hundreds of flights per day
- UAV Specifications: Small to medium-sized, electric-powered UAVs with GPS and advanced detect-and-avoid systems, redundant communication systems
- Training of staff and crew is included
- The maximum weight of the UAV (including parcel) is 25 kilograms

Step 2: Determination of the Intrinsic Ground Risk Class (GRC)

Analysis:

- Population Density: Urban and suburban, rural or sparsely populated
- Crash Consequences: Potential for injury or fatality if UAV crashes

The operations will be conducted BVLOS and can be over a sparsely populated area or over a populated area. The maximum wingspan of the UAV will be smaller than 3 meters, it is also possible that the wingspan is 1 meter.

The typical kinetic energy that is expected of the UAV is either <700 J or <34 kJ. The kinetic energy of 700 J aligns with a speed of 25 km/h (or 7,5 m/s) for a UAV with a mass of 25 kilograms[1].
The kinetic energy of 34 kJ aligns with a speed of 190 km/h (or 50 m/s) for a UAV with a mass of 25 kilograms.

Table 4: Determination of Ground Risk

maximum UAV characteristic dimension	**1 m**	**3m**	**8m**	**>8m**
Typical kinetic energy expected	<700 J	<34 kJ	<1084 kJ	>1084 kJ
BVLOS over sparsely populated area	**3**	**4**	5	6
BVLOS over populated area	**5**	**6**	8	10

[1] *These calculations have been performed by ChatGPT*

The intrinsic ground risk is 3 or 4 for a sparsely populated area and 5 of 6 for a populated area.

Step 3: Determination of Final Ground Risk Class

All mitigations must be applied in numeric sequence to perform the assessment.

The robustness designation is achieved using both the level of integrity (i.e. safety gain) provided by each mitigation, and the level of assurance (i.e. method of proof) that the claimed safety gain has been achieved. These are both risk-based.

- A low level of assurance is where the applicant simply declares that the required level of integrity has been achieved.
- A medium level of assurance is one where the applicant provides supporting evidence that the required level of integrity has been achieved. This is typically achieved by means of testing (for technical mitigations) or by proof of experience (for human-related mitigations).
- A high level of assurance is where the achieved integrity has been found acceptable by a competent third party.

M1
Criterion 1: Definition of the ground risk buffer
Low integrity: A ground risk buffer should be as wide as the height at which the UAV operation is conducted.
Medium and high integrity: The ground risk buffer takes into consideration malfunctions or failures which would lead to an operation outside of the operational volume, meteorological conditions, UAV latencies

Criterion 2: Evaluation of people at risk
Low integrity: in person on-site inspection to justify lowering the density of people
Medium or high integrity: Use of authoritative density data and in person on-site inspection to justify lowering the density of people. Or when it is reasonable to assume that most of the non-active participant will be located within a building.

Assurance levels as described above.

M2
Criterion 1: technical design
Low integrity: does not meet medium level criteria
Medium integrity: Effects of impact dynamics and post impact hazards are significantly reduced although it can be assumed that the fatality may still occur. In case of malfunctions, failures or any combination that may lead to a crash, the UAV contains all elements required for the activation of the mitigation. Any failure or malfunction of the proposed mitigation itself does not adversely affect the safety of the operation
High integrity: Activation of mitigation is automated. Effects of impact dynamics and post impact hazards are significantly reduced to a level where it can be assumed that the fatality will not occur.

Criterion 2: Any equipment used to reduce the effect of the UA impact dynamics are installed and maintained in accordance with the manufacturer's instructions.

Assurance levels as described above.

Criterion 3: Personnel responsible for the installation and maintenance of the measures proposed to reduce the effect of the UAV impact dynamics are identified and trained by the applicant.

Assurance levels as described above.

M3
Low integrity: No ERP is available, or the ERP does not cover the elements identified to meet a medium or high level of integrity.
Medium integrity: The ERP is suitable for the situation, limits escalating effects, defines criteria to identify an emergency situation, is practical to use, clearly delineates Remote Crew Member duties.

Assurance levels as described above.

Currently, high level of assurance is not availabe as there are no third parties that can offer such services. As a result of this, high level of robustness is not available yet. Therefore, the maximum level of robustness for the mitigation of ground risk is medium level.

Table 5: Determination of Mitigation Levels

	Robustness		
Mitigation level	**None/Low**	**Medium**	**High**
M1 – strategic mitigation for ground risk	**None: 0** **Low: -1**	**-2**	-4
M2 – effects of ground impact are reduced	**None/Low: 0**	**-1**	-2
M3 – An ERP is in place, the UAV operator is validated and effective	**None/Low: 1**	**0**	-1

Hence, after incorporating the different mitigation measures to reduce GRC, the new GRC can vary between 0 and 7.

Step 4: Initial Air Risk Class (ARC) Determination

- Airspace Type: U-space, with segregated air corridors for UAVs
- Traffic Density: Low in terms of manned air traffic. High in terms of unmanned traffic, due to high volume of UAV operations.
- Initial Air Risk Class (ARC): There is no classification for U-space airspace in the current SORA. The assumption of SORA is that an airspace with a high-density is the most dangerous ARC, ARC-d. This requires high tactical mitigation performance requirements and a high level of robustness for the mitigation measures. Currently, high levels of robustness are not feasible. Therefore, the UAV operations will not be authorised by the current risk assessment.

Step 5: Strategic Mitigations to Determine final ARC

Examples:
- Geofencing: Preventing UAVs from entering no-fly zones
- UTM Integration: Coordinating with U-space Traffic Management (UTM) for deconfliction
- Flight Planning: Pre-defined routes to minimise overflight of populated areas

Step 6: TMPR and Robustness Levels

Examples:
- Detect and Avoid Systems: ADS-B, radar, and optical sensors for collision avoidance

- Emergency Procedures: Auto-landing or return-to-home functions in case of system failure
- Transponders: Equipping UAVs with transponders for visibility to air traffic control
- Airspace Coordination: Continuous coordination with air traffic control for situational awareness

Step 7: Final SAIL Determination

SAIL (Specific Assurance and Integrity Level):
- Combining GRC and ARC: Using the SORA matrix

Table 6: Determination SAIL

Final GRC	Residual ARC			
	a	**b**	**c**	**d**
<= 2	I	II	IV	**VI**
3	II	II	IV	**VI**
4	III	III	IV	**VI**
5	IV	IV	IV	**VI**
6	V	V	V	**VI**
7	VI	VI	VI	**VI**
>7	Category 'Certified' Operation	Category 'Certified' Operation	Category 'Certified' Operation	Category 'Certified' Operation

Initial SAIL: VI

Step 8: Operational Safety Objectives (OSOs)

Step 9: Adjacent Area

Step 10: Comprehensive Safety Portfolio

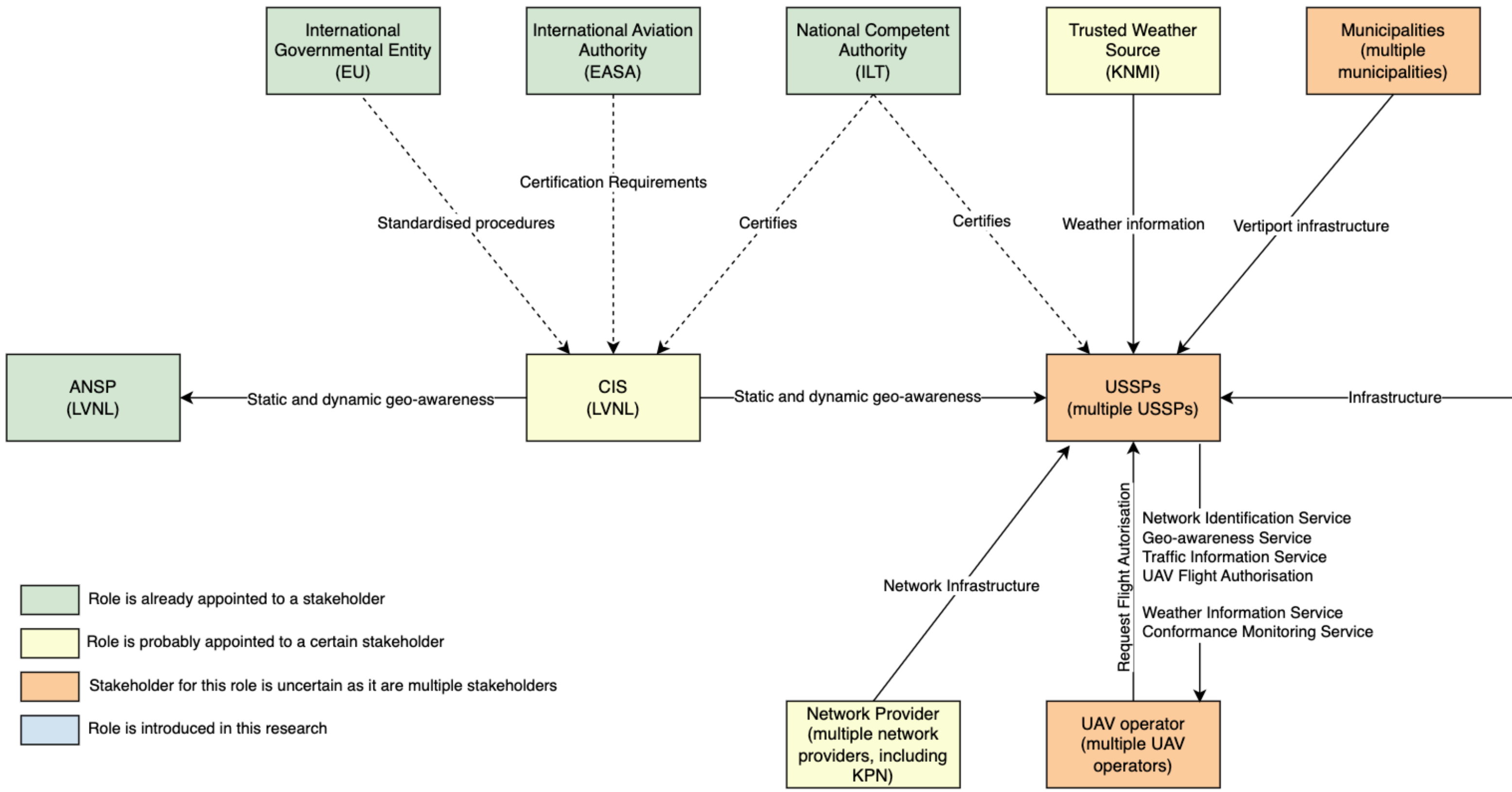

Figure 19: Stakeholder Map (Author's Image)