UNIVERSIDADE BEIRA INTERIOR

Enhancing Smart City Capabilities with the Integration of Unmanned Aircraft Systems: Unlocking Porto's Potential

(versão final após defesa)

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Resumo

O crescente número de cidadãos em meios urbanos traduz-se em desafios que exigem soluções inovadoras e eficientes. As cidades encontram-se numa busca incessante por abordagens mais inteligentes que envolvem a otimização da utilização de recursos e a melhoria de serviços públicos, visando aumentar a qualidade de vida e a satisfação geral dos residentes por meio de práticas sustentáveis (ambiental, económica e socialmente). As tecnologias inovadoras atuais e emergentes convertem-se em ferramentas eficazes para lidar com os desafios da mobilidade urbana, sendo os Sistemas Aéreos Não Tripulados (UAS) uma solução valiosa neste contexto devido à sua versatilidade e flexibilidade operacional, aos métodos eficientes de recolha de dados e ao menor impacto ambiental e até mesmo económico comparativamente a outras tecnologias (por exemplo, helicópteros, aeronaves da aviação geral e sistemas terrestres). Os UAS têm sido amplamente estudados, uma vez que podem ser utilizados em uma vasta gama de aplicações urbanas, como mapeamento e planeamento urbano, monitorização, gestão ambiental, gestão de tráfego multimodal e inspeção e manutenção de infraestruturas. Também se prevê que tenham um papel fundamental no transporte de passageiros e mercadorias, contribuindo para o desenvolvimento da Mobilidade Aérea Urbana (UAM), aceite como uma prioridade entre as diversas iniciativas de mobilidade urbana sustentável da União Europeia.

Neste contexto, este trabalho propõe a aplicação de uma análise SWOT (Forças-Oportunidades-Fraquezas-Ameaças) para avaliar qualitativamente os potenciais fatores que poderão influenciar a implementação de UAS no Porto e do conceito de matriz TOWS para definir estratégias de implementação. Para complementar esta análise, aplica-se o Processo Analítico Hierárquico combinado com a lógica Fuzzy (FAHP), permitindo identificar os fatores potencialmente mais relevantes de entre os identificados, e outros métodos quantitativos que irão permitir obter uma ordem de priorização de estratégias, com o objetivo principal de identificar iniciativas que aproximem o Porto das principais cidades inteligentes internacionais. Por fim, a este processo sucedeu-se uma validação de resultados por meio de entrevista estruturada, realizada com uma empresa fabricante e operadora de UAS sediada na cidade que foi objeto de estudo.

O conjunto de todas as etapas desenvolvidas permitiu concluir que o Porto apresenta um potencial significativo para a implementação de UAS no âmbito de uma cidade inteligente. Entre os principais fatores favoráveis, destacam-se a proatividade, dinamismo e a forte capacidade de colaboração local - a nível do ambiente urbano, a sustentabilidade ambiental intrínseca aos UAS - no âmbito do veículo em si, bem como a criação de postos de trabalho e de oportunidades de negócio - como benefícios derivados desta implementação. Todavia, este estudo evidenciou preocupações substanciais relacionadas tanto com a fragilidade do panorama legislativo atual como com a sua natureza em constante evolução e a complexidade inerente, fatores que intensificam os desafios associados com o que a *safety* e *security* diz respeito.

Palavras-chave

Cidade Inteligente; Qualidade de Vida; Sustentabilidade; Sistemas Aéreos Não Tripulados (UAS); Veículo Aéreo Não Tripulado (UAV); Drone; Mobilidade Aérea Urbana (UAM); Mobilidade Aérea Inovadora (IAM); Forças-Oportunidades-Fraquezas-Ameaças (SWOT); Processo Analítico Hierárquico e lógica Fuzzy (FAHP)

Resumo Alargado

Motivação

Em 2022, aproximadamente 56,9% da população mundial residia em áreas urbanas, e esse número está projetado para atingir 68% até 2050 [1]. No mesmo ano, 74.2% da população da União Europeia residia em cidades, uma percentagem também projetada para subir para 83.7% até 2050 [2]. A procura de soluções para o transporte de pessoas e mercadorias mais rápidas e eficazes é do interesse geral de toda a população, especialmente com o aumento significativo da população urbana a nível global. Desta forma, compreender como é que tecnologias atuais e emergentes podem servir as cidades torna-se cada vez mais importante, visto que estas se devem tornar mais inteligentes, algo somente possível com a integração de soluções inovadoras como os veículos autónomos, a Inteligência Artificial (AI), a "Internet das coisas" (IoT) e a análise de dados. Os ambientes urbanos procuram otimizar o uso de recursos e a melhoria dos serviços públicos, com a intenção de promover um ambiente mais seguro para os seus habitantes, e de melhorar a sua qualidade de vida e felicidade.

Os Sistemas de Aeronaves Não Tripuladas (UAS) representam um recurso muito valioso em áreas como a agricultura, topografia e monitorização ambiental (entre outras), devido à sua versatilidade e flexibilidade operacional, aos métodos eficientes de recolha de dados e ao menor impacto ambiental e económico comparativamente a outras tecnologias. Estas vantagens tornam os UAS instrumentos úteis em contextos urbanos, permitindo uma ampla gama de aplicações para abordar diretamente os desafios da mobilidade urbana. Entre as aplicações mais estudadas em ambientes urbanos, encontram-se:

- Monitorização;
- Mapeamento e planeamento urbano;
- Gestão de tráfego multimodal;
- Inspeção e manutenção de infraestruturas.

Existe um grande potencial para progresso nesta área, tornando-se relevante entender como é que as vantagens tecnológicas atuais e emergentes dos UAS conseguem resolver ou minimizar problemas urbanos e contribuir para o desenvolvimento de uma cidade inteligente, onde os principais pilares são a automação, a sustentabilidade, a conexão/digitalização e modernidade. No entanto, a integração de UAS em cidades pode levantar questões, especialmente de índole legal e ética. Preocupações com privacidade e segurança de dados tornaram necessário o reforço da governação de tudo o que está relacionado com os UAS, sendo crucial avaliar como as componentes legais envolvidas são condicionadas e compreender como o público encara estes aspetos [3], [4].

O processo de integração de UAS em ambientes urbanos em larga escala está ainda numa etapa inicial de implementação (certificação de produtos de maior robustez tecnológica aptos a operar em áreas urbanas e execução de provas de conceito pontuais a nível global), sendo essencial que todas as partes envolvidas se preparem para uma realidade que é considerada iminente. Por conseguinte, torna-se interessante selecionar um caso específico para explorar os benefícios e constrangimentos da introdução de UAS numa cidade em concreto a diversos níveis, avaliando em que áreas específicas nas quais a aplicação de UAS pode ou não ser benéfica, e que fatores podem condicionar positiva ou negativamente esta implementação. Assim, torna-se crucial compreender os passos que devem ser tomados de forma a melhorar o nível de preparação supramencionado e estabelecer estratégias para continuar este processo.

Objeto e Objetivos

O objeto desta dissertação é compreender a complementaridade entre os UAS e o paradigma de uma cidade inteligente.

Os principais objetivos são os seguintes:

1. Compreender de que forma os UAS contribuem para o desenvolvimento de uma cidade inteligente;
2. Avaliar o estado atual do uso de UAS num contexto europeu, com foco no caso de estudo escolhido – Porto;
3. Avaliar que medidas podem ser tomadas no Porto para a aplicação de UAS, em linha com a visão europeia;
4. Estabelecer prioridades para a implementação de UAS no Porto seguindo a filosofia de cidades inteligentes, e tendo em conta o contexto envolvente.

Metodologia

O presente trabalho iniciou-se com uma revisão bibliográfica extensiva, que consistiu numa profunda recolha de informação relativa aos principais temas desta dissertação –

as principais características das cidades inteligentes, as características tecnológicas dos veículos aéreos não tripulados e sistemas associados, o papel da Mobilidade Aérea Urbana como grande vetor de implementação dessa tecnologia e ferramentas de planeamento estratégico. Dessa forma, a realização do objetivo relacionado com o estabelecimento de uma conexão entre os conceitos de sistemas aéreos não tripulados e cidades inteligentes tornou-se possível, através de exemplos já implementados ou previstos para um futuro próximo, associando cada um destes às diferentes componentes de uma cidade inteligente.

De seguida, foi realizado um estudo da realidade da cidade do Porto no que diz respeito a aspetos atuais e relativamente ao potencial dos sistemas aéreos não tripulados no quotidiano urbano, num contexto de uma cidade inteligente. Este estudo permitiu a identificação de 20 fatores/subcritérios, integrantes de uma análise SWOT (Forças-Oportunidades-Fraquezas-Ameaças), de impacto significativo, seja como impulsionadores ou condicionantes, na implementação de UAS num contexto de cidades inteligentes e aplicados à realidade em questão. Os fatores foram divididos em cinco positivos e internos (resumidos num critério geral denominado de Forças), 5 negativos e internos (Fraquezas), 5 positivos e externos (Oportunidades), 5 negativos e externos (Ameaças). Através da interseção dos subcritérios e do conceito da matriz TOWS, foi possível proceder à elaboração de quatro estratégias de implementação.

Após o passo anteriormente mencionado, foram consultados especialistas de áreas como tecnologia, planeamento urbano e legislação para providenciarem a sua opinião sobre o assunto, através de variáveis linguísticas. Numa primeira parte, foi solicitado que comparassem individualmente cada um dos subcritérios englobados no mesmo critério e que de seguida comparassem coletivamente os 4 critérios, de forma a obter um ranking geral dos 20 subcritérios. A obtenção desta lista ordenada foi possível através da conversão das variáveis linguísticas em numéricas, atribuindo-se seguidamente um peso a cada de forma a balancear a contribuição das diversas áreas de especialidade, e contemplando isso no processo de agregação de resultados. Posto isto, reuniram-se as condições para aplicar modelos matemáticos recorrentemente usados num contexto de planeamento estratégico, como o FAHP (Processo Analítico Hierárquico e lógica Fuzzy), usado para determinar os pesos globais de cada subcritério.

Na segunda parte do inquérito, foi solicitado aos especialistas que estimassem a importância dos subcritérios positivos na concretização das estratégias, bem como o papel das estratégias na mitigação dos subcritérios negativos relacionados com a implementação de sistemas aéreos não tripulados num contexto de uma cidade inteligente, de forma a obter diretrizes gerais sobre possíveis passos a tomar. O processo de tratamento de dados assemelhou-se ao da primeira fase, havendo diferenças chave baseadas na escala linguística utilizada.

Por fim, os resultados obtidos permitiram tirar conclusões, tanto a nível dos subcritérios que passaram a uma exploração mais aprofundada para, porventura, viabilizarem a elaboração de novas estratégias ou a modificação das abordagens, bem como a perceção da priorização mais adequada das estratégias identificadas, entre outros aspetos. O processo de interpretação e discussão de resultados foi complementado com uma validação de resultados conduzida por uma empresa do setor localizada no Porto por meio de uma entrevista estruturada. Este processo consistiu, principalmente, em recolher informação sobre potenciais fatores e estratégias que não foram apontados na análise, e em analisar a opinião da empresa relativamente aos *rankings* obtidos no contexto da comparação de subcritérios e de priorização de estratégias.

Análise e Resultados

Da análise qualitativa, quantitativa e do processo de validação foram extraídas as seguintes conclusões:

- Critérios e subcritérios – os inquiridos identificaram o facto de o Porto ser um ecossistema urbano que reúne diversas características intrínsecas de cidades inteligentes (dinâmico, colaborativo, digital e ambientalmente sustentável), e a criação de postos de trabalho e de oportunidades de negócio, resultantes do desenvolvimento da indústria dos UAS, como os subcritérios positivos mais relevantes para a implementação desta tecnologia na cidade. Por outro lado, foram apontadas como principais limitações a inexistência de um conjunto robusto de leis e regulamentos que asseguram o suporte eficaz à implementação desta tecnologia em larga escala. Estas lacunas regulatórias são particularmente relevantes devido ao elevado potencial grau de comprometimento a nível de *safety* (especialmente devido aos desafios associados ao nível de coexistência dos UAS com a aviação tripulada e com o meio urbano) e de *security* agregados. A Speedbird Aero, responsável pelo processo de validação, concorda, de forma geral, com estes resultados, principalmente com as fraquezas e ameaças identificadas como sendo as mais significativas. No entanto, a empresa sublinha também que a proatividade das instituições europeias constitui uma oportunidade estratégica crucial. Para além disso, a empresa adota uma abordagem centrada no veículo para identificação dos fatores internos positivos com maior preponderância, destacando assim o impacto ambiental reduzido dos UAS como o benefício mais primordial;

Estratégias – a estratégia considerada mais relevante pelos inquiridos foi o desenvolvimento de parcerias com iniciativas ligadas às cidades inteligentes, com o objetivo de criar mecanismos de integração dos UAS no âmbito destas iniciativas. Numa ordem de implementação elaborada com base nas opiniões dos inquiridos, à estratégia acima mencionada sucedeu-se o desenvolvimento de um modelo de *safety* e *security* para abordar a complexidade e a constante evolução da legislação ligada às operações de UAS, bem como a criação de mecanismos de colaboração com parceiros europeus de forma a garantir os fundos necessários para, nomeadamente, satisfazer requisitos de infraestrutura. Em último lugar, apresenta-se a estratégia relacionada com o uso da fraqueza relacionada com o tempo necessário para a implementação em larga escala como uma oportunidade de melhorar a aceitação pública desta tecnologia. A Speedbird Aero concorda com a ordem de implementação e priorização destas três últimas estratégias, colocando, no entanto, a estratégia mais relevante na opinião dos inquiridos no último lugar da hierarquia. Com base na combinação dos contributos de ambas as partes envolvidas e na importância atribuída aos subcritérios relacionados, concluiu-se que a estratégia relacionada com o aproveitamento de forças para eliminar ameaças - desenvolvimento de um modelo de *safety* e *security* para abordar a complexidade e natureza de constante evolução da legislação ligada às operações de UAS - deverá ser o passo mais imediato a tomar de entre os identificados. Adicionalmente, a empresa sugeriu a adoção de outras estratégias, que assentam, entre outras coisas, em retirar benefícios de um *momentum* nacional e local transversal às áreas de foco desta dissertação.

Conclusão

De facto, a relação entre os UAS e as cidades inteligentes apresenta um potencial bastante significativo. Embora o conceito de cidade inteligente possua um grau considerável de subjetividade, existe um consenso generalizado de que o grande objetivo de uma cidade inteligente deve ser a melhoria de qualidade de vida dos seus habitantes, alicerçada numa filosofia de sustentabilidade e em progresso económico e social. O estatuto de cidade inteligente só pode ser adquirido ou consolidado através do cumprimento eficaz das diversas componentes nas quais o conceito de cidade inteligente se divide (*smart* *services*, *smart infrastructure*, *smart health*, entre outras). Neste contexto, os UAS, com base em aplicações práticas já estudadas, demonstram um potencial substancial para contribuir para a obtenção ou manutenção desse estatuto.

No entanto, tanto o Porto como a realidade europeia encontram-se ainda numa fase muito inicial do processo de implementação de UAS em larga escala, sendo as perspetivas de progresso rápido, de momento, pouco animadoras. Este facto deve-se, entre outros motivos, principalmente à inexistência de um enquadramento legislativo capaz de lidar eficazmente com questões relacionadas com *safety* e *security*, Adicionalmente, outros fatores, tais como a falta de compreensão generalizada acerca do tempo e dos recursos financeiros necessários para o desenvolvimento e certificação dos UAS têm contribuído para um aumento de receio por parte dos investidores, resultando numa retração significativa nos investimentos. Esta série negativa de eventos negativos tem, inclusive, levado ao encerramento de várias empresas do setor.

Porém, conforme verificado através dos resultados obtidos, existe também um número considerável de fatores positivos que reforçam o potencial da implementação desta tecnologia em meios urbanos como o Porto - um exemplo de ambiente digital, sustentável, proativo, e que possui o claro objetivo de diversificar a sua economia. Este fator, aliado ao elevado potencial destes veículos em responder eficazmente às necessidades dos meios urbanos, oferece grandes condições para proporcionar a receita ideal para o sucesso.

Investigação futura

Relativamente a perspetivas de investigação futura, seria relevante explorar os benefícios derivados dos fatores positivos e mitigar os negativos através do desenvolvimento e adoção de novas estratégias, elaboradas com base no peso atribuído a cada um dos subcritérios, para que as estratégias se foquem em abordar os fatores identificados como mais significativos. Caso seja adotada uma abordagem semelhante à deste trabalho, seria essencial considerar o nível de conhecimento dos inquiridos, de forma a melhorar a precisão dos resultados obtidos. Uma abordagem assente na constituição de um painel de especialistas diversificado para a definição qualitativa de fatores e estratégias poderia enriquecer substancialmente o processo. Por fim, uma última sugestão passaria por examinar mais detalhadamente alguns dos fatores identificados - caso se opte por estudar mais a fundo a realidade local do Porto, seria importante investigar a aceitação pública dos residentes em relação à implementação em larga escala de uma tecnologia como os UAS, por exemplo.

Abstract

The increasing number of urban residents presents growing challenges that require innovative and efficient solutions. Cities are looking for smarter approaches, which involve the optimization of resource usage and the improvement of public services, with the aim of enhancing the quality of life and overall satisfaction of residents through sustainable practices. Current and emerging innovative technologies provide effective tools for addressing urban challenges. Unmanned Aircraft Systems (UAS) present a valuable solution, due to their versatility, flexibility, efficient data collection methods, and lower environmental and economic impact compared to other technologies (e.g., helicopters, general aviation aircraft). UAS have been extensively studied as they offer a large variety of urban applications, such as monitoring, traffic management, and infrastructure inspection. In the near future, they are also expected to start carrying passengers and delivering goods in Europe, contributing to the development of Urban Air Mobility (UAM), a priority among the European Union's (EU) sustainable urban mobility initiatives.

This work proposed the application of a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis to qualitatively evaluate the key factors influencing the implementation of UAS in Porto, alongside the use of the TOWS matrix to define strategies of implementation. The Fuzzy Analytical Hierarchical Process (FAHP) was used to identify the most relevant factors from the perspective of respondents with expertise in various relevant fields. Other quantitative methods were also applied to establish a prioritization order for the proposed strategies, aiming to identify initiatives that would position Porto closer to widely recognized smart cities. The obtained results were validated in a partnership with a UAS sector company based in the city under study.

The combination of both stages allowed for the conclusion that Porto has significant potential for the implementation of UAS within the smart city paradigm. Among the key favourable factors are the city's proactive, dynamic and collaborative nature - regarding the urban environment, and the environmental sustainability intrinsic to UAS – regarding the vehicle itself. Additionally, the potential for creation of jobs and business opportunities with the development of this industry emerged as the major benefit of this implementation. However, the study highlighted also substantial concerns regarding both the fragility of the current legislative framework and its constantly evolving nature, as well as the inherent complexity, all of which amplify the challenges associated with safety and security.

Keywords

Smart City, Quality of Life, Sustainability, Unmanned Aircraft Systems (UAS), Unmanned Aerial Vehicle (UAV), Drone, Urban Air Mobility (UAM), Innovative Air Mobility (IAM), Strengths-Weaknesses-Opportunities-Threats (SWOT), Fuzzy Analytical Hierarchy Process (FAHP)

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List of Acronyms

ACAS	Airborne Collision Avoidance System
AED	Automated External Defibrillator
AHP	Analytic Hierarchy Process
AMC	Acceptable Means of Compliance
AltMOC	Alternative Means of Compliance
ANAC	Portuguese Civil Aviation Authority
ARA	Airspace Risk Assessment
AUVSI	Association for Unmanned Vehicle Systems International
B2B	Business to Business
B2C	Business to Costumer
BLU-Space	Blueprint U-Space
BMDV	German Ministry for Digital and Transport
BNP	Best Non-fuzzy Performance
BOS	Authorities and Organizations with Security Tasks
BVLOS	Beyond Visual Line-Of-Sight
CD	Common Drone
CHF	Confoederatio Helvetica Franc
DGES	Directorate General for Higher Education
EASA	European Union Aviation Safety Agency
EU	European Union
eVTOL	Electric Vertical Take-Off and Landing
FAA	Federal Aviation Administration
FAHP	Fuzzy Analytic Hierarchy Process
FEUP	Faculty of Engineering of the University of Porto
GCS	Ground Control Station
GM	Guidance Material
GPS	Global Positioning System
GRP	Gabinete de Relações Públicas
GWP	Global Warming Potential
IAM	Innovative Air Mobility
IBM	International Business Machines Corporation
ICAO	International Civil Aviation Organization
ICC	Intelligent Cities Challenge
ICT	Information and Communication Technologies
IMD	Institute for Management Development
IMU	Inertial Measurement Unit
IoT	Internet of Things
IT	Information Technology
LED	Light-Emitting Diode
LiDAR	Light Detection And Ranging
LOC-I	Loss of Control - In Flight
LOS	Line Of Sight
LUC	Light UAS Operator Certificate
MaaS	Mobility as a Service
MCDM	Multi-Criteria Decision Making

NASA	National Aeronautics and Space Administration
OA	Operational Authorization
OECD	Organization for Economic Cooperation and Development
PIC	Pilot In Command
RGB	Red Green Blue
SCF-NP	System/Component Failure or Malfunction [Non-Powerplant]
SORA	Specific Operations Risk Assessment
STCP	Sociedade de Transportes Coletivos do Porto
STS	Standard Scenarios
sUAS	Small Unmanned Aircraft Systems
SWOT	Strenghts-Weaknesses-Opportunities-Threats
TFN	Triangular Fuzzy Number
TOWS	Threats-Opportunities-Weaknesses-Strenghts
UAM	Urban Air Mobility
UAS	Unmanned Aircraft Systems
UAV	Unmanned Aerial Vehicle
UBI	Universidade da Beira Interior
UML	UAM Maturity Levels
VLOS	Visual Line Of Sight
VTOL	Vertical Take-Off and Landing
WRD	Weather-Resistant Drone
ZLT	Zonas Livres Tecnológicas

Chapter 1 - Introduction

1.1 Motivation

In 2022, it was estimated that 56.9% of the world's population was living in urban environments, a percentage expected to rise to 68% by 2050 [1]. In the same year, 74.2% of the European Union population lived in cities, a percentage projected to increase to 83.7% by 2050 [2]. The search for easier and more rapid solutions is of general interest to the entire population, and even more with the significant increase in urban population worldwide. Understanding how present or emerging technologies can serve cities is getting more important day by day as they must become smarter, something possible only with the integration of innovative technologies such as artificial intelligence, the Internet of Things (IoT) and data analysis. Urban environments seek an optimization of resource usage and an improvement of public services, with the intention of promoting a safer and more practical environment for residents and of improving their quality of life and happiness.

Unmanned Aircraft Systems (UAS) represent a valuable tool in a wide variety of areas (agriculture, topography, environmental monitoring, among others) due to numerous factors, like operational flexibility, speed, and environmental and economic impact compared to other tools. These advantages, combined with efficient data collection methods and their high versatility, make UAS an useful instrument in an urban context, as they enable a wide range of applications for a direct approach to urban challenges. Among the most studied and already implemented applications in urban environments, the following stand out:

- Monitoring;
- Mapping and urban planning;
- Multimodal traffic management;
- Infrastructure inspection and maintenance.

There is a lot of potential for advancement in this area, making it relevant to understand how current and emerging UAS technologies can resolve or minimize urban problems and contribute to the development of a smart city, where automation, sustainability, and modernity are predominant. However, the inclusion of UAS in urban environments raises some questions, especially of a legal and ethical nature. Concerns around privacy and data security have made enhancing UAS governance a necessity and have made it crucial to evaluate how the legal components involved are conditioned and to understand how the public perceives this implementation [3], [4].

The process of integrating UAS into urban environments on a large scale is at an early stage of development and preparation, as everyone is getting ready for this near-future reality. For that reason, it becomes interesting to proceed with the selection of a specific case study and to evaluate the benefits and constraints of introducing UAS to that city, to assess the specific areas and ways in which the application of UAS is beneficial, and to understand which steps should be taken next, including strategies for their adoption and the correct order for implementation.

1.2 Object and objectives

The object of this dissertation is the understanding of the complementarity between UAS and the smart city paradigm.

The main objectives are as follows:

1. Understand in which ways UAS contribute to the development of a smart city;
2. Evaluate the status regarding the use of UAS in European cities, with a focus on the chosen case study (Porto);
3. Assess the steps that can be taken in Porto for UAS application, in alignment with European goals;
4. Establish priorities for the smart implementation of UAS in Porto, considering the surrounding context.

1.3 Methodology

This work began with an extensive literature review, which consisted in a thorough collection of information related to the main themes of this dissertation – the main characteristics of smart cities, the technological features of UAS, the role of UAM as the main driver of UAS in urban environments, and strategic planning tools. Next, a study on the reality of the city of Porto regarding current aspects and the potential of UAS in the daily life in the context of a smart city.

Both proceedings allowed the identification of 20 factors/sub-criteria, inserted in a SWOT (Strengths-Opportunities-Weaknesses-Threats) analysis, which are predicted to have a significant impact, either as drivers or constraints, on the implementation of UAS in the chosen case study - Porto. The factors were divided into five positive and internal (which can be summarized into a general criterion called Strengths), five negative and internal (Weaknesses), five positive and external (Opportunities), and five negative and external (Threats). Through the intersection of the sub-criteria and the concept of TOWS (Threats-Opportunities-Weaknesses-Strengths) matrix, four strategies of implementation were developed.

After this step, experts in fields such as technology, urban planning, and legislation were asked to provide their opinions on the subject, using linguistic variables. In the first part, they were asked to individually compare each of the sub-criteria within the same criterion and then compare the four criteria in a collective way, in order to elaborate an overall ranking of the 20 sub-criteria. This ordered list was achieved by converting linguistic variables into numerical values, followed by assigning a weight to each to balance the contribution from the different areas of expertise, incorporating this into the result aggregation process. This set the stage for applying mathematical models commonly used in strategic planning contexts, such as the FAHP (Fuzzy Analytic Hierarchy Process), which was used to determine the global weights of each sub-criterion.

In the second part of the survey, experts were asked to estimate the importance of the positive sub-criteria in achieving the strategies, as well as the role of the strategies in mitigating the negative sub-criteria related to the implementation of UAS within a smart city framework, to obtain general guidelines on possible steps to take. The data processing method was like that of the first phase, with key differences based on the linguistic scale to be noticed.

Finally, the results obtained allowed conclusions to be drawn, both in terms of which sub-criteria should be further explored to perhaps develop new strategies or modify approaches, and in terms of understanding which of the identified strategies should be prioritized, among other aspects. The process of results interpretation and discussion was further enriched through a validation process conducted by SpeedBird Aero, a company working in the sector and located in the city central to this study.

Figure 1 summarizes the overall methodological framework used in the core analysis of this dissertation, with the primary objectives of identifying the most relevant SWOT sub-criteria within the current context and prioritizing strategic approaches accordingly.

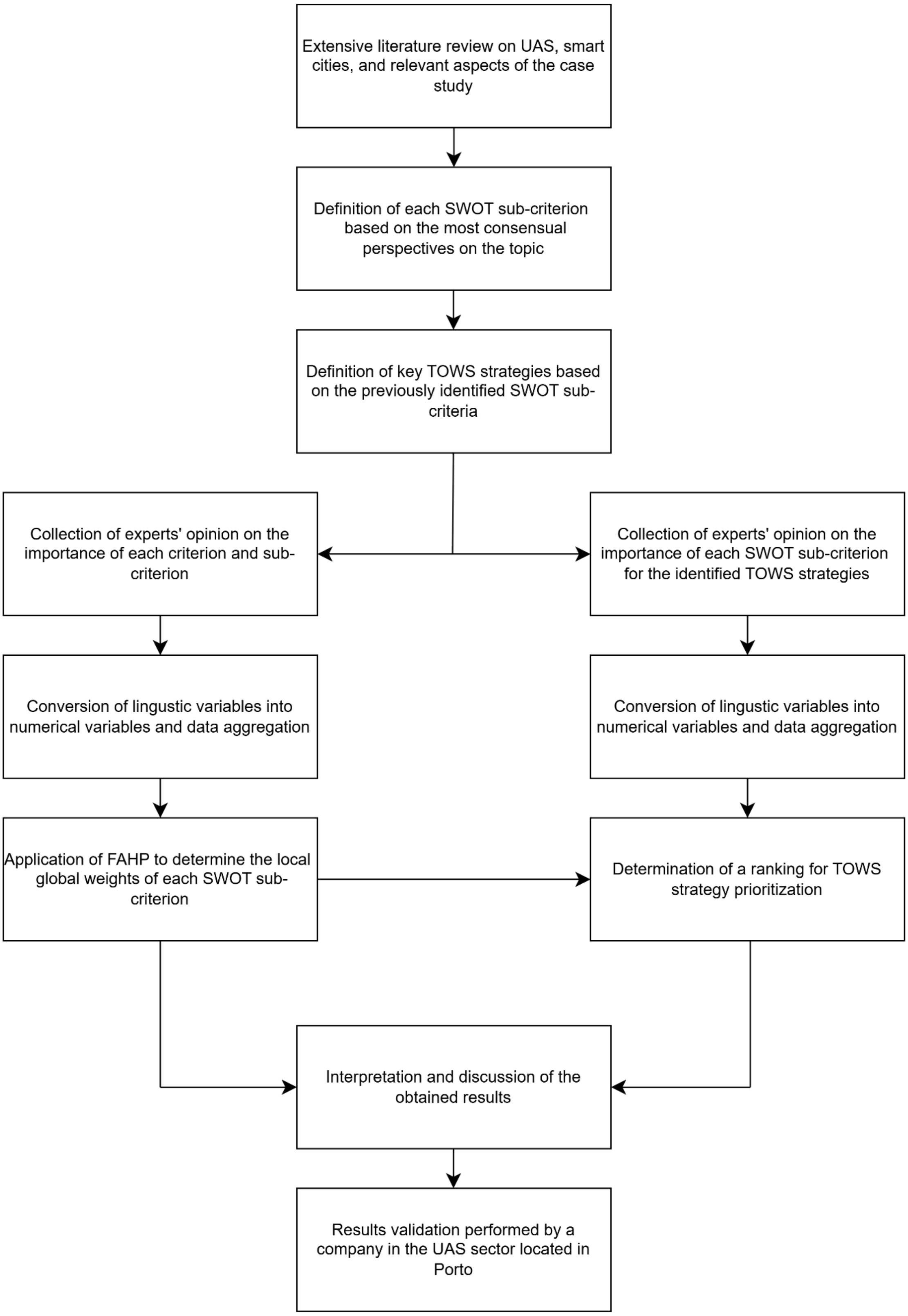

Figure 1 - SWOT-FAHP analysis and results validation: methodology flowchart - Source: own elaboration

1.4 Dissertation structure

The development of the dissertation will begin with the clear and objective definition of the research questions, followed by a detailed reading of articles related to the topics, allowing for the collection of maximum information to elaborate a concrete study. Therefore, Chapter 1 will include the motivation, object, objectives, methodology, and the structure of the dissertation.

Chapter 2 will present the necessary theoretical framework and an overall overview of key concepts for further particularization, based on a literature review. As a result, the concept of smart cities, its various interpretations, and different components will be introduced. Following this, general considerations about UAS will be discussed, especially their main technological features and elements. The role of UAM as the main driver for the large-scale implementation of unmanned aviation in cities and the main challenges related to the integration of UAS and UAM in urban environments will also be highlighted. This chapter also aims at building a bridge between two key aspects of this dissertation: UAS and smart city, by specifying existing cases on how unmanned aviation can be integrated into each smart city component. Finally, a theoretical framework related to the qualitative and quantitative analyses that will be performed for the case study will be conducted.

In Chapter 3, an analysis of the current state regarding the implementation of UAS in Porto will open the case study. In addition to this, a SWOT analysis will be performed, identifying strengths, weaknesses, opportunities, and threats of the implementation of UAS in Porto, and a TOWS matrix will be developed to explore strategic options. Both analyses will be based on a literature review and will be complemented by quantitative methods such as FAHP, which will allow the assessment of the factors and strategies identified by the SWOT and TOWS analyses, through the feedback provided by respondents from various fields – technology, governance, etc.

In Chapter 4, the results obtained from the previous chapter will be analysed and interpreted, to clarify the feasibility and strategic pathways for using unmanned aviation to enhance Porto's "smartness". As a result, the importance of each internal and external factors that could influence the smart implementation of UAS in Porto will be evaluated and an order of strategy implementation will be discussed and elaborated. The chapter will close with a results validation process conducted by Speedbird Aero, a company actively operating in the field of UAS and based in Porto that will also provide valuable insights on the results obtained from the above-mentioned qualitative and quantitative analyses.

Finally, in Chapter 5, the main conclusions drawn throughout the document will be summarized to reinforce the most important general points and an assessment of the objectives drawn will be made. Suggestions for future research will also be mentioned whether through further analysis or a different approach.

Chapter 2 - Literature Review

2.1 Introduction

This chapter focuses on the essential foundations necessary for a comprehensive and detailed study. In first place, the concept of smart cities, their characteristics, components, and globally recognized examples will be explored. Next, the main technological elements of UAS will be introduced, without ignoring the role of Urban Air Mobility (UAM) as a critical enabler of UAS in urban environments, as well as the main associated challenges.

An interconnection between the two key concepts of this dissertation – smart cities and UAS - will then be established, through the link of studied UAS applications to their relevant smart city components. Finally, the main theoretical concepts needed for a thorough strategic planning analysis will be presented, explaining both the theoretical and numerical methodologies involved.

2.2 Smart cities: an overview

In 2022, it was estimated that 56.9% of the world's population and 74.2% of the European Union population was living in urban environments, a percentage expected to rise to 68% and 83,7% by 2050, respectively [1], [2].

In both developed and developing countries, this increase is motivated by rural exodus, a phenomenon that has direct impacts on both rural and urban environments and that leads to a permanent need for adaptation to the challenges faced by both. In urban environments, these challenges require creative and innovative approaches to manage the increasing complexity of urban-level issues such as overpopulation, resource management, energy consumption and environmental protection in an efficient way [5]. One of the most popular approaches is the concept of smart cities.

In this subchapter, the definition and main aspects of a smart city will be explored, as well as its key characteristics and components. The world's most widely accepted examples of smart cities will also be showcased.

2.2.1 Purpose and concept

In recent years, there has been a lot of global interest in smart cities. The increasing popularity of this concept is justified by the fact that it is extremely current, since it makes a healthy balance between technological development, automation, and sustainability, with the objective of improving the quality of life of its inhabitants.

The European Commission defines a smart city as "a place where traditional networks and services are made more efficient with the use of digital solutions for the benefit of its inhabitants and business" [6]. Some authors define smart cities as "cities that balance economic, environmental, and societal advances to improve the well-being of residents through a widespread introduction of Information and Communication Technologies (ICT) and other technological tools" [7][1], or as a city that "employs a combination of data collection, processing, and disseminating technologies in conjunction with networking and computing technologies and data security and privacy measures encouraging application innovation to promote the overall quality of life for its citizens and covering dimensions that include utilities, health, transportation, entertainment, and government services" [8][2]. Other authors add the word "sustainable" to underscore the necessity of fulfilling the requirements of both present and future generations: "a smart sustainable city is an innovative city that uses ICT and other means to improve quality of life, the efficiency of urban operations and services, and competitiveness, while ensuring that it meets the needs of the present and future generations concerning economic, social and environmental aspects" [9][3].

Based on the definitions presented above and on the most widely accepted perspectives on the topic, there is clear consensus regarding the use of innovative approaches and technologies, leading to an increase in efficiency in urban operations. There are also agreements on the importance of environmental sustainability as part of a smart solution and, most notably, that the primary goal of smart cities should be to improve the quality of life of residents, which is only achieved through progress in economic, societal, and environmental domains and by covering a wide range of dimensions (health, transportation, entertainment, etc.).

Although the previously mentioned agreements allow to conclude there is a lot of common ground on the overall perspective about a smart city, there is no universally

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[1] [7] – pp.4
[2] [8] – pp.1
[3] [9] – pp.606

accepted decision on the definition of smart cities [10]. Defining and measuring a smart city might be complex due to the variations in economic and social contexts from city to city. These differences lead to diverse priorities, meaning that it becomes challenging to define a universal and consistent system of evaluation [11]. The evolving nature related to the concept is another obstacle that increases the difficult to reach an agreement on a globally recognized vision of the topic, which is noticeable by the fact that technology is constantly evolving, meaning that the range of technological options for urban purposes is in permanent change and, as a consequence of that, new and potentially better possibilities to achieve efficiency of operation in the management of urban environments become available. The economic, societal, and environmental challenges of a certain city also change in a permanent and rapid way, which leads to drastic changes in terms of priorities in urban planning and management, reflected in the approaches and tools used to respond to these challenges.

Figure 2 illustrates a Top 10 list of the most frequently used words in smart city definitions, based on a list of 34 definitions proposed by various authors [10].

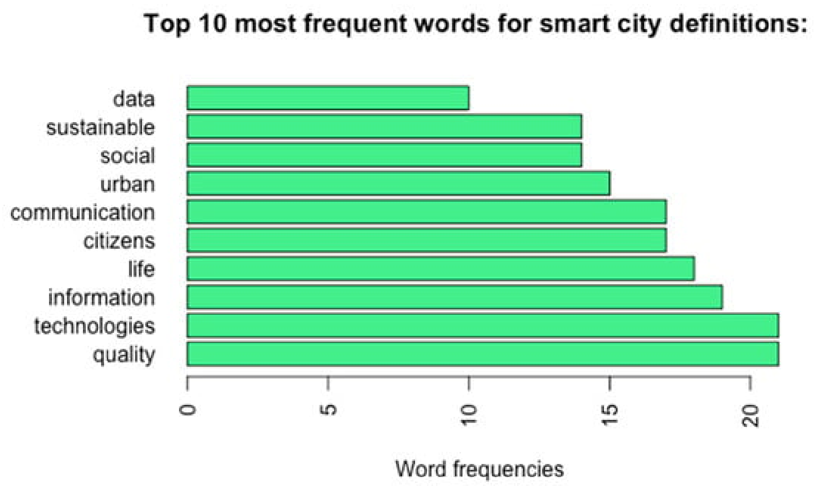

Figure 2 - Word Frequency Plot Generated Using Compiled List of Smart City Definitions - Source: [10]

From this plot, it is evident that the most frequent words in the list of 34 definitions correspond to the components of smart cities where there is a consensus. The word 'quality' is the most common and is mostly associated with the fourth and fifth words of the list – 'life' and 'citizens', reinforcing the primary goal of a smart city, which is to improve the quality of life of citizens. The words 'information', 'communication', and 'technologies' appear together most of the time, highlighting the importance of ICT in the process. As a result, the same authors propose a concise definition, that covers which could be regarded as the main aspects of modern smart cities: "Smart cities use digital technologies, communication technologies, and data analytics, to create an efficient and effective service environment that improves urban quality of life and promotes sustainability" [10][4].

For a better understanding the concept, it is essential to highlight some of the main characteristics of smart cities, and their role on a city's objective of becoming smarter. Figure 3 illustrates the most relevant aspects of smart cities, and the tools used to ensure that these characteristics are fulfilled.

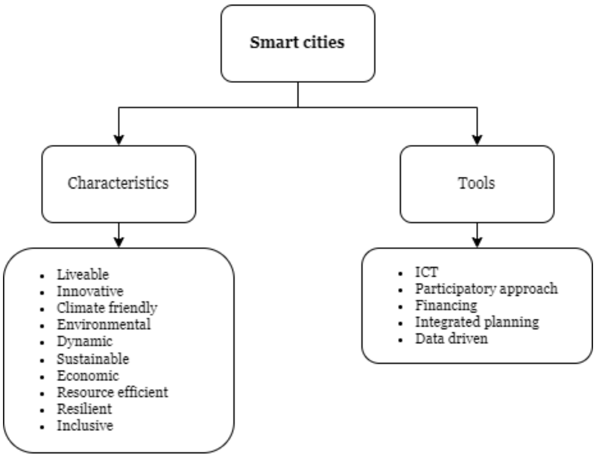

Figure 3 - Characteristics and tools of a smart city - Source: own elaboration based on [5]

2.2.2 Key dimensions

The components of a smart city are an integral part of the whole concept. They consist of requirements that must be carefully assessed to determine whether they are already smart or if different approaches are necessary to fulfil them. A city can only be deemed as smart if all these key elements meet this standard. The lack of consensus in finding a single, universally accepted definition for smart cities also extends to the breakdown of its constituent parts, especially regarding what criteria must be met for each element to be considered smart. These needs differ due to a multitude of factors, most notably distinct social and economic realities, influencing the key priorities and focus of each initiative. Figure 4 proposes a list of eight key components and covers every relevant requirement that must be fulfilled for a city to be smart.

[4] [10] – pp. 1724

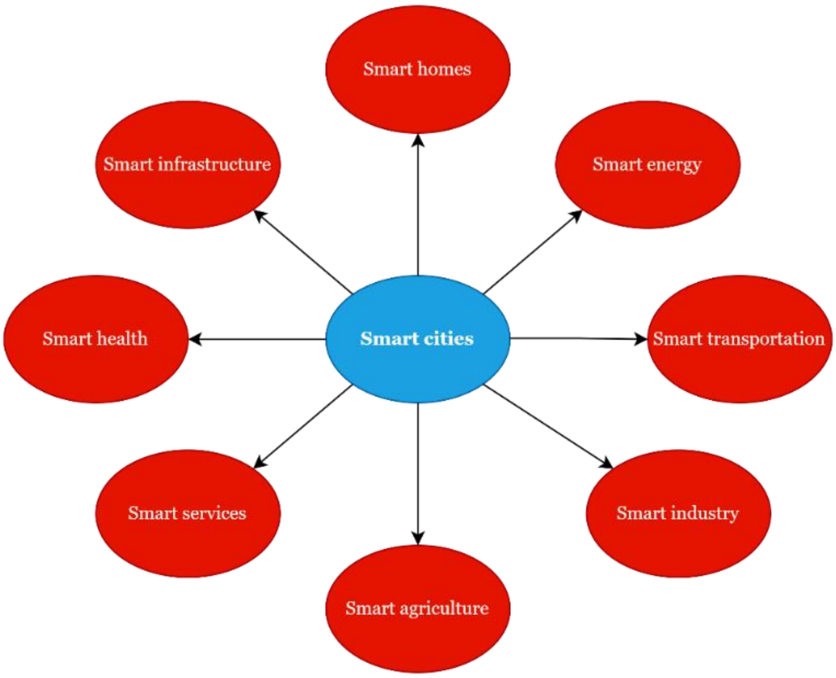

Figure 4 - Key Components of a Smart City - Source: own elaboration based on [12]

Here is a summary of every smart city component identified in Figure 4:

- Smart homes – key within the smart city paradigm, as it is a critical aspect for enhanced quality of life for citizens. A smart home essentially consists of the application of sensors or microprocessors for improved comfort or security. Homes have been increasingly integrated with devices that can be managed through smartphones, ranging from simple applications, such as lighting, to more advanced ones, like entertainment, security or luxury systems [13], [14]. The main benefits of current smart home practices include their high adaptability to residents' preferences and their capacity to ensure a safer space, while being energy efficient [14];
- Smart energy – a concept developed with the goal of promoting sustainable practices to optimize energy production and consumption, as the increasing use energy has been a significant factor of compromised environmental sustainability [15]. The main objective of this component is to optimize the generation and usage of various energy sources (e.g., electricity and natural gas) [12]. The promotion and support of the adoption of electric vehicles is also a relevant example of an environmentally friendly practice that aims at managing energy in the smartest possible way in urban environments;

- Smart transportation – use of innovative technologies (notably IoT) to make transportation more efficient, more sustainable, and safer. Common applications include accident detection, parking optimization, detection of road anomalies, and infrastructure improvement [16], with the general advantages of a smart transportation system ranging from improved environmental impact to efficiency in addressing traffic problems, only possible through improved connection between the various involving parts in a safe transportation framework (vehicles, pedestrians, infrastructure) [12], [17];
- Smart industry – aims at increasing the overall productivity while reducing cost, using IoT (Internet of Things), and AI (Artificial Intelligence). This concept is often associated with Industry 4.0, a paradigm that has increased the efficiency of production processes and that has achieved better quality control at all stages of the supply chain, while contributing positively to the global need of better environmental sustainability [18]. The implementation of IoT and sensors in a wide range of industrial processes provides opportunities for faster and better innovation, increased automation, optimization of manufacturing schemes, better quality of products, improved safety, and to perform business intelligence operations [12];
- Smart agriculture – a smart urban environment is highly dependent on a smart and sustainable agriculture system. The world population's rapid growth and food insecurity (affecting around 26% of the global population) are two of the most impactful ongoing challenges in the world. Therefore, the increasing food demand highlights the need for cities to have strong and reliable food supplies while managing these resources efficiently. This goal has been and will continue to be achieved using innovative agricultural models leveraging IoT technologies [19];
- Smart services – involve the use of the above-mentioned technologies and solutions for better efficiency in various urban services. While the concept has a broad range of interpretations and approaches, it is often associated with smart municipal services, such as supply of water, resource management, as well as as various types of monitoring, including crowd monitoring, disaster management, and more [12];
- Smart health – use of IoT and refined machine learning algorithms to improve medical services [20], through applications like medicine delivery, improved diagnosis assistance, and health trackers. As a matter of fact, a smart healthcare is associated with increased accessibility and quality, as well as with an increased link not only between patients and doctors, but also between medical

professionals themselves and researchers [20], [21]. The prioritization of this aspect occurs because it is perceived as a key factor for residents, and especially with the increasing number of people living in urban environments [22];

- Smart infrastructure – Smart infrastructure refers to the integration of digital technologies and data-driven solutions to ensure the well-functioning of urban infrastructure systems. These initiatives involve the use of technologies, particularly sensors, in the continuous maintenance of physical infrastructure, with the aim of ensuring roads, bridges, and buildings remain operational by monitoring parameters such as structural health [12].

There is no consensus on this topic among authors either, and consequently the focus of each perspective varies a lot. Some encompass all economic activities in a single category called "smart economy" [11], while others defend that governance should be given more emphasis and have its own component [11], [23], rather than being included in "smart services" or "smart infrastructure" or than being perceived as a cohesion element between all the above.

2.2.3 Worldwide examples

Having already explored the concept, its major components, it becomes relevant to provide concrete examples of smart cities now, and to specify the most distinctive factors contributing to their high degree of intelligence, sustainability, and innovation, to serve as examples afterwards. Since it has been highlighted throughout this subchapter, there is a high level of subjectivity associated with the elements that define a smart city, leading to a broad range of interpretations in the attribution of that status. It is common for cities to align with many of the previously presented characteristics and components but, at the same time, be far from meeting requirements often perceived as key and determinant to be classified as smart.

Table 1 provides a valuable tool for choosing two of the most widely recognized examples of smart cities, to later mention some key aspects that contribute to their smartness. It shows the evolution of the rankings for cities that were in the top 10 in the 2023 Institute for Management Development (IMD) Smart City Index. This ranking is obtained through the perceptions of citizens on issues related to structures (corresponding urban infrastructures) and technology applications (technological provisions and services) available to them. Both structures and technological applications are evaluated over five areas: health and safety, mobility, activities, opportunities, and governance [24].

Table 1 - IMD Smart City Index Rankings (2019-2023) - Source: [24]

City	Rank 2023	Rank 2021	Rank 2020	Rank 2019
Zurich	1	1	1	1
Oslo	2	2	2	2
Canberra	3	-	-	-
Copenhagen	4	5	3	4
Lausanne	5	4	-	-
London	6	3	10	3
Singapore	7	7	7	10
Helsinki	8	9	5	6
Geneva	9	6	8	7
Stockholm	10	11	9	9

Despite not being in the podium of the IMD Smart City Index 2023, Singapore is quite often seen as the best example of a smart city [25], while Zurich has been consistently holding the top spot of the mentioned ranking. For those reasons, the chosen cities for the effect were Singapore and Zurich.

Singapore's status of city-state is by itself a significant advantage, since any smart city initiative will automatically have a national and government dimension [25], allowing the city to be part of the world's first Smart Nation initiative [26]. Several challenges, like the lack of underground resources, increasing population density and very disparate weather conditions throughout the year led Singapore to adopt a smart response to address all the above. This response includes a list of several remarkable projects like the platform *GoBusiness* – directed at companies to have access to government e-services and licensing, and *E-Payments* - aimed at improved efficiency financial transactions. *Smart Urban Mobility* is another noteworthy example, as it involves the identification of commonly used points for commuters and the exploration of the use of hands-free fare gates, to make access easier to bus and train stations for people with reduced mobility. Self-driving vehicles are also being explored, as there have already been performed several experiments [27]. These initiatives and others are illustrated in Figure 5.

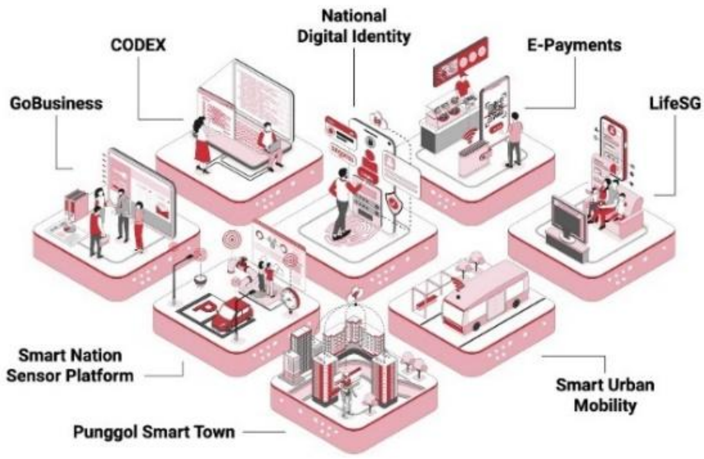

Figure 5 - Singapore Smart Nation Strategic National Projects - Source: [28]

As for Zurich, various lighthouse projects have been conducted under an initiative called *Smart City Zürich*. These projects include an online platform that provides the opportunity to submit ideas for the city district of Wipkingen. These ideas are then discussed and developed further, with residents of Wipkingen being able to allocate a budget of 40,000 CHF and decide which ideas should receive financial support. Another project consists of a mobility platform app that offers Mobility as a Service (MaaS), integrating various mobility providers in the urban area of Zurich, and offering a list of travel options between two points in the city [29]. Additionally, Zurich has a highly-rated online platform that provides real-time traffic situation within the city – another factor that contributes to the Swiss city's very high placement in mobility rankings [30].

There are numerous factors that contribute to each of these cities' smartness, but the mentioned ones are particularly valuable examples to follow in the pursuit for more automation, intelligence, and sustainability. It is worth noting that both are engaged in initiatives entirely dedicated to improving urban smartness, which is an aspect that certainly contributes for the global recognition of Singapore and Zurich as smart cities.

2.3 Unmanned Aircraft Systems

According to the 2021 International Civil Aviation Organization (ICAO) Annual Report, of UAS supported transportation and logistics global market was expected to rise from U$ 11 billion in 2022 to U$ 29 billion by 2027. Similarly, the same report refers to a projection in the growth in the production of UAS, with the produced units rising from 2 million in 2021 to 6.5 million in 2030 [31].

In this subchapter, the most relevant aspects of UAS will be presented, starting with an exploration of the concept and main technological aspects, before delving into their role in urban environments. The concept of UAM (Urban Air Mobility) as the main enhancer of the use of unmanned aircraft in urban environments and the challenges related to UAM initiatives will also be explored. Finally, the concept of U-space will also be showcased, as an example of a space fully dedicated to enable a safe and efficient access to urban airspaces for UAS, that might inspire the future assessment of the case study.

2.3.1 Definition and concept

ICAO defines UAS as "an aircraft and its associated elements which are operated with no pilot on board" [32][5].

The first use of unmanned aircraft dates to as early as the 19th century. In 1849, it is reported that unmanned balloons were used in a military action, with two hundred ballons carrying 33 pounds of explosives equipped with 30-minute time fuses. They were used in an attack on Venice, which was perpetrated by the Austrian military [33]. Since then, unmanned aviation technologies have been getting more sophisticated and increasingly common, as almost two centuries later UAS represent the most efficient tool to solve challenges that need rapid and innovative solutions in various sectors. Some of the operation fields of UAS are presented in Figure 6.

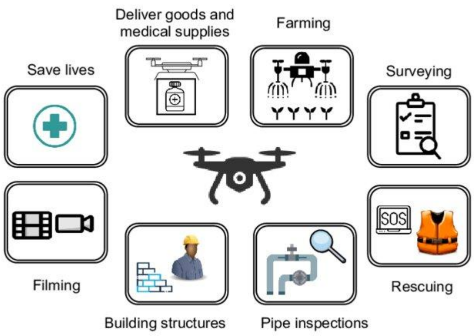

Figure 6 - Application of UAS in various fields - Source: [34]

2.3.2 UAS components

As stated above, UAS refers to the whole package involved, including not only the aircraft itself (UAV) but also ground control stations, communication and navigation systems,

[5][32] – pp. x

human elements, payload sensors, and launching, recovery and retrieval equipment [35]. A summary of the elements that allow UAS to operate effectively will now be presented.

2.3.2.1 UAV

A UAV is defined by ICAO as “a pilotless aircraft, in the sense of Article 8 of the Convention on International Civil Aviation, which is flown without a pilot-in-command on-board and is either remotely and fully controlled from another place (ground, another aircraft, space) or programmed and fully autonomous” [36][6].

UAVs include the airframe, motors, propellers, fuel, and the flight control system [35], and their classifications can be based on many aspects, such as weight, flying mechanism, range, altitude, speed, flight time, and power supply [37]. Many of these categorizations vary a lot according to the regulations and guidelines set by different aviation authorities.

2.3.2.2 Ground control station

This system allows the drone to be managed and operated remotely. It enables human operators to fly and interact with the aircraft, controlling its movements and actions from distance. Flight missions can be pre-planned by operators using the Ground Control Station (GCS) software, which will be pre-loaded into the drone before take-off to guarantee some degree of autonomy in the operation. Human operators then use the GCS to monitor the status of the aircraft, most specifically telemetry data like altitude, speed, battery, or fuel level. Therefore, this enables the operators to issue commands in response to appearing conjectures, which might include pausing the flight of the aircraft, changing its flight mission, its flight path or even land if a malfunction that justifies it eventually appears. In most commercial UAS, GCS typically consists of a mobile device with ground control software, like a laptop or a tablet [35].

2.3.2.3 Navigation system

This system allows drones to fly from one point to another, in an autonomous or remotely operated way. Navigation systems consist of sensors mounted on the drone that provide crucial data, enabling human operators to permanently monitor the drone’s position, velocity, altitude, orientation, and others. Some components of a navigation system include [38], [39]:

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[6] [36] – pp. B-6

- Global Positioning System (GPS) receivers - allow to determine the drone's exact location through signals from satellites;
- Inertial Measurement Unit (IMU) sensors - include accelerometers – used to measure the drone's linear acceleration in multiple axis, and gyroscopes – used to measure the rate of rotation, thus ensuring stability;
- Barometers - measure air pressure to determine the UAV's altitude;
- Magnetometers - measure the Earth's magnetic field to help determine UAV's attitude and orientation.

2.3.2.4 Communication system

The communication system is also known as data link, which usually uses a radio-frequency transmission to exchange information between the GCS and the UAV. Data link can be divided into uplink and downlink. The downlink transmits telemetry data from the drone to the GCS, allowing the human operators to monitor the UAV's status and act accordingly. The uplink transmits the control commands given by the human operators in the GCS [40].

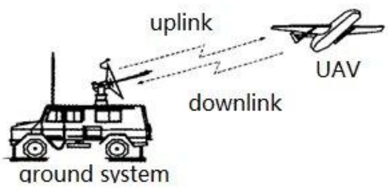

Figure 7 - Basic composition of a UAV data link system - Source: [40]

2.3.2.5 Payload sensors

The term "payload" refers to the equipment and cargo that a UAV is designed to deliver, varying according to its mission. For example, a surveillance and reconnaissance drone's payload includes a camera, a military drone's payload could consist of munitions, while the one of a drone designed for agricultural purposes might include sprayers or spreaders for the application of agrochemicals. Generally, remote sensing technology, such as video, Red Green Blue (RGB), thermal infrared, multispectral cameras, or even Light Detection and Ranging (LiDAR) technology, is installed on the aircraft. These sensors are usually attached to the airframe on two or three-axis gimbals. This setup serves to diminish vibrations and motion blur, with the big advantage of enabling the human operator to direct the sensor to a point of interest [35].

2.3.2.6 Human element

The role of the human element has been highlighted throughout this overview because operators assure the efficient functioning of other components. The significance of human operators can be summarized in three aspects: planning the flight mission of the UAV, monitoring its status, and issuing commands. Every operation needs a remote pilot in command (PIC), who is usually the person operating the controls, though someone under the direct supervision of the remote PIC may also operate them. Some missions require at least one visual observer, and their main objective is to constantly observe the UAV, to alert the pilot when necessary. The pilot (or other crew members) monitors the GCS and operates payload sensors, but sometimes another person may also be needed to direct a payload sensor to a specific point of interest, while the pilot controls the aircraft [35].

2.3.3 Urban air mobility – a UAS-centered approach

2.3.3.1 Concept of UAM

The European Union Aviation Safety Agency (EASA) defines UAM as "a new air transportation system for passengers and cargo in and around densely populated and built environments, made possible by vertical take-off, and landing electric aircraft (eVTOL) equipped with new technologies such as enhanced battery technologies and electric propulsion. These aircraft will have a pilot on board or be remotely piloted" [41][7].

The first evidence of the implementation of flying aircraft in urban environments dates to the 1940s, with helicopters being used in several operations. Recurring accidents, high operational costs, and noise issues have negatively influenced their feasibility, leading to the discontinuity of this approach [42]. However, the Vertical Take-Off and Landing (VTOL) capability provided by these helicopters has worked as a source of inspiration for the development of more feasible solutions, aiming to prevent accidents, to reduce noise, and to improve the cost-effectiveness ratio.

The growing pursuit of climate-friendly and sustainable solutions has extended to this field, leading to the adoption of electric vehicles by stakeholders and making the designation intrinsically linked with UAM. The eVTOL concept emerged in 2009 when a video showcasing the National Aeronautics and Space Administration (NASA) Puffin

[7] [41] - https://www.easa.europa.eu/en/light/topics/urban-air-mobility-uam

concept was published by NASA. Months later, a paper explaining the comprehensive development of the concept was published. This paper identifies some key advantages electric propulsion provides compared to other propulsion systems, and that also accurately justify the success of eVTOL technology in UAM research - "elimination of engine noise and emissions, drastic reduction in engine cooling and radiated heat, drastic reduction in vehicle vibration levels, drastic improvement in reliability and operating costs, variable speed output at full power, for improved cruise efficiency at low tip-speed, elimination of high/hot sizing penalty, and reduction of engine-out penalties" [43][8].

2.3.3.2 Guiding principles and maturity levels of UAM

The guiding principles for UAM are defined as crucial components that should be prioritized in the development of a UAM ecosystem – an ecosystem that protects public interest, guarantees inclusiveness, and consists of user-centered policies and initiatives. The World Economic Forum highlights seven key elements for a scalable policy framework [44]:

- Safety – the levels of safety performance brought by the introduction of new forms of air transport should be similar with those of conventional aviation operations;
- Sustainability – Environmental outcomes must be improved by UAM. The adoption of sustainable behaviours will only be possible through the embracement of innovation;
- Equity of access – Disadvantaged communities should have equitable access to mobility, with UAM playing a preponderant role;
- Low noise – The measurement and mitigation of noise disturbances by a community-first approach should be a priority;
- Multimodal connectivity – The connection between UAM and existing options of transport should be developed and emphasized, as a key for a functional mobility network;
- Local workforce development – UAM should create new (and more) job opportunities, on the ground and in the air;

[8] [43] – pp. 1

- Purpose-driven data sharing – Providers must have a quick response to the citizen needs and market demands, something that should be facilitated by efficient data sharing practices.

The UAM maturity levels (UML) presented in Figure 8 are a projection of the implementation of UAM features over time and are differentiated by a combination of three key attributes: traffic density, which is a "measure of the number of aircraft simultaneously aloft in a single, hypothetical, metropolitan area" [45][9]; operational complexity, seen as "a combination of: maximum capacity at major UAM-ports (...) the level of distribution of the port network (...) the level of weather tolerance (...) the integration with other vehicle types (...) and the level of operational integration into densely populated areas" [45][10]; and reliance on automation – "degree of integration and level or trust/responsibility held by automated systems" [45][11]. Their objective is to assess the evolution of a UAM system, from the current state of the art to a ubiquitous state. The following scale was developed by NASA, primarily focusing on the passenger-carrying use case, even though there is some applicability in non-passenger carrying missions. This makes it a reliable tool to access stages of UAM development in all dimensions.

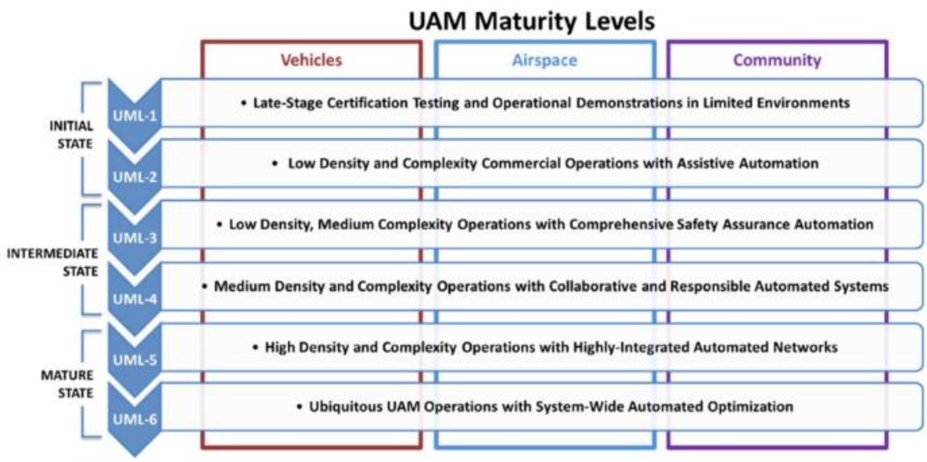

Figure 8 - Urban Air Mobility Maturity Scale - Source: [45]

UAM opens the door for many opportunities, but there remains a list of research fields composed by obstacles and uncertainties related to the implementation of eVTOL

[9] [45] – pp. 2
[10] [45] – pp. 2/3
[11] [45] – pp. 3

aircraft in urban areas. These challenges cannot be overlooked and continue to contribute to large disparities in the degree of implementation of UAM initiatives.

2.3.4 U-space

A U-space is defined as a "UAS geographical zone designated by the Member States, where UAS operations are only allowed to take place with the support of U-space services" [46][12], while a UAS geographical zone – or UAS geozone – is defined as "a portion of airspace established by the competent authority that facilitates, restricts or excludes UAS operations in order to address risks pertaining to safety, privacy, protection of personal data, security or the environment, arising from UAS operations" [47][13]. The main objectives of the implementation of a U-space airspace are to enable a wide range of safe UAS operations, to allow complex drone operations like Beyond Visual Line-Of-Sight (BVLOS), and to ensure a safety continuum of manned aircraft operations nearby, ensuring separation between unmanned and manned aircraft [48].

U-space airspace may be designed for several reasons [49]:

- Safety – improve aircraft visibility through electronic conspicuity, mitigate risks on the ground in densely populated areas with multiples UAS flying over, and reduce the risk of mid-air collisions through the implementation of route structures;
- Economy – ensure a fair airspace volume sharing between manned and unmanned aircraft, enable more complex UAS operations, and support the development of the sector and associated services;
- Security – support the enforcement of regulations and rules to a local and municipal dimension, assist national authorities in responding to malicious use of UAS, and protect services from unlawful UAS use;
- Privacy – support the enforcement of privacy conditions for UAS operations (like restricted areas);
- Environment – to define environmental requirements for UAS operations, to distribute traffic density to minimize disturbance over environmentally sensitive zones, to promote respect for environmentally protected areas, and to minimize CO_2 emissions (especially in urban environments).

[12] [46] – pp. 139
[13] [47] – pp. 152/48

The concept of U-space encompasses a wide range of technologies, infrastructure, and regulatory frameworks to support safe and efficient access to U-space airspace for UAS, to allow more UAS operations, including those with a higher degree of complexity, while ensuring a healthy coexistence between unmanned and manned aviation. While idealized for densely populated areas due to the expected large volume of operations in cities, this concept is not limited to urban environments [50].

The first real model of a U-Space within EASA's scope is in Hamburg, most specifically a project named BLU-Space. Given the high complexity of planning and implementation, a test airspace will be established based on a technical, organizational, and procedural concept of U-Spaces, with the project expected to be concluded in 2026 [51].

2.3.5 Regulatory framework

Most regulations and guidelines developed by European regulatory authorities like EASA are applicable to Portugal and other member countries. However, some details might vary and be adapted by national and local authorities to correspond to their specific realities. In addition to EASA's framework, national civil aviation authority's regulations also apply to certain aspects — such as third-party insurance and Alternative Means of Compliance (AltMOC) — which, in Portugal, fall under the Portuguese Civil Aviation Authority's (ANAC) responsibility. EASA also delegates specific functions and obligations to national civil aviation authorities, including the evaluation and approval of operational authorization requests and the definition of national geographical zones.

According to [47] there are currently three categories of operation for drones - open, specific and certificate. Regarding the open category, the operation is classified as such if it does not require any authorisation or declaration by the drone pilot. All operations in this category must be conducted within VLOS. As for the specific category, the operation is classified as such if a permit or operational authorization from the respective Civil Aviation Authority is obtained. In this category, operations can vary from low-risk scenarios very close to those in the open category to high-risk ones closer to the certified category. Typically, operations that are BVLOS or involve higher risks fall under this category. Regarding the certified category, there is a demand for both UAS and operator certification and, when applicable, licensing of the remote pilot. They include the highest-risk operations and those involving human passengers [52].

Although there has been a growing amount of focus on rules and procedures for UAS operation, the first commercial UAM operations in Europe are expected to be executed with a pilot on board [53], and consequently, pilot licensing is also inevitable. In 2019, EASA released preliminary activities aimed at enabling the development of regulation concerning onboard pilots, remote pilots, operators of these vehicles, and the infrastructure, such as vertiport operators [54]. More recently, in October 2024, EASA released the Easy Access Rules for small category VTOL-capable aircraft, consolidating existing materials to simplify the use of requirements for these vehicles [55].

In 2022, EASA developed a U-space regulatory list for U-space implementation – which has been recently updated and refined, and includes general requirements, criteria for performance requirements and operational conditions, regulations/guidelines for operators, services, service providers, etc. Some of the guidelines regarding U-space consist of [46], [49]:

- A guideline advising Member States not to set a maximum height higher than 150 m above the ground for the U-space. EASA encourages Member States to adopt this limitation due to the lack of experience with U-space implementation, which might eventually lead to decreased safety, although it is up to each Member State to make a final decision;
- The elaboration of an Airspace Risk Assessment (ARA) of operational, safety and security risks, considering the required level of safety performance as defined in the *European Plan for Aviation Safety* and in the *State Safety Programme*.

2.3.6 Ground infrastructure

There is an imperial necessity to assure there is appropriate ground infrastructure to include eVTOL aircraft in urban environments – to allow operational procedures and to support charging, refuelling, and connectivity [56]. Ground infrastructure represents an imperative requisite for operational success. Vertiplaces is the word commonly used to refer to ground infrastructure for eVTOL vehicles, consisting in three categories (vertistations, vertiports, vertihubs), varying in size, location, and overall purpose [57].

Several aviation authorities established technical standards and specifications for the design of vertiplaces. In 2022, EASA has released a document that aims at offering guidance for safe vertiport design in congested urban environments. One of the most notable innovations highlighted is the concept of an obstacle-free volume, allowing for aircraft to perform VTOL operations with a significant vertical segment. Omnidirectional trajectories to vertiports might also be possible, depending on the aircraft and urban environment [58].

2.3.7 Societal acceptance

Since the UAM ecosystem is directed at protecting the public interest and ensuring inclusiveness through the adoption of user-centered initiatives, it becomes imperative to evaluate public perception on the topic. Understanding the preferred fields of application for residents in their specific urban environment - and consequently how UAM could help improving their quality of life and assessing citizens' possible objections/obstacles to adjust approaches according to their feedback, are key aspects for a successful implementation of UAM in cities.

Hence, EASA has made an extensive study on the societal acceptance of UAM, that allows to draw some relevant conclusions [59]:

- Positive attitude towards UAM among the surveyed participants, especially those who live in southern Europe cities;
- Quantitative and qualitative approaches confirmed that survey participants have shown more interest for use cases that contribute to the public interest;
- The most expected benefits by surveyed participants are improved response time, reduction of traffic jams, and reduction of local emissions;
- The most concerning aspects of the implementation of drones and air taxis are similar to the challenges of UAM showcased by previous studies - safety, noise, environment, and security;
- Most surveyed participants are in favour of introducing an eco-label for commercial VTOL.

The study also provides noteworthy insights on the perception of unmanned aviation [59]:

- Participants feel safer with manned aircraft than with unmanned ones;
- Pedestrians feel more comfortable with manned operations of air taxis (70% accept the fact that manned air taxis could fly above their heads, while 44% responded positively to unmanned air taxis flying above them);
- Passengers feel more comfortable with manned operations of air taxis (75% would be interested in trying out manned air taxis themselves, a number that decreases to 43% with unmanned air taxis);
- Passengers feel slightly safer than pedestrians regarding unmanned operations.

2.4 The fusion of UAS and smart urban environments

Unmanned aviation can be a determinant tool in the transformation of a "normal city" into a smart urban environment, where automation, innovation, quality of life, and environmentally friendly practices prevail. Throughout the previous subchapters, the concepts of smart city and unmanned aircraft systems were explained individually, thus understanding the increasing role of UAS represents in that transformation is key in this context.

As stated before, a smart city involves the use of advanced ICT-based solutions to address urban challenges, in which UAS, as an innovative and disruptive technology, are perceived as a valuable tool to improve the quality of life of its residents, due to factors like high versatility, high flexibility, efficient data collection methods, higher speed of operation, and lower environmental impact. These aspects are key for UAS's increasing popularity in smart urban planning and initiatives, as they provide effective approaches to achieve smart cities' goals, of becoming dynamic, sustainable, economic, and inclusive urban ecosystems [60], through a wide range of applications (as demonstrated in Figure 9).

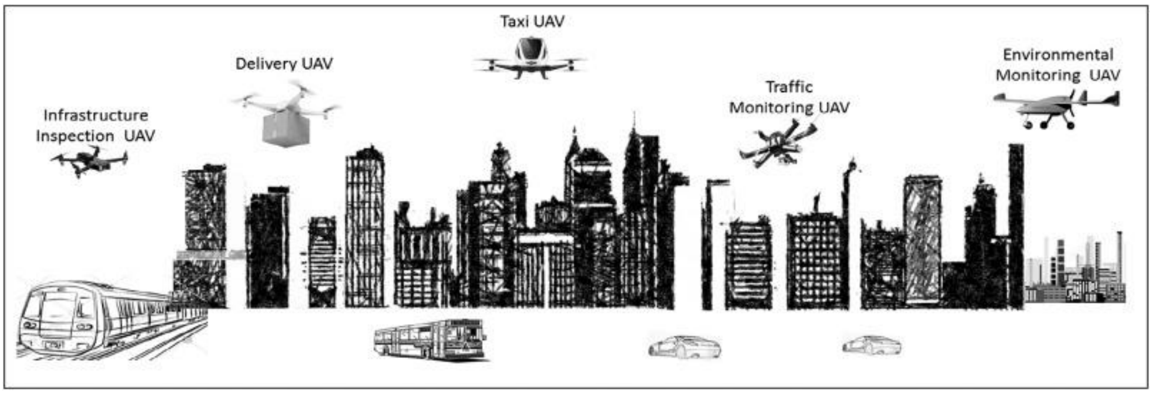

Figure 9 - Different applications of UAVs in smart cities - Source: [60]

2.4.1 Smart transportation

Smart transportation consists of the use of advanced and innovative technologies to improve transportation's efficiency, sustainability, and safety. Urban air mobility initiatives and traffic management represent the two most studied applications in the present context. In terms of tested UAM applications, one of fields that has shown more potential is the delivery of goods, representing a faster and cheaper solution than many traditional delivery modes [61]. UAS can operate autonomously while being capable of making a delivery with precision within a specified time window, whilst potentially reducing CO_2 emissions and promoting energy-saving practices [62]. Current challenges include the lack of supporting infrastructure and operational factors.

Regarding traffic management, authors have proposed advanced drone surveillance systems using current drone technology, for purposes like traffic monitoring, detection of incidents, and traffic flow analysis [63]. UAVs with attached camera sensors can also be used for traffic data collection and for traffic flow analysis at roundabouts [64]. One key aspect of smart transportation and traffic control is the efficient provision of real-time information on accidents, and in this matter, studies have highlighted the significant reduction in data collecting time using unmanned aircraft compared to classical police procedures [65].

UAS-based smart parking is an aspect that has motivated the development of systems driven by image processing and analysis algorithms [66], aiming at the provision of information about parking spot availability in urban environments, which results in a facilitated job for users and in the optimization of parking space utilization. Figure 10 shows a scheme for UAS-based lane occupancy and parking space analyses.

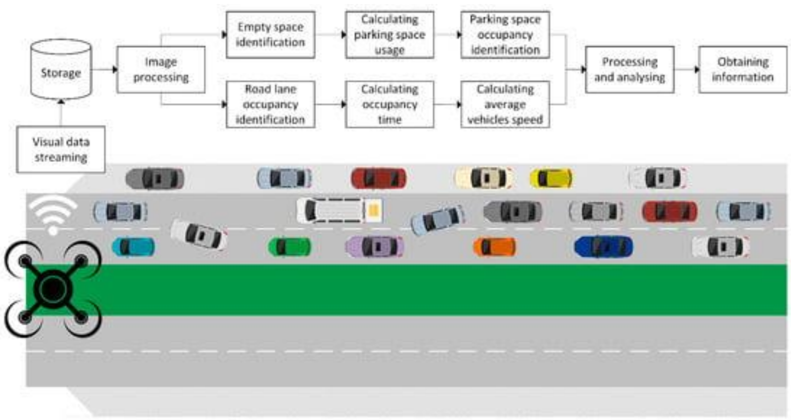

Figure 10 - Proposed scheme of automatic analysis of lane occupancy and parking space management - Source: [66]

2.4.2 Smart services

Smart city services involve tasks that sustain and support the inhabitants of a city [12]. The best examples of UAS applications aiming at the improvement of smart city services are environmental monitoring and conservation, and management of waste, resources, disasters, and crowds.

Studies have been conducted to evaluate the feasibility and advantages of utilizing UAVs for environmental monitoring of pollutant-emitting facilities, highlighting several positive benefits such as greater flexibility and the elimination of temporal and spatial limitations of satellite and aerial images [67]. Additionally, drones facilitate higher precision modelling, through machine learning and advanced data analysis [67]. They are commonly used to monitor illicit activities, deemed harmful because of their negative environmental impact, such as illegal dumping spots. The effectiveness of drones can be illustrated by their use in American cities, where the occurrence of illegal dumping decreased following their introduction [68].

UAVs have been extensively studied for rapid and efficient disaster management. Research includes the use of UAV use in damage assessment during the 2017 hurricanes in Texas and Florida, as well as the damage-map estimation using imagery collected by drones and deep learning algorithms in the context of forest fires [69]. Regarding concrete urban applications, studies of the rapid urban flood damage assessment using high resolution remote sensing data have been conducted [69].

Additionally, UAVs have also been increasingly studied and utilized for their applications in crowd management and analysis, emerging as cutting-edge solution in this field. Some research is centered on single-drone deployment for continuous tracking and crowd management, with applications such as crowd detection, crowd size estimation, crowd tracking (as exemplified in Figure 11), and crowd analyses [70].

Figure 11 - Crowd tracking for COVID-19 standard operating procedures breachers - Source: [71]

Authors highlight safety, security, privacy concerns, and weather dependency as setbacks in the implementation of UAS for the improvement of smart city services [67], [72].

2.4.3 Smart health

Smart health leverages technology to improve the accessibility and quality of medical services. One of the most popular and already implemented applications of UAS is the routine transportation of biomedical goods, representing a valuable solution to challenges related to more remote and inaccessible areas [73]. Their efficient data collection methods make pandemic outbreak control and public health surveillance as key possible urban applications of UAS [74]. Several studies have also simulated the transportation of AED (automated external defibrillators) to cardiac arrest patients, demonstrating effective time savings, although these benefits are more evident in rural areas than in urban ones [75].

Access to healthcare has been identified as a significant challenge in underdeveloped regions. In Africa, these technological tools have proven to have had a positive influence by developing opportunities to close the gap between rural and urban populations on that regard [76]. The same authors also highlight the role of medical UAVs during COVID-19 outbreak in delivering test samples, test tubes, and personal protective equipment in Ghana [76].

Drones can be ten times faster than traditional emergency services and represent a cost-efficient solution, particularly in more remote areas with demanding accessibility [77]. Other studied applications of UAS within the smart health paradigm include healthcare logistic chain support, air ambulance services, remote monitoring of patients' vital signs, and real-time scheduling of the transmission of these signs [73].

2.4.4 Smart infrastructure

Smart infrastructure consists of the integration of digital technologies for the development of urban infrastructure systems, including initiatives that leverage these technologies in the management of physical infrastructure.

Regarding the implementation of UAS in a civil-engineering context, infrastructure – both rural and urban – was listed as one of the most popular application areas of unmanned operations recently, according to the FAA (Federal Aviation Administration) [78]. UAS have become indispensable tools for infrastructure inspection and monitoring due to their cost-effectiveness and ability for monitoring in many scales. One of the most prominent applications is bridge deck inspections, where UAS are used to evaluate structural integrity. They are also increasingly used in construction safety and progress monitoring, being efficient tools for safety managers on construction sites, allowing the development of 3D models at construction sites, and tracking construction workflows [78]. Another common application of UAS is post-disaster reconnaissance, as they have also proven to be highly effective in mitigating obstacles like ensuring personnel safety and accessing sites that are difficult to reach. UAVs have also been used to capture footage of buildings in urban and suburban residential areas who have suffered damage [78].

Authors suggest that while UAS applications for smart infrastructure, such as infrastructure mapping, are increasingly popular, their potential use in urban environments is still highly dependent on the development and advancement of UAV regulations [79].

2.4.5 Other components

One initiative simultaneously related to smart energy, homes and infrastructure is the use of UAS equipped with thermal imaging technology for building inspections. They represent a more accessible, more efficient, and safer than conventional auditing procedures, providing a great opportunity to accelerate the improvement and retrofitting of aging and energy-inefficient building infrastructure [80]. Drones also represent a relevant contribution in the smart city component related to agriculture, being currently used in applications such as crop monitoring, irrigation management, pest and disease management, field mapping, and livestock management [81]. Regarding industrial activities, some of the most prominent applications of UAS include inventory management, quality control, and supply chain management [82].

2.5 SWOT-FAHP: theoretical framework

In this subchapter, the theoretical concepts behind two types of analysis will be explained: the Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis and the Fuzzy Analytic Hierarchy Process (FAHP), providing a solid foundation to evaluate the implementation of UAS in a specific context. A SWOT analysis will be performed to facilitate the qualitative assessment of this implementation by identifying internal and external factors. Meanwhile, the FAHP and other quantification processes will be applied for strategy prioritization purposes, with the primary goal of identifying initiatives that would position Porto closer to the leading smart cities in Europe, maximizing strengths and opportunities while mitigating existing weaknesses and potential threats.

2.5.1 Qualitative analysis

Used for planning and management in the last 60 years, the SWOT analysis is a simple but effective method of evaluation of any process, person, project, industry or business on four criteria: strengths, weaknesses, opportunities, and threats [83], [84] – as showcased in Table 2. A SWOT analysis is a strategic planning tool that provides help to decision-makers in defining effective strategies, policies and improvements, through the scrutiny of internal and external factors related to a specific business or project [83]. This examination includes both broad and detailed factors, aiming to assess the feasibility and potential success of a process or project [84].

Table 2 - SWOT analysis internal and external factors - Source: own elaboration based on [85]

Internal factors Elements that directly influence a specific activity or organization	**Strengths (S)**	Advantageous internal factors. Positive and favourable characteristics
	Weaknesses (W)	Disadvantageous internal factors. Negative and unfavourable characteristics
External factors Elements that could influence a specific activity or organization	**Opportunities (O)**	Advantageous external factors. Driving force for an activity to take place.
	Threats (T)	Disadvantageous external factors. Situations or conditions that put in danger the feasibility of an activity

A SWOT analysis usually evaluates general solutions and works as a door that guides one to the details and to the specific parts, and it can be used at different analytical levels – individually, organizationally, nationally and internationally – across contexts such as businesses, governments, and educational institutions [85]. By identifying future challenges and current conditions, this analysis helps organizational management to discuss about the future of a specific project or organization, and a key aspect is that it aids in strategy development by taking into consideration internal and external factors, both the ones who work as driving forces in both directions (positive and negative), all together in a related perspective [85].

As a result, a TOWS matrix is often used to identify various classes of strategies [86]. These strategies are typically divided into four categories: SO - that maximize both strengths and opportunities, WT - that minimize both weaknesses and threats, WO - that minimize weaknesses and maximize opportunities, and ST - that maximize strengths and minimize threats. In Table 3, the configuration of a TOWS matrix is presented.

Table 3 - TOWS matrix framework - Source: adapted from [87]

	Strengths (S)	**Weaknesses (W)**
Opportunities (O)	**SO** strategy – Using strengths to take advantages of opportunities	**WO** strategy – Overcoming weaknesses by taking advantage of opportunities
Threats (T)	**ST** strategy – Using strengths to avoid threats	**WT** strategy – Minimize weaknesses and avoid threats

SWOT analyses have been applied within the framework of smart and intelligent cities in several studies, which include studying the potential impact of renewable energy sources in the reduction of air pollution for smart energy management [88], characterizing intelligent sustainable buildings and possibilities for their development [89], and examining smart city initiatives in Organization for Economic Cooperation and Development (OECD) countries [90].

However, there are several disadvantages widely recognized by authors. A commonly highlighted drawback is its ineffectiveness as part of an organizational strategy, as it cannot go beyond defining the current situation and is therefore not accepted as an analytical technique, not taking in consideration the dynamic and complex nature of external factors [85]. The biased and subjective nature of SWOT analysis is often perceived as a significant disadvantage, as it is highly dependent on who conducts it and on their interpretation of data [85]. Several Multi-Criteria Decision Making (MCDM) methods have been proposed as supporting tools to the qualitative approach specific to the SWOT analysis, since they introduce a quantitative element to determine the ranking and weight of the factors, and to validate perspectives and recommendations [85]. The Analytic Hierarchy Process (AHP) is a common tool utilized for this purpose.

2.5.2 Quantitative analysis

2.5.2.1 Criteria and sub-criteria comparison – FAHP

Developed by Saaty in 1980, the AHP is a multiple criteria decision-making (MCDM) method adequate for complex systems involving the selection of numerous alternatives and offers a comparative analysis of the considered options [91]. The problems are organized hierarchically into criteria and sub-criteria, and decisions are made based on experts' assessment on paired comparisons of those parameters [92]. The ability to link information based on knowledge to make decisions is the core principle of this analysis, which can be acquired either through experience or derived from the application of other tools [91]. Over time, AHP has been used in several fields, such as "education; engineering; government; industry; management; manufacturing; personal, political, and social systems; and sports" [93][14].

However, the downsides of AHP are its lack of ability to comprise the uncertainty of the decision maker [94], and its inadequacy in handling the ambiguity associated with human's subjective judgement, influenced by factors such as bias and incomplete information [95]. Real-world decision-making processes often face uncertain conditions, where information is limited in terms of completion and precision, and crisp numbers assume a level of precision incompatible with subjective contexts and with human thinkings and perceptions. Since evaluation criteria are often subjective and qualitative, it becomes hard for decision-makers to express preferences through exact statements [96]. The Fuzzy Analytic Hierarchy Process (FAHP), which combines fuzzy logic and the AHP, presents itself as a good solution for dealing with decision-making processes, as it handles more adequately the subjectivity of human preferences [95].

The earliest literature reference to the FAHP dates to 1983. Since then, it has gained popularity as a MCDM method in various applications, such as airline retail, pharmacy, sustainability management, and risk analysis [97]. The FAHP offers more flexibility compared to the traditional AHP by dealing with subjective opinions more effectively, and another primary upside of the FAHP is the fact that decision-makers will express their judgments in the form of linguistic variables - later converted into fuzzy numbers, which reflects their subjective beliefs that are often related with uncertainty [98]. This method is also useful for more complex MCDM problems, where there are involved multiple and interrelated criteria.

There are several sub-methods and approaches within the FAHP framework. For this purpose, the Method of Extent Analysis, proposed by Da-Yong Chang, will be applied [99].

A fuzzy number $M \in F(\mathbb{R})$ can be called that way if [99]:

1) exists $x_0 \in \mathbb{R}$ such that $\mu_M(x_0) = 1$.

[14][93] – pp. 3

2) For any $\alpha \in [0,1]$, $A_\alpha = [x, \mu_{A_\alpha}(x) \geq a]$ is a closed interval. $F(\mathbb{R})$ represents all fuzzy sets.

A fuzzy number M on $\mathbb{R}$ is a Triangular Fuzzy Number (TFN) if its membership function $\mu_M\ (x): \mathbb{R} \to [0,1]$ is equal to

$$\mu_M\ (x) = \begin{cases} \dfrac{x}{m-l} - \dfrac{l}{m-l}, & x \in [l,m], \\ \dfrac{x}{m-u} - \dfrac{u}{m-u}, & x \in [m,u], \\ 0, & otherwise \end{cases} \tag{1}$$

where $l \leq m \leq u$, and

l – lower value of the support of M;
m – modal value of the support of M;
u – upper value of the support of M.

The TFN can be denoted by $M = (l,m,u)$, and the support of M is the set of elements $\{x \in \mathbb{R} \mid l < x < u\}$. Figure 12 represents a graphical representation of a triangular membership function.

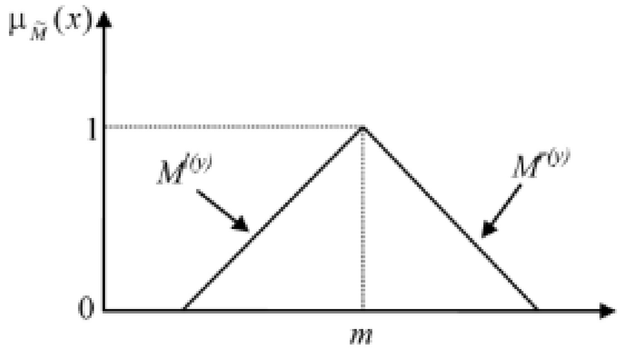

Figure 12 - Graphical representation of a triangular membership function - Source: [100]

Firstly, experts will use linguistic assessments to compare each SWOT criterion (strengths, weaknesses, opportunities, threats) along with their sub-criteria. The outlined data analysis and process will allow the calculation of local weights related to each criterion and sub-criterion, which will then be used to determine global weights and an order of importance for SWOT criteria and sub-criteria.

Experts usually express their preferences through verbal expressions, which means that a link between linguistic assessments and numerical expressions to facilitate the quantitative analysis of qualitative data is needed. Authors commonly use 9-level and 5-level fuzzy scales for this purpose [97]. The linguistic variables associated with 5-level scales are semantically like those shown in Table 4 – but not necessarily equal, as authors often use different terms to describe the same scale. Typically, 9-level scales include intermediate levels between those presented in Table 4 for more detailed feedback.

For clarity and length purposes, a 4-level scale will be used. Table 4 provides the linguistic scale used for criteria comparison, and the corresponding triangular fuzzy number and triangular fuzzy reciprocal number. Note that if a triangular fuzzy number M is defined by $M = (l, m, u)$, the corresponding triangular fuzzy reciprocal number M' is defined by $M' = \left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right)$.

Table 4 - Triangular fuzzy conversion for criteria comparison - Source: own elaboration based on [100]

Linguistic variables	**Triangular fuzzy number**	**Triangular fuzzy reciprocal number**
Equally important	(1/2, 1, 3/2)	(2/3, 1, 2)
Slightly more important	(1, 3/2, 2)	(1/2, 2/3, 1)
More important	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Much more important	(2, 5/2, 3)	(1/3, 2/5, 1/2)

A crucial part of the process is to aggregate data from experts to obtain valid results for the pairwise comparison matrix. Several methods are used for aggregation purposes, including arithmetic mean, geometric mean, max-min method with arithmetic mean, max-min method with geometric mean, and a method based on consensus degree. The geometric mean is often chosen due to its effectiveness in providing a balanced representation of experts' opinions and for reducing the influence of extreme values [97].

Let $(E_1, E_2, \dots, E_q)$ be the q experts, $(C_1, C_2, \dots, C_n)$ be the n performance criteria, $\tilde{C}_{ij}^{(t)} = (l_{ij}^{(t)}, m_{ij}^{(t)}, u_{ij}^{(t)})$ be a TFN representing the relative importance of C_i over C_j judged by E_t, and $\tilde{C}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ be the aggregated relative importance of C_i over C_j. $\tilde{C}_{ij}$ can be expressed as:

$$\tilde{C}_{ij} = \left(\prod_{t=1}^{q} \tilde{C}_{ij}^{(t)}\right)^{\frac{1}{q}} = \left(\left(\prod_{t=1}^{q} l_{ij}^{(t)}\right)^{\frac{1}{q}}, \left(\prod_{t=1}^{q} m_{ij}^{(t)}\right)^{\frac{1}{q}}, \left(\prod_{t=1}^{q} u_{ij}^{(t)}\right)^{\frac{1}{q}}\right) \tag{2}$$

The geometric mean method has several extensions, with the weighted geometric mean method being particularly significant in this context due to the incorporation of the weights of experts, which is especially important in situations when experts vary in terms of their field, experience, or knowledge [97].

Let $(\alpha_1, \alpha_2, \ldots, \alpha_q)$ denote the exponential weighting vector of the q experts. The weighted geometric mean for the collective relative importance of C_i over C_j is given by

$$\tilde{C}_{ij} = \left(\left(\prod_{t=1}^{q} l_{ij}^{(t)^{\alpha_q}}\right)^{\frac{1}{\sum_{t=1}^{q}\alpha_q}}, \left(\prod_{t=1}^{q} m_{ij}^{(t)^{\alpha_q}}\right)^{\frac{1}{\sum_{t=1}^{q}\alpha_q}}, \left(\prod_{t=1}^{q} u_{ij}^{(t)^{\alpha_q}}\right)^{\frac{1}{\sum_{t=1}^{q}\alpha_q}}\right), \tag{3}$$

where $\sum_{t=1}^{q} \alpha_q = 1$. Therefore,

$$\tilde{C}_{ij} = \left(\left(\prod_{t=1}^{q} l_{ij}^{(t)^{\alpha_q}}\right), \left(\prod_{t=1}^{q} m_{ij}^{(t)^{\alpha_q}}\right), \left(\prod_{t=1}^{q} u_{ij}^{(t)^{\alpha_q}}\right)\right) \tag{4}$$

With data aggregation performed, Chang's method will now allow to determine the local and global weights of each criterion and sub-criterion [99]. Let $X = \{x_1, x_2, \ldots, x_n\}$ be an object set, and $U = \{u_1, u_2, \ldots, u_m\}$ be a goal set. According to Chang's method, each object is taken and extent analysis for each goal is performed. Therefore, it is possible to get m extent analysis values for each object, with the following signs:

$$M_{gi}^1,\ M_{gi}^2, \ldots,\ M_{gi}^m, \qquad i = 1, 2, \ldots, n, \tag{5}$$

where all the M_{gi}^j $(j = 1, 2, \ldots, m)$ are TFNs.

- **Step 1**

The value of fuzzy synthetic extent with respect to the i-th object is defined as

$$S_i = \sum_{j=1}^{m} M_{gi}^j \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^j\right]^{-1}, \tag{6}$$

where

$$\sum_{j=1}^{m} M_{gi}^j = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right), \tag{7}$$

and

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i\right). \tag{8}$$

Therefore, based on operational laws for TFNs, (8) can be expressed as

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right). \tag{9}$$

Consider two TFNs $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$. Note that

$$M_1 \otimes M_2 = (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) \approx (l_1 l_2, m_1 m_2, u_1 u_2). \tag{10}$$

- **Step 2**

The degree of possibility, V, of $M_2 \geq M_1$ is defined as

$$V(M_2 \geq M_1) = \sup_{y \geq x} \left[\min\left(\mu_{M_1}(x), \mu_{M_2}(y)\right)\right], \tag{11}$$

where $x, y \in \mathbb{R}$.

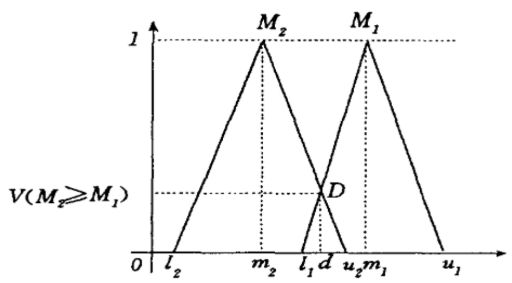

Figure 13 - Graphical representation of the intersection between μ_{M_1} and μ_{M_2} - Source: [101]

As a result, equation (11) can also be expressed as

$$V(M_2 \geq M_1) = hgt\ (M_1 \cap M_2) = \mu_{M_2}(d), \tag{12}$$

where d is the ordinate of the highest intersection point, D, between μ_{M_1} and μ_{M_2} – as represented in Figure 13.

Equation (12) can be written as

$$V(M_2 \geq M_1) = \begin{cases} 1 & if\ m_2 \geq m_1 \\ 0 & if\ l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & otherwise \end{cases} \quad . \tag{13}$$

- **Step 3**

The degree of possibility for a convex fuzzy number to be greater than k convex fuzzy numbers M_i $(i = 1, 2, \dots, k)$ is defined by:

$$V(M \geq M_1, M_2, \dots, M_k) = V[(M \geq M_1)\ and\ (M \geq M_2)\ and \dots and\ (M \geq M_k)] = \\ = min\ (M \geq M_i) \tag{14}$$

For $k = 1, 2, \dots, n;\ k \neq i$, it can be assumed that

$$d'(A_i) = min\, V(S_i \geq S_k)\ . \tag{15}$$

Therefore, the denormalized weight vector will be given by

$$W' = \left(d'(A_1), d'(A_2), \dots, d'(A_n)\right)^T , \tag{16}$$

where A_i $(i = 1, 2, \dots, n)$ are n elements.

- **Step 4**

Finally, the denormalized weight vector (W'), calculated in (16), is normalized. As a result, normalized priority weights are calculated by

$$d(A_i) = \frac{d'(A_i)}{\sum_{i=1}^{n} d'(A_n)} , \tag{17}$$

and the final weight vector (W) is then given by

$$W = \left(d(A_1), d(A_2), \dots, d(A_n)\right)^T , \tag{18}$$

where W is a nonfuzzy number.

Finally, the global weight of a certain SWOT sub-criterion, $(GW)_{SC}$, is given by

$$(GW)_{SC} = (LW)_C \times (LW)_{SC} \tag{19}$$

where $(LW)_C$ represents the local weight associated with the corresponding criterion and $(LW)_{SC}$ represents the local weight associated with the given sub-criterion.

2.5.2.2 Strategy prioritization

In Part 2, experts will evaluate each TOWS strategy against all SWOT sub-criteria, to determine an ordered list regarding strategy prioritization. For this purpose, a connection between linguistic terms and numerical variables is also needed, to enable the quantitative analysis of the input of experts. Table 5 provides the linguistic scale used and the corresponding triangular fuzzy number.

Table 5 - Linguistic markings and semantics for rating the criteria - Source: own elaboration based on [101], [102]

Linguistic markings	Triangular fuzzy number
Very Low (VL)	(0, 0, 0.25)
Low (L)	(0, 0.25, 0.5)
Medium (M)	(0.25, 0.5, 0.75)
High (H)	(0.5, 0.75, 1)
Very High (VH)	(0.75, 1, 1)

Let $(E_1, E_2, \dots, E_q)$ be the q experts, $(C_1, C_2, \dots, C_n)$ be the n performance criteria, $\tilde{C}_{ij}^{(t)} = (l_{ij}^{(t)}, m_{ij}^{(t)}, u_{ij}^{(t)})$ be a TFN representing the relative importance of C_i over C_j judged by E_t, and $\tilde{C}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ be the aggregated relative importance of C_i over C_j, $(\alpha_1, \alpha_2, \dots, \alpha_q)$ denote the exponential weighting vector of the q experts.

The lower and medium values for Very Low (VL) and the lower value for Low (L) are equal to zero, which would nullify the result if the weighted geometric mean was used. Additionally, since the markings shown in Table 5 already reduce the potential influence of extreme values, the weighted arithmetic mean is more suitable in the calculation of the aggregated result.

The weighted arithmetic mean for the collective relative importance of C_i over C_j is given by:

$$\tilde{C}_{ij} = \left(\left(\sum_{t=1}^{q} l_{ij}^{(t)} \alpha_q \right), \left(\sum_{t=1}^{q} m_{ij}^{(t)} \alpha_q \right), \left(\sum_{t=1}^{q} u_{ij}^{(t)} \alpha_q \right) \right) \quad (20)$$

Consider a TFN defined by $M = (l, m, u)$. To defuzzify the results the Best Non-fuzzy Performance (BNP) method can be used instead of Chang's method (only suitable for criteria comparison purposes). The BNP for M is given by [103]:

$$BNP = l + \frac{(u - l) + (m - l)}{3} \quad (21)$$

The global weight of each sub-criterion, $(GW)_{SC}$, is multiplied by the respective BNP, and the values of $(GW)_{SC} \times$ BNP associated with the same TOWS strategy will be added. The repetition of this calculation for every TOWS strategy identified will enable the elaboration of a ranking regarding the prioritization of these strategies, where the TOWS strategy with the highest total score corresponds to the strategy that should be given the most priority.

2.6 Conclusion

The chapter began with an exploration of the concept of smart cities, where its multifaceted interpretations and components were explored. Then, general considerations about UAS were provided, their technological aspects were presented, the crucial role of UAM as a primary driver for the high-volume implementation of unmanned aviation in cities was addressed, and the main challenges related to the integration of UAS and UAM in urban environments were highlighted. This chapter also built a bridge between unmanned aviation and smart city initiatives, by specifying how UAS can be integrated into each smart city component. Finally, a list of relevant theoretical concepts related to the SWOT analysis and to the FAHP was also presented.

In summary, this literature review provided a good understanding of the most relevant general aspects that will serve as an important support for further particularization in the case study. It also provided an overview of the methodologies that will be used, ensuring a solid foundation for exploring the bond between UAS and smart cities. This work is essential to create well-informed and strategic insights, that will guide the implementation and integration of these technologies in urban contexts.

Chapter 3 – Case Study

3.1 Introduction

This chapter focuses on the assessment of a specific case: the city of Porto. First, a scenario description will be presented, mentioning the technologic, economic, demographic, and social reasons that make Porto a valuable choice for evaluating the implementation of unmanned aviation within the smart city paradigm. The current state of drone implementation in the city – which is significantly behind near-future prospects - will be briefly explained from an operational regulatory perspective.

Next, one of the main focuses of this research will be introduced through a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis, applied to qualitatively evaluate the implementation of UAS in the Portuguese city by defining and explaining 20 internal and external factors based on literature findings. Four different strategies will be elaborated based on the intersection of these factor, where the TOWS matrix framework will be used to guide the strategic planning process. These sub-criteria will then be reviewed by experts, who will examine the importance of each factor/sub-criteria within the same category/criteria using comparison linguistic variables, later converted into numerical values to enable the application of quantitative tools for criteria comparison and strategy prioritization.

This chapter will conclude with an explanation of the validation process applied to the results obtained from both the quantitative and qualitative analyses. The company and the process of data collection will also be described.

3.2 Scenario description

Porto, the capital of the second most populous and economically active metropolitan area in Portugal, has a population of around 246,000 people [104]. Known for its captivating and appealing combination of tradition and modernity, Porto is characterized by cultural richness and by being a dynamic ecosystem.

For this particular purpose, Porto was chosen due to the numerous opportunities it presents to be a pioneer in the implementation of UAS in Portugal, which is mainly driven by these reasons:

- The city is the biggest urban center in northern Portugal and the second biggest in the whole country;
- As a multidisciplinary urban environment, Porto is a strong entrepreneurial ecosystem supported by high-quality industries and universities, making it an attractive city for businesses of all sizes;
- The city is going through a digital and green transformation process, hugely influenced and supported by a proactive municipal government. Within the smart city framework, Porto is often recognized as a model for the European community;
- Porto is involved in various smart city commissions and initiatives, including in ones developed by the EU and European Commission;
- Tourism, as one of the main contributors to the local economy, might open new horizons for unmanned aviation technologies. UAS could serve as a valuable tool to significantly improve the experience of tourists and contribute for the technological advancement of the city.

3.2.1 UAS implementation: the present of Porto

The reality regarding the implementation of unmanned aviation initiatives in Porto is similar to that of the main urban centers in the European Union: UAS are getting increasingly popular, but their high-volume implementation is still a future prospect, as the full-scale deployment of UAM initiatives in Europe is predicted to become a reality within the next 3-5 years [53], with manned eVTOL vehicles expected to be the first used for UAM purposes.

UAS operations in Porto are governed by a regulatory framework established by both national and European aviation authorities. Several operations classified under the three drone operation categories - open, specific, and certified – have been conducted in Porto for various purposes, including recreative activities, event filming, and promoting the city for tourism. Drones have also been as proposed as part of a set of measures to prevent or minimize the breeding of seagulls in urban space of the Porto Metropolitan Area. They would be primarily used in places with difficult access [105].

To regulate open category operations, and therefore preserve the safety of aircraft and citizens, UAS geographical zones have been established by each country's national aviation authorities, like ANAC in Portugal's case. Regarding Porto, the dimensions of geozones are conditioned by the Porto airport, by the Matosinhos hospital heliport and by the Massarelos heliport. Figure 14 illustrates the five geozones that regulate the open operation of UAS in Porto.

Figure 14 - Porto city limits and UAS geozones - Source: own elaboration based on [106]

Where the following constraints apply to open category operations [106]:

1 - All flights in open category are strictly prohibited – *Matosinhos hospital heliport*

2 - All flights in open category are strictly prohibited – *Porto airport: prohibited area*

3 - Flying in open category is allowed up to the height of the tallest obstacle in a 75 m radius. If the operation needs to exceed that height, authorization from the heliport director is required – *Massarelos heliport*

4 - Flying in open category is allowed up to 30 m above surface or up to the height of the tallest obstacle in a 75 m radius. The inclusion of equipment to provide height above surface is mandatory – *Porto Airport Area 1*

5 - Flying in open category is allowed up to 60 m above surface or up to the height of the tallest obstacle in 75 m radius. The inclusion of equipment to provide height above surface is mandatory – *Porto Airport Area 2*

As depicted in Figure 14, region 2 (*Porto airport: prohibited area*) intersects region 3 (*Massarelos heliport*). However, UAS operations in prohibited areas are forbidden, so the restrictions of region 2 overlaps those of region 3. Region 3 also intersects both region 4 (*Porto Airport Area 1*) and region 5 (*Porto Airport Area 2*). Figure 15 provides an overview of all intersections of UAS geozones within city limits.

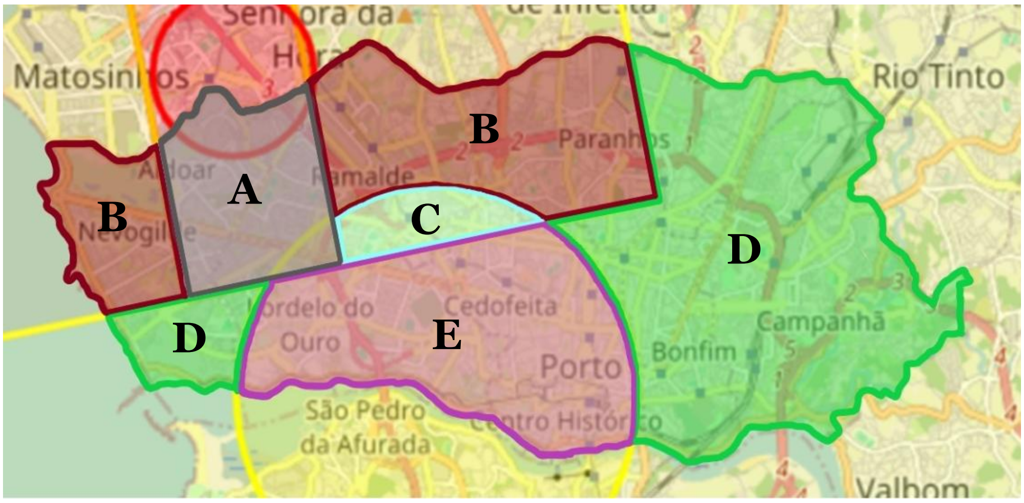

Figure 15 - Intersection of UAS geozones within the city limits - Source: own elaboration

Therefore, the rules for each of the highlighted regions are:

A - All flights in open category are strictly prohibited;

B - Flying in open category is allowed up to 30 m above the surface or up to the height of the tallest obstacle in a 75 m radius;

C - Flying in open category is allowed up to 30 m above the surface. If the height of the tallest obstacle in a 75 m radius is lower than 30 m (above the surface), and the operation needs to exceed that height, authorization from the Massarelos heliport director is required;

D - Flying in open category is allowed up to 60 m above the surface or up to the height of the tallest obstacle in a 75 m radius;

E - Flying in open category is allowed up to 60 m above the surface. If the height of the tallest obstacle in a 75 m radius is lower than 60 m (above the surface), and the operation needs to exceed that height, authorization from the Massarelos heliport director is required.

In all the above cases, these restrictions will be in effect until the end of 2027, with specific category authorization is needed to tackle them. In Portugal, the process to obtain an Operational Authorization (OA) requires operators to submit an application to ANAC, as well as an operational risk analysis carried out using the Specific Operations Risk Assessment (SORA) methodology. As an alternative to executing SORA to obtain an OA, the operator may submit a declaration of compliance with one of the Standard

Scenarios (STS). Additionally, a collective UAS operator may also request a LUC (Light UAS Operator Certificate), in accordance with Part C of Implementing Regulation (EU) 2019/947 in its consolidated version, demonstrating compliance with all applicable requirements and submit all documentation for the process to be completed [107].

3.3 Qualitative analysis

In this subchapter, a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis will be applied to qualitatively identify 20 key factors/sub-criteria that could potentially influence the smart implementation of UAS in Porto, which will be complemented by a TOWS matrix with strategies of implementation based on the factors identified. This analysis was performed based on a literature review that balances valuable insights from state-of-the-art general considerations on UAS and aspects specific to the city.

3.3.1 Strengths

Five internal positive factors will be presented within this context, which are intrinsically related to either UAS and or Porto itself. As one of the core goals of this research is to intersect unmanned aviation and smart urban environments, it becomes appropriate to effectively identify some key smart city characteristics Porto already possesses. Additionally, a huge level of professionalism is required in a process with such multidisciplinarity and complexity, with UAS's flexibility often categorized as a significant contributing reason to potential success. Finally, and as much as environmental impact and cost-effectiveness of drones are two highly dependent characteristics on the situation and require specific approaches and analyses, previous studies have shown very promising results, particularly considering the importance of economic and environmental factors in smart cities.

S_1 - Porto as a dynamic, collaborative, digital and green ecosystem

Porto has implemented various digital and green projects that fit perfectly into the paradigm of smart cities. "Porto Free Wi-Fi", which consists of more than 300 access points to provide Internet access to the city users, offers wi-fi network in highly frequented areas, like parks, gardens, beaches, and even buses of Sociedade de Transportes Coletivos do Porto (STCP) since 2016 [108]. This Wi-fi network is supported by routers installed on urban furniture and is integrated with over 7,500 kilometres of fiber optic network [109]. Other examples include "VisitPorto" – a tourism-focused platform that provides information on points of interest and activities, "ShopInPorto" –

a platform dedicated to traditional commerce, as well as "Explore.Porto" – a service that provides information on the specific locations the users are standing and its surroundings, real-time information on public transports, and about the best routes to get anywhere at a certain time, allowing tourists to plan their trips more efficiently, whether they have a predefined plan or prefer a more spontaneous discovery of the city [110], [111].

Most of these initiatives are inserted in "Porto Digital", created to stimulate the development of an ICT-based community that is positioned as the essential toolkit for Porto's digital transformation and innovation. The main objectives of this project are to allow an active sharing and collaboration between city stakeholders and to propel the city as an innovation living lab – "developing a platform to support experimentation, replication, and scalability" [110][15]. The initiative "Desafios Porto" was also included in the "Porto Digital" framework, being launched by the Porto City Hall in 2015 to solve problems identified by Porto users – consisting of a competition where those problems were pinpointed to be later be addressed with the creation of technological and innovative solutions, financed by developing local projects and thus resulting in a good boost for the maturing of the entrepreneurship ecosystem of Porto. The areas of expertise match were Health & Well-Being, Energy, Digital City, Mobility & Environment [110]. Figure 16 highlights key projects for the city's journey toward a more resilient, greener and fairer urban environment.

Figure 16 - Porto's path towards a more resilient, greener, and fair city: remarkable projects and initiatives - Source: [112]

S₂ – Highly educated, trained and experienced professionals in the field

[15] [110] – pp.51

While the areas of expertise of most Portuguese drone enterprises differ to those of a smart city might typically require, Portugal is home to several drone companies composed of highly educated professionals, and the expertise of these people has consistently led the enterprises of the UAS to have the ability not only to keep up with international trends but also innovate them [113]. Regarding Portuguese companies with applications within the smart city paradigm, Connect Robotics, located in São João da Madeira and founded in January 2015, have put efforts that can translate into smarter transportation systems, as their field of expertise is the development of delivery systems and were responsible for the first autonomous BVLOS deliveries within the urban area of Lisbon [114]. There are numerous companies competing in the sector of filming services (e.g., television productions and public event coverage), while Pro-Drone has won international awards for their expertise in inspecting wind turbines [113].

Although educational trends must be considered external factors, the growing interest of public Portuguese universities in aerospace engineering demonstrates commitment to improving the number and quality of experts in aeronautic and aerospace engineering, and potentially UAS technology. Figure 17 illustrates the above-mentioned phenomenon, showing the increase in the number of places available for aeronautical and aerospace engineering 1st cycle students in the National Call, the public university admission contest. According to data from the responsible entity for the Portuguese public higher education system, the Directorate General for Higher Education (DGES), the number of available places went from 137 in 2019 - distributed across 2 public universities to 306 in 2024 - distributed across 5 public universities) [115]. University of Porto is part of this list since 2024.

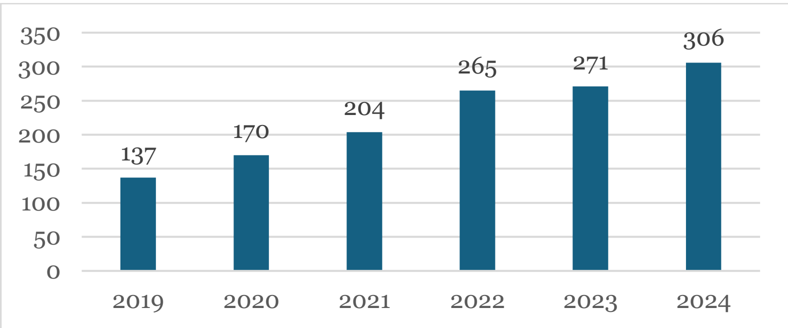

Figure 17 - Evolution of the number of available places for Aeronautical and Aerospace Engineering in the 1st phase of the National Call (2019-2024) - Source: own elaboration based on [115]

From a fully local perspective, the University of Porto is among the top two best universities in the country for engineering, according to the Times Higher Education (THE) Rankings 2024, being ranked within the top 400 out of more than 1,300 universities included in the study [116]. In the QS World University Rankings by Subject 2024 other rankings, which evaluates more than 1,500 universities from all over the world, the University of Porto is ranked 205th in the Engineering & Technology domain, 148th in the Mechanical Engineering subdomain, in the Top 200 in Electrotechnical Engineering subdomain, in the Top 300 in the Physics & Astronomy subdomain, and in the Top 400 in the Management domain [117]. In all these subdomains, the University of Porto is the national leader except for the latter two, where it holds the 2nd place in the country rankings [117].

S_3 – UAS lower environmental impact during operation compared to traditional methods

Research has demonstrated that the energy consumption per package delivered by UAVs can be up to 94% lower than traditional transportation methods, with only electric cargo bicycles generating lower greenhouse gases per package, and that drone-assisted delivery can reduce carbon emissions when compared with traditional truck delivery [118], [119]. Other studies reveal that the Global Warming Potential (GWP) for 1 km of drone delivery distance was one-sixth of the same indicator for 1 km of motorcycle delivery, the particulate emissions of UAVs were estimated to be roughly half that of motorcycles, and that UAVs were estimated to have an overall environmental impact that is one-twelfth that of motorcycles [120]. Moreover, drones have demonstrated more environmental friendliness for online shopping than traditional transportation methods, particularly in operational contexts. They have also been recognized as especially effective for short distances and lightweight packages [121].

In a reality where climate change presents itself as one of the main global challenges, changing transportation modes is crucial for dealing with this aspect and, therefore, enhance the sustainability of cities. This effort aligns with the smart city concept and with Porto's commitment to green and digital practices. Since unmanned aircraft produce less pollution and consume less energy than current traditional methods, they could prove to be a valuable tool in contributing to achieve the city's sustainability goals.

S_4 – UAS operational flexibility

UAS operational flexibility refers to the adaptability and versatility of UAS in various operational environments. This is a key advantage for a potential use of UAS in urban environments and can be divided in several dimensions:

- Mission versatility – as explored before, UAS can perform a wide range of tasks across different sections and environments (rural, urban, remote, maritime, etc.). They can be used in urban environments in applications such as surveillance, mapping, environmental monitoring, infrastructure inspection, delivery services, disaster management, emergency response, and many others;
- Autonomy and control – several sensors, microprocessors and other electronic gadgets enable autonomous and semi-autonomous operations [122]. Semi-autonomous drones operate either within VLOS or BVLOS without a pilot on board, though they can still be remotely controlled by a pilot at a GCS [123]. A fully autonomous UAV, on the other hand, uses machine learning and deep learning techniques to independently modify its motion, direction, and location to fulfil its operational objectives [122];
- Access to difficult areas – due to their technological capabilities and reduced size, UAS can operate in areas of difficult or dangerous access for ground vehicles and manned aircraft. Drones can serve as a cost-effective alternative to traditional methods on several occasions, such as when road transportation is a challenge – their rapid deployment and BVLOS technology allow them to cover long distances [124].

S_5 – Cost-effective and affordable operational approach

The cost-effectiveness of drone operations has been demonstrated in various contexts, particularly in delivery services, which is one of the most extensively studied applications of UAS in urban environments. An economic assessment of a drone delivery system involving the Swedish cities of Linköping and Norrköping is illustrated in Figure 18. The functional unit was defined as a standard delivery of 250 packages, each weighing 2 kg, divided into three stops, with a maximum payload of 500 kg [125].

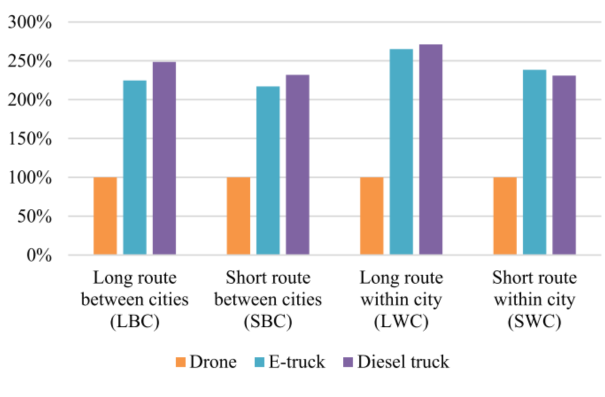

Figure 18 - Economic assessment – Lifecycle cost per functional unit – Delivery system in Swedish cities [125]

The drone's outcome was set as the baseline at 100%, with the outcomes for other vehicles compared relative to the drone. The final two data sets, corresponding to deliveries inside the city of Norrköping, show that the lifecycle cost for electric trucks was at least 140% higher than that of drones. For diesel trucks, the value was at least 130% higher than that of drones. In the "long route within city" scenario, the drone's lifecycle cost per functional unit was 2.5 times lower than that of both types of trucks. The study also highlights that in urban scenarios, whether routes are long or short, the delivery time of drones is less than the delivery time of both trucks by a minimum of 128% [125].

UAS have also been recognized as a cost-effective alternative for last-mile Automated External Defibrillator (AED) and biologic samples delivery compared to traditional transportation methods in various intensities [126], [127], [128]. Besides that, UAS have proven to be cost-effective for law enforcement monitoring in urban contexts [129].

3.3.2 Weaknesses

The internal negative factors related to the smart implementation of UAS in Porto will now be explained. Once again, the approach aimed at collecting insights from a broad range of dimensions. From an economic perspective, the cost-effectiveness of drones has been proved on several occasions, though most of the analysed studies do not address the financial components involved with initial infrastructure requirements, which can be significant in a municipal context. The reliance on skilled and trained personnel for efficient operations are also seen as significant obstacles – more so than in in most conventional transportation methods - while the time required for implementation and the lack of adequate legislation limit drones' ability to have an immediate impact on addressing issues that slow down Porto's development as a smart city.

W_1 – Significant initial investment required for infrastructure

UAS infrastructure is a critical enabler for realizing the full potential of UAM and for the high-volume implementation of UAS in urban environments. Vertiports are essential to allow VTOL operations and to support charging, refuelling, and connectivity [56], although 'infrastructure' extends beyond ground facilities. While guidelines and regulations for the development of vertiports are being developed by EASA, financial concerns related to infrastructure requirements are raised. Additionally, the cost-effectiveness of UAS for designated missions has been proved in various studies, but these analyses only focus on operational contexts and often do not contemplate the funds required for infrastructure.

Research estimates that, depending on the size and purpose, vertiport costs could range between USD (United States dollar) 3.5 million and USD 12 million for a leading global city, ignoring additional costs such as possibly upgrading electricity grid capacity and managing traffic disruptions [130]. Another study, analysing the case of an energy-efficient eVTOL air taxi designed to meet UAM requirements, estimates that the construction costs of a major urban vertiport matching the technological capabilities of that vehicle could be around USD 6 million, while a suburban vertiport in the same conditions might cost US 9.5 million [131].

For comparison purposes, Porto investments directly conducted by the Porto municipality in 2023 were below 15 million euros [132]. Although this is a more complex factor whose influence could only be accurately measured through specific analyses, the estimated cost involved in the construction of suitable ground infrastructure, along with other infrastructure requirements and operational costs, such as staffing and maintenance, suggest that the total investment required for UAM infrastructure could present a challenge. This may potentially require enhanced strategic planning and the fostering of partnerships with different stakeholders to ensure financial feasibility.

W_2 – Dependence on skilled operators and technicians

Most UAM operations involving UAS are considered high-risk and fall under the certified category defined by EASA. As previously discussed, the certified category requires both UAS and operator certification, as well as, when applicable, licensing for the remote pilot [52], [133]. Examples include operations that involve the transport of people, the carriage of dangerous goods posing risks, and all UAS operations in urban environments where U-space services are granted. As a result, ensuring safe and legal operations with high volumes of UAS traffic requires proficient expertise in multiple areas (i.e., operational dimension, piloting, air traffic management).

For example, one of the primary fields projected for UAS use is the delivery of goods, which is currently conducted by conventional transportation methods, such as cars or trucks, operating under established rules, with mature licensing and permitting systems in place for drivers. By contrast, licensing and certification for UAS operators and pilots are still emerging, with a sector having to comply with a new safety framework that remains relatively unknown, even for experts. This issue extends for maintenance and repair purposes, in which available infrastructure and labour are much more available for conventional transportation methods.

On the other hand, this weakness can be perceived as an opportunity to create new jobs. While EASA has already started actively working on that, national and European authorities are currently prioritizing this issue for manned aviation, as the first UAM operations are expected to have a pilot on board [54].

W_3 – Technical limitations related to weather dependency

Weather is considered a critical and inadequately resolved factor that could delay efforts to expand UAS operations, particularly Small Unmanned Aircraft Systems (sUAS). Research has identified atmospheric phenomena like temperature, wind speed, and precipitation to have a negative effect on "UAV endurance, control, aerodynamics, airframe integrity, line-of-sight (LOS) visibility, airspace monitoring, sensors for navigation, and collision avoidance" [134][16]. Accurately measuring how adverse conditions affect drone operations is still a significant challenge, and further research is needed to fully understand the impact of weather in UAS operations [134], [135].

Figure 19 contains four different maps containing info on the flyability of Common Drones (CD) and Weather-Resistant Drones (WRD) in different conditions. Note that a CD has an operational range of 0° to 40° C, maximum wind speed resistance of 10 m/s, and cannot fly in the rain, while a WRD has an operational range of -20° to 46° C, maximum wind speed resistance of 14 m/s, and precipitation tolerance of 50 mm/h [134].

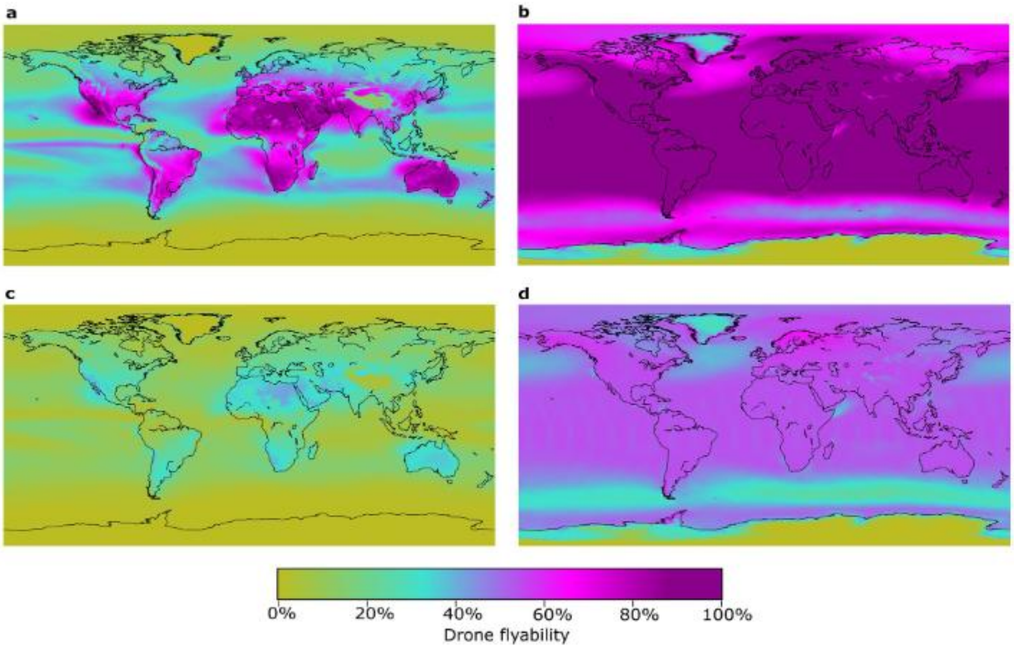

Figure 19 - Global flyability of sUAS - Source: [134]

[16] [134] – pp.1

Each map corresponds to the global flyability of a [134]:

- a – CD in day-and-night conditions – around 70% in Porto;
- b – WRD in day-and-night conditions – around 90% in Porto;
- c – CD in daytime only conditions – around 30% in Porto;
- d – WRD in daytime only conditions – around 60% in Porto.

Based on Porto's climate and on the technological capabilities of UAS, strong winds are likely to be the most significant factor when evaluating weather dependency, although intense rain, cloud cover, fog and high temperatures may also play a role. Wind significantly reduces flight stability, increases energy consumption, and complicates data collection in drones. UAVs are more vulnerable to wind disturbances than manned aircraft due to their lower flight speeds, smaller size and lighter take-off weight [136], [137].

Even though there have been significant advancements in technology, weather dependency remains a technical limitation that affects the planning and execution of some missions, which could have a negative influence the safe and efficient operation of UAS.

W_4 – Amount of time required for implementation

UAS are predicted to be integrated in the same airspace as manned aviation as soon as a multitude of requirements are met, with unmanned aviation only expected to become a solution for UAM after manned operations are regularized. A long and comprehensive process of preparation and testing that span across multiple dimensions is required.

Key factors include the development of an informed robust regulatory framework that can ensure the operational functioning and safety of UAS implementation, technology developing infrastructure that efficiently responds to the inclusion of UAS in urban environments. Municipalities and urban areas will need time to adapt and to these systems, with the construction and integration of necessary infrastructure within their environment playing a critical role.

For example, regarding the full implementation of a U-space, the processes of designation and certification are complex and time-consuming. The designation process is essentially divided into three main different phases. The preparation phase includes identifying stakeholders, defining the scope and establishing a preliminary list of assumptions and constraints later analysed in further detail. The reference scenario phase includes an extensive analysis of the studied airspace before U-space implementation, assessing ground infrastructure and providing a baseline for the safety case. Within the same case, the assessment phase involves applying risk assessment methods and includes elements such as describing the operational environment and determining safety criteria [138]. The flowchart in Figure 20 illustrates the designation process for U-space.

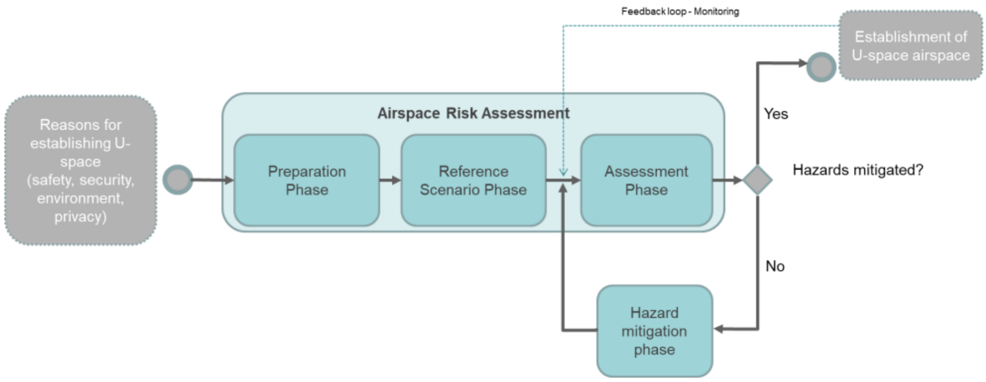

Figure 20 - U-space airspace designation process – Source: [138]

Another potential time-consuming aspect of the overall implementation of unmanned aviation is improving public acceptance, especially as public concerns have placed conditions on the implementation of emerging technologies, even when their technical and economic feasibility has been proven [139]. Education, awareness, and collaboration are key to improving societal acceptance, though these efforts might require time to have the desired effect [140]. The public acceptance of UAVs remains relatively low, with acceptance rates typically being around 50%, and gaining public trust and acceptance for the presence of UAVs in the daily life of residents could prove to be crucial, as public acceptance is a key factor in encouraging the spread of new technologies [141].

The above-mentioned factors suggest that the process of full-scale implementation of UAS, where these technologies are widely used across multiple sectors and integrated into daily operations, can take several years due to its multidisciplinary nature and to the high dependence on the duration and degree of development of each stage.

W_5 – Inadequate and insufficient current legislative and regulatory landscape for UAS

The in-force regulations are insufficient for the anticipated volume of UAS implementation, as they were originally designed for a low volume of UAS traffic and are primarily suited to that context. They fail to address many critical elements that have become increasingly important, such as airspace management, integration with urban infrastructure, and operational procedures. These elements are crucial for public safety and for a safe coexistence between manned and unmanned aviation, an increasing point of focus as the high volume of UAS operations becomes a reality.

Legislation is seen as the major setback in similar contexts [102], with several entities alerting for the lack of international guidelines and regulatory frameworks. They have also highlighted the need for a collaborative and multidisciplinary global effort for elaborating comprehensive a set of rules and guidelines to allow the efficient integration of manned and unmanned eVTOL vehicles in urban airspaces [142]. Therefore, European authorities, in collaboration with national authorities, are working on UAS operation guidelines, conceptualizing ideas (e.g., U-space), and scheduling tests to evaluate the practicality of these initiatives.

3.3.3 Opportunities

A list of positive external factors will now be presented. Opportunities are often seen as a set of factors that serve as driving force for an action. These factors can either be leveraged to benefit the entity or lead to potential advantages resulting from the actions taken – this potential for benefit should also be considered a motivating force that prompts action. Some factors in the list of opportunities are derived from the involvement of Porto in a collaborative continental environment. Specifically, these benefits include the proactive posture of European authorities and institutions towards the integration of unmanned aviation, the city's participation in several smart city initiatives, and the knowledge gained from the implementation of UAS in various contexts, both within Europe and globally. Considering the key characteristics of smart cities, the interrelation between economic development and the implementation of UAS is also believed to be crucial, with each acting as a potential driver for the other.

O_1 – EU's efforts to be a pioneer in the implementation of UAS

EU and EASA play a crucial role in supporting the breakthrough of the intrinsically related field of UAM, facilitating the European industry's leadership on a global scale [53]. Regulatory process has been evident, with European authorities taking important steps in recent years. For example, EASA published a Special Condition to authorize small VTOL aircraft operations in 2019, for Light UAS operating in medium risk situations in 2020, and guidelines on the design verification of UAS operating in the specific category in 2021. Additionally, EASA has also published the Commission Implementing Regulation (EU) 2021/664 of 22 April 2021, the first regulatory framework for U-Space [53], and Commission Implementing Regulations (EU) 2021/665 and 2021/666 of 22 April 2021, addressing coexistence issues between unmanned and manned aviation [143], [144]. Since then, the Acceptable Means of Compliance (AMC) and Guidance Material (GM) for Regulation (EU) 2019/947 - concerning the rules and procedures for the operation of unmanned aircraft - have been amended based on studies and new insights [145], [146].

This proactivity is also evident by the projects developed under the scope of European authorities. A study from 2024 examined over 150 European projects that focus on UAV research and innovation, funded by EU contributions ranging from €50,000 to €50 million, totalizing over €500 million [147]. Within the U-Space framework - a concept entirely developed by EASA - projects have focused on addressing challenges such as air traffic management in urban airspace, flight operation density, and regulatory framework, with European funding exceeding €65 million [147]. The main achievements include improvement of technological features of the vehicles and supporting infrastructure in challenging weather conditions [147]

O_2 – Integration of Porto in several European smart city initiatives

Several smart city initiatives involving the city of Porto have been conducted over the years. In 2013, the University of Porto and International Business Machines Corporation (IBM) have signed an agreement aiming at the development of advanced solutions for a center of competences at the Faculty of Engineering of the University of Porto (FEUP). This agreement aimed at enhancing research competences that would allow Porto's quality of life of its citizens to significantly improve and ultimately affirming Porto as one of the European smart cities until 2015 [148].

Porto's efforts and smart policies are held in high esteem for European institutions, serving as a strong foundation to keep building upon. The Intelligent Cities Challenge (ICC), a European Commission initiative, aims at assisting European cities in the green and digital transformation of their economies. By utilizing disruptive technologies, ICC facilitates the provision of support to European cities to enhance the quality of life of its residents and to improve socioeconomic competencies. Porto and Lisbon are two of the eleven mentor cities identified within this initiative, which mostly consists of northern European cities. Their main role is to provide support to core cities – the project's primary beneficiaries – offering knowledge and aiding to scale intelligent city solutions from all over the continent. In this regard, the highlighted features that contribute for Porto's status as a mentor city are [149]:

- Development of an environmental sustainability strategy since 2014;
- Creation of the *Porto Climate Pact* in 2022, bringing together public and private entities to achieve carbon neutrality by 2030;
- Conversion of all public lighting to Light-Emitting Diode (LED) technology;
- 75% of all the municipal fleet consists of electric vehicles.

The benefits derived from the knowledge exchange through the city's participation in initiatives like ICC or *Scalable Cities* – an European Commission's initiative with the goal of promoting innovation and sustainability in the European community of smart cities that has facilitated over 550 demonstrations of innovation across various domains, including mobility, logistics and ICT infrastructure [150] - can prove to be a valuable tool for further implementation of smarter practices.

O_3 – Experience acquired with UAS implementation in other contexts

Worldwide experience with UAS implementation can provide valuable lessons for the EU and for Porto in specific, as they look to adopt this technology. By learning from these applications, and even though some contexts differ from those of a smart city, the EU can gain insights into the challenges associated with UAS deployment and leverage the opportunities they present across various sectors. Among currently implemented applications of UAS previously highlighted throughout this dissertation are infrastructure inspection and maintenance, environmental monitoring, and delivery services. For example, UAS were used in the deliveries in rural zones in Ghana during COVID-19 outbreak. Although this differs a lot from the expected high-volume urban unmanned aviation implementation, it can offer valuable logistical and operational insights that can inform future implementation in more complex environments.

The most remarkable initial insights can be derived from the implementation of the first real model of a U-Space within EASA's scope, located in Hamburg and called BLU-Space. The conceptual work will focus on Authorities and Organizations with Security Tasks (BOS) deployment coordination and U-Space airspace designation scenarios, while a project advisory board will oversee the project, which is expected to be concluded in mid-2026 [51]. EASA highlights the main benefits of BLU-Space as the establishment of a robust system architecture for UAM, a secure regulation framework for drone operations and precisely defined roles, duties, and responsibilities for various U-Space stakeholders

[151]. As the first practical implementation of the U-Space concept, this project is expected to set an important precedent for future implementations across Europe, providing valuable experience and insights for enhanced safety and more efficient employment of UAS and UAM initiatives in other European cities.

O_4 – Job creation and business opportunities

As the widespread implementation of UAS approaches, the growth of the drone industry is set to become a key driver of job creation in this field. As the industry expands, a greater number of professionals will be needed to design, build, maintain, and operate drones, leading to new opportunities for engineers, Information Technology (IT) professionals, and UAS operators. As a matter of fact, the Association for Unmanned Vehicle Systems International (AUVSI) states that at least 100,000 jobs for drone pilots will be created by 2025 [152].

Likewise, there is increased potential for competitiveness and business development not only within the drone industry itself, but also in related to economic activities directly benefiting from UAS applications. The implementation of UAS can work as a driver for increased economic efficiency across multiple sectors, contributing to the development of local and regional economies and enhancing Porto's position on the national and European stage, either by stimulating flourishing economic activities or by consolidating areas where Porto already excels, such as tourism.

O_5 – Economic growth as a door for the implementation of unmanned aviation

Porto is recognized as one of the leading technological and economic hubs in Portugal. While the tertiary sector remains the largest contributor to Porto's economy, the municipality has shown commitment to diversify its economic entrepreneurial system by retaining and enhancing IT services and technological industries, aligning with one of the city's key goals: attracting investment while fostering greater innovation and creativity within the city and ensuring the quality of life of who works, visits and lives in the city or in the region [153]. Besides that, it is noteworthy that this mindset is accompanied by progress within the framework of the circular economy, with the municipality aiming to establish a strong circular component in the medium and long term. Efforts in this direction have already begun [154]. The combination of economic growth and diversification, coupled with the municipality's permanent commitment to innovation and sustainability, presents significant opportunities for UAS integration.

This is facilitated by an increased availability of economic resources, which can translate into greater investment in research and development.

3.3.4 Threats

The negative external factors that could endanger the successful smart implementation of UAS in urban environments will now be presented. The choice of safety, and especially security and privacy over other commonly mentioned factors in literature such as noise, job loss, or visual pollution, aligns with the smart city mentality and reflects the main public concerns associated with delivery drones – the primary focus of research of the unmanned aviation component of EASA's study on the societal acceptance of UAM [59]. Since the lack of a comprehensive regulatory framework is considered by many as the principal challenge in this context, questions on whether involved parties can provide an effective response to the evolving nature of technology and to the permanently changing regulatory needs are raised. Portugal's struggle in retaining talent is another aspect that poses a significant threat, particularly in the fields of IT and engineering, as further explained below.

T_1 – Safety aspects and public concerns related to the application of UAS in cities

Along with infrastructure and noise, safety has been identified as a major challenge in the implementation of UAM initiatives [59]. EASA's study on the societal acceptance of UAM highlights safety as the leading factor mentioned in literature for unmanned aviation, aligning with the findings for UAM. When it comes to public perception on the topic, safety represents the major concern regarding the use of delivery drones, being ranked as a Top 3 concern by 44% of the respondents and the top public concern for 22% - the highest out of any concern [59]. An interesting take-away also shows that European cities trust commercial aviation safety levels, so establishing equal levels of safety to them would mitigate the public concerns regarding the safety of UAS operations [59].

Due to the increasing popularity of UAS, EASA has included a chapter fully dedicated to UAS in their Annual Safety Review report for the first time ever in 2024 [155]. This report refers to data from the year before, when there were registered twelve accidents or serious incidents involving UAS, from which nine resulted in non-fatal accidents, two were classified as serious incidents, and one resulted in casualties. From these twelve, two also involved manned aviation [155]. Figure 21 depicts the number of occurrences by occurrence category involving UAS. The categorization follows the ICAO Accident

Incident Data Reporting taxonomy for occurrence categories, and various categories can be assigned to a single occurrence, as an engine failure – categorized as System/Component Failure or Malfunction [non-powerplant] (SCF-NP) – can be followed by loss of control – categorized as Loss Of Control - Inflight (LOC-I) [155]. Besides 'Other', the two most frequent categories are 'Airprox/Airborne Collision Avoidance System (ACAS) alert/loss of separation/(near) midair collisions', which was assigned to five accidents or serious incidents, and 'Low altitude operations', which was assigned to three.

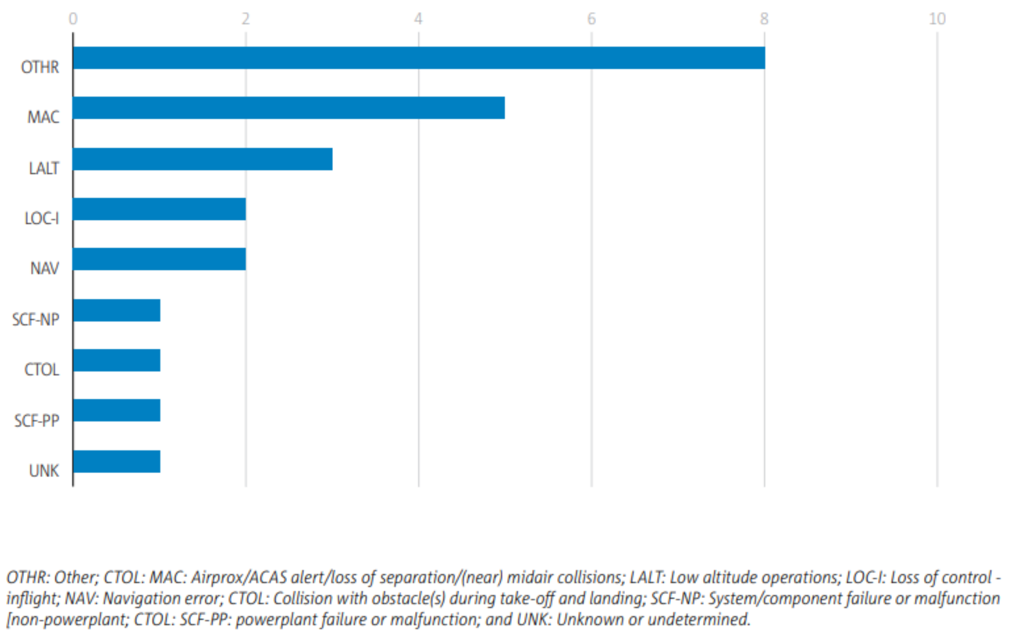

Figure 21 - Number of occurrences by occurrence category involving UAS – Source: [155]

Even though these occurrences took place in very different contexts from the predicted future of urban environments - where perceptions of safety will likely differ - this EASA initiative shows European authorities' commitment to start addressing safety aspects, with the most significant occurrence categories already contemplating the main predicted sources of compromised safety in a near-future reality (e.g., mid-air collisions between unmanned aircraft, mid-air collisions between unmanned and manned aircraft, mechanical or software malfunctions).

UAM initiatives are expected to begin with a pilot on board, with unmanned aviation gradually replacing manned aviation. Compared to manned aviation, where these concerns do not exist due to the nature of UAS operations and particularly BVLOS ones, potential safety threats include the lack of visual contact from the pilot to prevent a potential mid-air collision, and the existence of communication system failures or data link disruptions between the GCS and UAV could compromise the safety of several entities [156].

T_2 – Security aspects and public concerns related to the application of UAS in cities

Although security is not ranked among the ten most mentioned challenges for UAM in literature, it is ranked as the second-biggest concern regarding drone deliveries – just below safety. Another interesting finding related to the distrust of unmanned aviation compared to manned aviation shows that the percentage of trust in drone deliveries is 10% higher of that of manned air taxis regarding security concerns [59].

Common security threats are often related to cybersecurity. The compromise of communication systems/data link for hijacking purposes is widely recognized as a top security concern. Communications between GCS and the UAV are particularly vulnerable to attacks especially when communication signals lack encryption [60], [157], as passwords become easy to crack, and attackers can perform man-in the middle attacks via Wi-Fi links [158]. Through this method, an inexpensive $40 hardware can take control of a police quadcopter valued at thousands of dollars from a distance up to 2 km [159].

Attacks against navigation systems are also common and include GPS jamming, where attackers block the signals from reaching the receiver, and GPS spoofing, where attackers deceive the receivers by broadcasting fake signals. The intent is to make the receiver think the UAV is travelling in a different direction than it is, but in fact it is following the path set by the attacker, as pictured in Figure 22 [160].

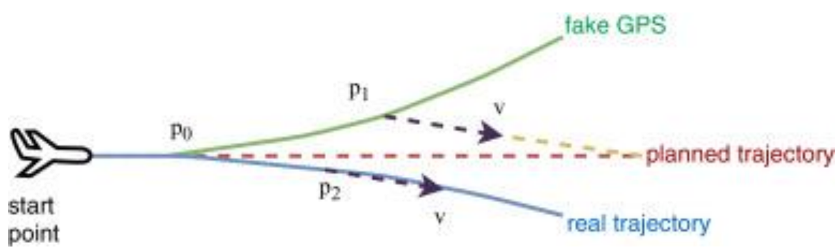

Figure 22 - Example of a hijacking attack through GPS spoofing - Source: [160]

Other security breaches include transporting of illegal or malicious goods, monitoring areas for criminal or illegal purposes, and stealing trade secrets or sensitive information [156].

Most security threats are particularly concerning due to the lack of countermeasures to address potential issues in an effective way. Among the twelve cybersecurity threats identified in [157], only five of them are associated with mentions on the existence of countermeasures. It is undoubtedly essential to ensure protection against different types of attacks, especially for their implementation in smart cities [161].

T_3 – Privacy issues arising from UAS implementation

EASA's study and literature review on the societal acceptance of UAM highlights privacy as a significant concern regarding UAM and UAS, especially in the smart home space [59]. Regarding drone deliveries, privacy was identified as a top 3 concern for 29% of respondents, making it the third most relevant public concern, a percentage that drops ten points for manned air taxis [59]. Privacy concerns are often categorized in two main areas: issues related with individuals and with legislation. The former is associated with physical, location and behaviour privacy, while the latter is associated with data protection, policy and compliance issues [162].

UAVs typically incorporate several data collection sensors and cameras, which raises privacy concerns [60]. These concerns exist due to the potential misuse of these technologies' purposes other than the original intent. The use of drones for delivery or postal services raises significant privacy issues, as attackers may capture images and video of individuals and their houses without their consent for malicious purposes, leading to physical privacy concerns [162], [163]. Furthermore, they may unlawfully track people's movements, either by very specifically targeting their physical locations for business purposes – location privacy – or by monitoring their actions in public spaces – behaviour privacy [162], [163].

On the other hand, legislation privacy is associated with the arising issues - related with drone regulations - that compromise citizens' privacy. Even when drones are authorized to fly from competent legal authorities, UAVs can still obtain personal data without citizens' consent - data protection issues. Similarly, creating a complete list of policy measures for UAS operations can definitely help to mitigate key privacy concerns, though it might be challenging to monitor them in a real-time, potentially triggering responsibility issues – policy privacy issues. Finally, the differing reality of aviation agencies, like EASA and FAA present significant challenges for drone manufacturers in aligning with the guidelines and rules of all (or most) of these agencies – compliance issues [162].

As UAS are predicted to be a growing reality in urban environments, the preparation and application of a code of ethics for the use of UAVs in smart cities is imperative [60], and the regulatory framework dedicated to ethic issues needs to be strengthened, as it is the only way to address potential privacy and ethical considerations and improve public acceptance.

T_4 – Complex and evolving legislative and regulatory landscape

While there is some common ground between this potential threat and the internal factor related to the existence of an inadequate and insufficient current legislative and regulatory landscape for UAS, the current external factor is more forward-looking, as it involves potential issues related to planning and preparing for a regulatory landscape that will continue to evolve to respond to future challenges and realities, where a proactive approach is necessary by national (within their jurisdiction) and European authorities and where the need to anticipate and adapt is imperative. Therefore, while W_5 refers to present issues, this external challenge refers to the potential difficulty in establishing a future regulatory framework that can give a solid response to the evolving landscape of UAS technology and operations.

T_5 – Potential shortage of necessary expertise due to migration of skilled talent

The importance of skilled talent and expertise in the large-scale implementation of UAS in Porto is indescribable, given the multidisciplinary and complex nature of the entire process. As of 2023, more than 25% of Portuguese individuals aged 15 to 39 years live abroad - over two-thirds of emigrants who have left Portugal throughout the last decade fall within that age group. The proportion of qualified workers among emigrants is also increasing every year [164]. A study highlights that 81% of Portuguese employers report difficulties in filling roles, with engineering and IT being identified as the most affected areas [165]. The emigration of highly educated, trained and qualified professionals, and the consequent lack of retention of this talent, may lead to the shortage of expertise in various fields, which can prove to be a significant obstacle especially as the process reaches more advanced stages.

3.3.5 TOWS matrix

Having defined all SWOT sub-criteria, a TOWS matrix can now be elaborated based on the intersection of internal and external factors. A TOWS matrix is typically divided in four parameters: SO - that maximize both strengths and opportunities, WT - that minimize both weaknesses and threats, WO - that minimize weaknesses and maximize opportunities, and ST - that maximize strengths and minimize threats. These strategies were elaborated based on a literature review, with the aim of meaningfully intersecting as many factors as possible.

SO – Develop partnerships with existing smart city initiatives in Porto to integrate UAS operations – As previously highlighted, Porto has been actively involved in several smart city initiatives, particularly within a European context. Considering that, the proposed strategy aims to promote the adoption of a UAS implementation framework and enhance the role of UAS in the improvement of smart city capabilities. The positive internal and external factors identified clearly indicate that the high-volume implementation of UAS would align with Porto's vision of developing a dynamic and sustainable ecosystem. Furthermore, their advanced technological features, lower environmental impact, and greater cost-effectiveness compared to traditional methods make UAS a valuable tool for improving the quality of life for all citizens.

ST – Establish a comprehensive safety and security framework to address the complexity and the evolving legislation of urban UAS operations – EASA is actively working on a robust set of operational guidelines for Member States to adopt or adapt (when applicable) to their specific contexts, with the aim of guaranteeing the safe and secure integration of UAS into urban environments. National authorities, in coordination with municipal governments, must give the appropriate emphasis to the safety and security components within their jurisdiction. Given the dynamic and evolving nature of aviation risks, it is essential to address these challenges through regulations that remain current and effective. This approach could also benefit from leveraging the specialized expertise available at both local and national levels and would be strengthened through the collaboration with industry stakeholders, research institutions, and emergency response and public safety organizations.

WO – Collaborate with European partners to secure funding and reduce initial investment costs for infrastructure – As demonstrated in a wide range of contexts and fields, European partnerships have proved to be crucial in advancing knowledge and providing funding for innovation, technology, and sustainable development initiatives (e.g., Cohesion Policy - European Structural and Investment Funds, Horizon Europe) [166], [167]. As evident from the depiction of sub-criterion O1, regarding drone research and U-space, the same holds true, with European entities showing an increasing commitment in supporting this path [147], [168]. This collaboration could simultaneously help in the mitigation of some financial barriers previously presented and, therefore, accelerate the development of UAS-related projects.

WT – Use the time to engage with the community and educate and inform about the benefits and safety measures of UAS operations – This strategy would consist in leveraging the implementation timeline to actively engage with the community, educating and informing them about the benefits and safety measures associated with UAS operations. Safety concerns and the limited acceptance of UAS among some Europeans, as highlighted in EASA's studies, remain significant barriers. However, the extended timeline for full-scale UAS deployment in urban environments provides an opportunity to address these challenges. By employing effective communication strategies, stakeholders can raise awareness and improve public acceptance of UAS – an essential step in the context of smart cities, where the primary goal is to enhance residents' satisfaction and quality of life.

3.4 Quantitative analysis

The internal and external factors have been qualitatively defined and the strategies of implementation based on the intersection of some of these factors have been developed. It is now possible to assess respondents' perspectives on the importance of each criterion and strategy in comparison to others. This subchapter is divided into three parts, with the first part explaining the data aggregation process, which forms the foundation for the subsequent sections. The second part contains the calculations for estimating the most relevant criteria for the smart implementation of UAS in Porto. Finally, the third part includes the calculations required to determine a proposed order of implementation for the strategies.

3.4.1 Data aggregation process

Respondents were initially asked to select their field or combination of fields from four pre-defined categories, which encompass key areas related to smart cities and align with the target audience for whom the questionnaire was designed: Technology, Governance, Urban Planning and Legislation/Regulation. Four respondents added other fields of expertise – Aeronautics, Design and Advanced Air Mobility. Table 6 presents the number of respondents per field or combination of fields.

Table 6 - Distribution of number of respondents per field/combination of fields – Source: own elaboration

	Field	**Tec.**	**Gov.**	**U. P.**	**L./R.**	**Aeron.**	**Design**	**A.A.M.**
Pre-defined fields	**Technology**	**8**[17]		**1**[18]	**3**			
	Governance		**2**	**1**	**2**			
	Urban Planning							
	Legislation/Regulation				**2**			
Fields added by respondents	**Aeronautics**					**2**		
	Design						**2**	
	Advanced Air Mobility							**1**

As stated before, the weighted geometric mean was used for aggregation purposes for criteria and sub-criteria comparison, while the weighted arithmetic mean was used for the same purposes for strategy prioritization. Using a weighted version of the method is particularly appropriate in the present context, as the SWOT analysis was a multidisciplinary process involving various fields, and it was not possible to collect a balanced number of respondents for each field.

Therefore, let $(\alpha_1, \alpha_2, \ldots, \alpha_q)$ denote the weighting vector of the q experts. The weighted geometric mean for the collective relative importance of C_i over C_j is given by

$$\tilde{C}_{ij} = \left(\left(\prod_{t=1}^{q} l_{ij}^{(t)\,\alpha_q} \right), \left(\prod_{t=1}^{q} m_{ij}^{(t)\,\alpha_q} \right), \left(\prod_{t=1}^{q} u_{ij}^{(t)\,\alpha_q} \right) \right), \tag{22}$$

while the weighted arithmetic mean for the collective relative importance of C_i over C_j is given by

$$\tilde{C}_{ij} = \left(\left(\sum_{t=1}^{q} l_{ij}^{(t)}\, \alpha_q \right), \left(\sum_{t=1}^{q} m_{ij}^{(t)}\, \alpha_q \right), \left(\sum_{t=1}^{q} u_{ij}^{(t)}\, \alpha_q \right) \right). \tag{23}$$

[17] - 8 respondents have indicated that “Technology” is their area of expertise
[18] - 1 respondent has indicated that “Technology” and “Urban Planning” are their areas of expertise

The unnormalized weight α' assigned to a respondent R from a field of expertise S is calculated by

$$\alpha'_R = \left(\frac{f + 0.1q_S}{q_S}\right), \tag{24}$$

while unnormalized weight α' assigned to a respondent R from a combination of fields of expertise S and T is calculated by

$$\alpha'_R = \frac{1}{2}\left(\frac{f + 0.1q_S}{q_S} + \frac{f + 0.1q_T}{q_T}\right), \tag{25}$$

Regarding equations (24) and (25):

- $f = 0.5$ for respondents from pre-defined fields – which represent areas identified as critical by the research framework, and $f = 0.25$ for respondents from fields added by respondents themselves – allowing for flexibility while being associated with a more conservative baseline weight;

- q_S and q_T represent the number of experts from the combination of fields of expertise S and T and their calculation is depicted in Table 7;

- $0.1q_S$ and $0.1q_T$ were included to adjust the weights based on the number of experts, as some fields had a significantly higher number of respondents than others. This adjustment ensures that fields with a disproportionately high number of respondents do not dominate the results, overshadowing less represented but equally important fields. By including these factors, the method aims at mitigating overrepresentation while preserving the influence of respondent count in a controlled and balanced manner.

The data from Table 6 can be reorganized as seen in Table 7.

Table 7 – Respondents per field/combination per fields (reorganized) – Source: own elaboration

Field	Only field (O)	Combined with another field (C)	$(O + \frac{C}{2}) \rightarrow q_S, q_T$
Technology	**8**	**4**	**10**
Governance	**2**	**3**	**3.5**
Urban Planning	**0**	**2**	**1**
Legislation/Regulation	**2**	**5**	**4,5**

Field	Only field (O)	Combined with another field (C)	$(O + \frac{C}{2}) \rightarrow q_S, q_T$
Aeronautics	2	0	2
Design	2	0	2
Advanced Air Mobility	1	0	1

Equations (24) and (25) was used to calculate the unnormalized weight assigned to one respondent from each field or combination of fields. After normalization, the following weights obtained for each field or combination of fields are demonstrated in Table 8.

Table 8 – Weight assigned to one respondent from each field/combination of fields – Source: own elaboration

Combination/Field	Weight assigned to one respondent	Number of respondents	Total weight
Tec.	**0.0291**	8	0.2330
Tec. + U. P.	**0.0728**	1	0.0728
Tec. + L./R.	**0.0351**	3	0.1052
Gov.	**0.0472**	2	0.0943
Gov.+ U. P.	**0.0818**	1	0.0818
Gov.+ L./R.	**0.0441**	2	0.0881
L./R.	**0.0410**	2	0.0820
Aeronautics	**0.0437**	2	0.0874
Design	**0.0437**	2	0.0874
Advanced Air Mobility	**0.0680**	1	0.0680
Σ	-	24	1

Table 8 demonstrates that the weighting method is both balanced and equitable. It ensures proportionality based on respondent count while safeguarding against overrepresentation. Respondents from underrepresented fields are assigned more individual weight, ensuring their feedback remain significant despite smaller group sizes. On the other hand, fields with higher respondent counts contribute proportionally more to the overall weight, but their influence is moderated by the formula to maintain balance. For example, the cumulative weight of combinations that include the field of Technology is greater than that of any other field, reflecting its larger respondent count. However, smaller fields still maintain meaningful contributions.

The normalized weights highlighted in Table 8 were subsequently used to construct the weighting vector $(\alpha_1, \alpha_2, \dots, \alpha_q)$ for application in equations (22) and (23).

3.4.2 Criteria comparison – FAHP application

Firstly, respondents were asked to compare sub-criteria as explained above (an example of a respondent's answer can be consulted in Appendix 1 - Figures 24, 25, 26 and 27) After converting linguistic variables into fuzzy numbers (exemplified in Appendix 1 - Figure 28), equation (22) and Table 8 were used to aggregate the fuzzy numbers associated with respondents' opinions. Tables 9, 10, 11 and 12 represent the aggregated pairwise comparison matrixes of every criterion.

Table 9 - S (Strengths) matrix - aggregated results - Source: own elaboration

Sub-criterion	S1	S2	S3	S4	S5
S1	(1.00,1.00,1.00)	(0.74,1.18,1.63)	(0.77,1.09,1.49)	(0.76,1.10,1.50)	(0.77,1.12,1.50)
S2	(0.61,0.85,1.35)	(1.00,1.00,1.00)	(0.74,1.12,1.53)	(0.77,1.20,1.65)	(0.77,1.09,1.47)
S3	(0.67,0.92,1.30)	(0.65,0.90,1.35)	(1.00,1.00,1.00)	(0.91,1.37,1.86)	(0.73,1.09,1.50)
S4	(0.67,0.91,1.31)	(0.61,0.84,1.30)	(0.54,0.73,1.10)	(1.00,1.00,1.00)	(0.70,1.09,1.53)
S5	(0.67,0.89,1.30)	(0.68,0.92,1.31)	(0.67,0.92,1.37)	(0.65,0.92,1.43)	(1.00,1.00,1.00)

Table 10 - W (Weaknesses) matrix - aggregated results - Source: own elaboration

Sub-criterion	W1	W2	W3	W4	W5
W1	(1.00,1.00,1.00)	(0.73,1.12,1.55)	(0.80,1.16,1.56)	(0.67,1.03,1.42)	(0.57,0.80,1.11)
W2	(0.65,0.90,1.38)	(1.00,1.00,1.00)	(0.90,1.27,1.70)	(0.76,1.14,1.55)	(0.71,1.02,1.38)
W3	(0.64,0.86,1.26)	(0.59,0.79,1.11)	(1.00,1.00,1.00)	(0.80,1.15,1.56)	(0.62,0.90,1.24)
W4	(0.71,0.97,1.50)	(0.65,0.88,1.31)	(0.64,0.87,1.25)	(1.00,1.00,1.00)	(0.58,0.85,1.16)
W5	(0.90,1.25,1.76)	(0.73,0.98,1.40)	(0.81,1.11,1.61)	(0.86,1.18,1.71)	(1.00,1.00,1.00)

Table 11 - O (Opportunities) matrix - aggregated results - Source: own elaboration

Sub-criterion	O1	O2	O3	O4	O5
O1	(1.00,1.00,1.00)	(0.73,1.16,1.62)	(0.65,0.95,1.31)	(0.55,0.84,1.18)	(0.59,0.92,1.28)
O2	(0.62,0.86,1.37)	(1.00,1.00,1.00)	(0.65,1.02,1.44)	(0.67,0.96,1.31)	(0.64,0.99,1.38)
O3	(0.76,1.05,1.54)	(0.69,0.98,1.54)	(1.00,1.00,1.00)	(0.64,1.05,1.49)	(0.68,1.05,1.48)
O4	(0.85,1.19,1.81)	(0.76,1.05,1.50)	(0.67,0.95,1.56)	(1.00,1.00,1.00)	(0.63,1.08,1.56)
O5	(0.78,1.09,1.71)	(0.72,1.01,1.55)	(0.68,0.95,1.47)	(0.64,0.92,1.60)	(1.00,1.00,1.00)

Table 12 - T (Threats) matrix - aggregated results - Source: own elaboration

Sub-criterion	T1	T2	T3	T4	T5
T1	(1.00,1.00,1.00)	(0.63,1.10,1.58)	(0.72,1.10,1.53)	(0.64,1.04,1.48)	(0.67,1.07,1.42)
T2	(0.63,0.91,1.58)	(1.00,1.00,1.00)	(0.75,1.18,1.63)	(0.69,1.17,1.66)	(0.80,1.28,1.77)
T3	(0.65,0.91,1.39)	(0.61,0.85,1.33)	(1.00,1.00,1.00)	(0.71,1.11,1.53)	(0.69,1.06,1.48)
T4	(0.68,0.96,1.56)	(0.60,0.86,1.45)	(0.65,0.90,1.42)	(1.00,1.00,1.00)	(0.80,1.24,1.71)
T5	(0.70,0.93,1.48)	(0.56,0.78,1.24)	(0.68,0.95,1.46)	(0.59,0.80,1.25)	(1.00,1.00,1.00)

Once the pairwise comparison matrixes have been defined, the local weights of each sub-criterion can be calculated using Chang's method of extent analysis – depicted in sub-section 2.5.2.1 - and are presented in Table 13. An example of Chang's method application for the Strengths matrix can be found in Appendix 1 – Figures 29, 30 and 31.

Table 13 - Local weights of each SWOT sub-criterion - Source: own elaboration

Sub-criterion	Local weight	Sub-criterion	Local weight	Sub-criterion	Local weight	Sub-criterion	Local weight
S1	0.2151	**W1**	0.2025	**O1**	0.1941	**T1**	0.2087
S2	0.2074	**W2**	0.2110	**O2**	0.1935	**T2**	0.2158
S3	0.2081	**W3**	0.1863	**O3**	0.2038	**T3**	0.1958
S4	0.1830	**W4**	0.1825	**O4**	0.2086	**T4**	0.1985
S5	0.1864	**W5**	0.2176	**O5**	0.1999	**T5**	0.1813

Respondents were then asked to compare SWOT criteria. Each sub-criterion was grouped with others from the same category (internal/external or positive/negative), resulting in four groups of five sub-criteria each, as presented in Appendix 1 - Figure 32: Group A - Strengths, Group B - Weaknesses, Group C - Opportunities, Group D - Threats. This comparison aimed at providing insights into the importance and influence of each criterion compared to others, and an example of a respondent's answer can be found in Appendix 1 – Figure 33.

As explained above, data was aggregated using the weighted geometric mean for fuzzy numbers. After data aggregation, Chang's method of extent analysis was applied to calculate the local weights associated with each criterion. The aggregated comparison matrix and the local weights associated with each criterion are presented in Table 14.

Table 14 – SWOT matrix - aggregated results and local weight of each criterion - Source: own elaboration

Criterion	S	W	O	T	Local weight
S	(1.00,1.00,1.00)	(0.74,1.14,1.58)	(0.60,0.97,1.37)	(0.59,0.92,1.32)	**0.2513**
W	(0.63,0.88,1.36)	(1.00,1.00,1.00)	(0.62,0.98,1.37)	(0.66,1.00,1.39)	**0.2416**
O	(0.73,1.03,1.66)	(0.73,1.02,1.60)	(1.00,1.00,1.00)	(0.65,1.02,1.43)	**0.2536**
T	(0.76,1.08,1.69)	(0.72,1.00,1.52)	(0.70,0.98,1.54)	(1.00,1.00,1.00)	**0.2535**

Finally, the local weight of each sub-criterion was multiplied by the local weight of the corresponding criterion (e.g., the local weight of 'S1' is multiplied by the local weight of 'S', while the local weight of 'O4' was multiplied by the local weight of 'O') as shown in Equation (19), and shown in Appendix 1 – Figure 34. This process allows for the calculation of the global weights of each SWOT sub-criterion, with the results presented in Table 15, ultimately allowing the assessment of the importance of each factor in respondents' eyes. The sum of the global weights equals one.

Table 15 - Global weights of each SWOT sub-criterion - Source: own elaboration

Sub-criterion	Global weight	Sub-criterion	Global weight
T2	0.0547	**T4**	0.0503
S1	0.0540	**T3**	0.0496
T1	0.0529	**O1**	0.0492
O4	0.0529	**O2**	0.0491
W5	0.0526	**W1**	0.0489
S3	0.0523	**S5**	0.0468
S2	0.0521	**S4**	0.0460
O3	0.0517	**T5**	0.0460
W2	0.0510	**W3**	0.0450
O5	0.0507	**W4**	0.0441

3.4.3 Strategy prioritization

After collecting respondents' opinions on the level of complementarity between sub-criteria and strategies (an example of a respondent's answer can be consulted in Appendix 1 - Figures 35 and 36), the associated linguistic variables were converted into fuzzy numbers using the scale represented in Table 4 (exemplified in Appendix 1 - Figure 37), with equation (22) and Table 8 being used to aggregate the triangular fuzzy numbers associated with respondents' feedback on the importance of each strategy, in relation to each sub-criterion. The data results obtained from the aggregation process are presented in Table 16.

Table 16 - Aggregated results - evaluation of the level of complementarity between each strategy and sub-criterion - Source: own elaboration

Sub-criterion	SO	ST	WO	WT
S1	(0.49,0.73,0.94)	(0.40,0.65,0.86)	(0.43,0.68,0.85)	(0.49,0.74,0.92)
S2	(0.40,0.65,0.89)	(0.42,0.67,0.89)	(0.38,0.63,0.81)	(0.53,0.78,0.93)
S3	(0.32,0.57,0.82)	(0.30,0.55,0.80)	(0.35,0.60,0.82)	(0.43,0.68,0.88)
S4	(0.35,0.60,0.85)	(0.34,0.59,0.81)	(0.37,0.62,0.84)	(0.32,0.57,0.81)
S5	(0.48,0.72,0.91)	(0.28,0.52,0.75)	(0.45,0.70,0.89)	(0.26,0.51,0.73)
W1	(0.33,0.58,0.82)	(0.32,0.54,0.76)	(0.52,0.77,0.92)	(0.25,0.46,0.70)
W2	(0.36,0.61,0.86)	(0.36,0.59,0.81)	(0.30,0.53,0.78)	(0.23,0.45,0.70)
W3	(0.26,0.50,0.73)	(0.28,0.49,0.73)	(0.26,0.49,0.71)	(0.22,0.43,0.68)
W4	(0.37,0.61,0.83)	(0.35,0.60,0.83)	(0.39,0.63,0.86)	(0.34,0.58,0.81)
W5	(0.34,0.56,0.75)	(0.45,0.70,0.89)	(0.38,0.63,0.84)	(0.27,0.51,0.75)
O1	(0.50,0.75,0.93)	(0.40,0.65,0.85)	(0.46,0.71,0.88)	(0.40,0.65,0.85)
O2	(0.56,0.81,0.93)	(0.45,0.70,0.89)	(0.47,0.72,0.90)	(0.44,0.69,0.87)
O3	(0.47,0.72,0.92)	(0.46,0.71,0.92)	(0.40,0.65,0.86)	(0.42,0.67,0.86)
O4	(0.42,0.67,0.88)	(0.34,0.57,0.79)	(0.44,0.69,0.88)	(0.44,0.69,0.89)
O5	(0.42,0.67,0.92)	(0.34,0.59,0.83)	(0.39,0.63,0.82)	(0.41,0.65,0.86)
T1	(0.42,0.67,0.89)	(0.50,0.75,0.94)	(0.33,0.57,0.80)	(0.40,0.65,0.86)
T2	(0.43,0.68,0.90)	(0.46,0.71,0.91)	(0.30,0.53,0.78)	(0.41,0.65,0.85)
T3	(0.34,0.58,0.81)	(0.38,0.62,0.81)	(0.28,0.51,0.74)	(0.39,0.63,0.85)
T4	(0.37,0.62,0.83)	(0.44,0.69,0.89)	(0.38,0.62,0.85)	(0.26,0.47,0.71)
T5	(0.37,0.62,0.84)	(0.32,0.55,0.78)	(0.31,0.56,0.81)	(0.27,0.50,0.72)

Afterwards, the BNP for each case was calculated through equation (21). This parameter provides an accurate perception of the relation between each sub-criterion and each TOWS strategy per respondents' eyes – a higher BNP reflects the associated sub-criterion could either play an important role in the realization of the corresponding TOWS strategy (in case of positive factors) or be mitigated (in case of negative factors) through the realization of the corresponding strategy. An example of the calculation of this parameter is shown in Appendix 1 – Figure 38.

Each BNP was multiplied by the global weight of the corresponding sub-criterion, and the values of $(GW)_{SC}$ × BNP associated with the same TOWS strategy were added. The repetition of this calculation for every TOWS strategy identified will enable the elaboration of a ranking regarding the prioritization of these strategies, where the TOWS strategy with the highest total score corresponds to the strategy that should be given the most priority, as shown in Table 17.

Table 17 - Ranking of prioritization of strategies – source: own elaboration

Sub-criterion	**Global weight**	**BNP**				**Global weight × BNP**			
		SO	**ST**	**WO**	**WT**	**SO**	**ST**	**WO**	**WT**
S1	0.0540	0.7203	0.6371	0.6564	0.7200	0.0389	0.0344	0.0355	0.0389
S2	0.0521	0.6487	0.6624	0.6067	0.7470	0.0338	0.0345	0.0316	0.0389
S3	0.0523	0.5664	0.5461	0.5888	0.6651	0.0296	0.0286	0.0308	0.0348
S4	0.0460	0.6014	0.5765	0.6086	0.5691	0.0276	0.0265	0.0280	0.0262
S5	0.0468	0.7029	0.5176	0.6762	0.4997	0.0329	0.0242	0.0317	0.0234
W1	0.0489	0.5752	0.5375	0.7351	0.4709	0.0281	0.0263	0.0360	0.0230
W2	0.0510	0.6104	0.5857	0.5360	0.4623	0.0311	0.0299	0.0273	0.0236
W3	0.0450	0.4952	0.5004	0.4864	0.4389	0.0223	0.0225	0.0219	0.0198
W4	0.0441	0.6041	0.5971	0.6294	0.5780	0.0266	0.0263	0.0278	0.0255
W5	0.0526	0.5486	0.6816	0.6177	0.5117	0.0288	0.0358	0.0325	0.0269
O1	0.0492	0.7271	0.6323	0.6836	0.6353	0.0358	0.0311	0.0336	0.0313
O2	0.0491	0.7666	0.6793	0.6967	0.6659	0.0376	0.0333	0.0342	0.0327
O3	0.0517	0.7033	0.6937	0.6390	0.6482	0.0363	0.0359	0.0330	0.0335
O4	0.0529	0.6598	0.5690	0.6716	0.6705	0.0349	0.0301	0.0355	0.0355
O5	0.0507	0.6717	0.5866	0.6155	0.6418	0.0341	0.0297	0.0312	0.0325
T1	0.0529	0.6588	0.7289	0.5670	0.6393	0.0349	0.0386	0.0300	0.0338
T2	0.0547	0.6697	0.6929	0.5369	0.6357	0.0366	0.0379	0.0294	0.0348
T3	0.0496	0.5774	0.6018	0.5083	0.6216	0.0287	0.0299	0.0252	0.0309
T4	0.0503	0.6109	0.6766	0.6182	0.4811	0.0307	0.0341	0.0311	0.0242
T5	0.0460	0.6131	0.5501	0.5582	0.4985	0.0282	0.0253	0.0257	0.0229
Σ	1	N/A	N/A	N/A	N/A	**0.6378 (1)**	**0.6150 (2)**	**0.6119 (3)**	**0.5930 (4)**

3.5 Validation process: an overview

Even though the questionnaire was sent directly to entities and experts either located in or familiar with the economic and technological context of Porto, the outcome revealed a noticeable underrepresentation of respondents from the city and low engagement from targeted entities and experts. As a result, to enhance not only the credibility but also the applicability of the findings, Speedbird Aero – a UAS manufacturer and operator based in Porto and recognized for its expertise in UAS applications such as drone delivery - was involved in a validation process. This initiative aimed mainly to align the results with local realities, thereby providing a more accurate representation of the situation.

Speedbird Aero was founded in 2018, after its co-founders identified a gap in healthcare logistics. They have concluded that that while telemedicine met initial diagnostic needs successfully, it fell short in addressing critical services like local sample collection, rapid laboratory deliveries, and the timely dispatch of emergency medical supplies. The company has consolidated its position as a leader in drone logistics over the last years, expanding its expertise across various industries. Its cutting-edge technology operates BVLOS in eight countries, with products engineered to meet strict standards. Speedbird Aero's portfolio includes three specialized aircraft designed for aerial logistics, featuring capabilities such as automated payload release systems, winch-based delivery solutions, and proprietary software tailored to support a broad range of operational use cases. More details about the company are available in Appendix 2.

A document containing the order per respondents' eyes was sent to Speedbird Aero, allowing them to rearrange the ranking and provide brief considerations and justifications for their choices. This included both the local and global weights associated with sub-criteria and strategies, as well as the possibility of adding factors and strategies they considered essential. The validation process was divided in two interviews. In the first, justifications for the sub-criteria ranking rearrangement were provided, while in the second, the focus consisted of the same exercise for strategies. The elaboration of subchapter 4.5 - that contains the results of the validation process – was based on both interviews and on the supporting document, which can be consulted in Appendix 2.

3.6 Conclusion

This chapter focused on assessing a specific case – the city of Porto. To provide a better understanding of why Porto was chosen to perform this study, a contextual description was presented, along with an overview of the current reality of implementation of unmanned aviation in the city. Based on widely accepted perspectives and on aspects specific to Porto, 20 qualitative factors that are predicted to have an impact on the implementation of UAS within a smart city paradigm were identified. They were categorized as positive or negative and internal or external. Four strategies were subsequently elaborated based on the intersection of these factors.

Afterwards, a quantitative component of the study was introduced. Respondents were asked to compare sub-criteria associated with the same criteria and to evaluate the relative importance of the criteria themselves. Later, they were requested to establish a relationship between the importance of each sub-criterion and strategies, considering whether positive sub-criteria acted as enablers for each strategy or whether the strategies mitigated negative ones. Several quantitative methods, including FAHP and the calculation of BNP, have provided valuable support in the calculation of relevant global weights. Therefore, this chapter serves as the foundation for the penultimate one, where the results obtained will be analysed and discussed to draw key conclusions of this case study.

Chapter 4 - Results Analysis and Discussion

4.1 Introduction

In Chapter 4, the results obtained in Chapter 3 will be analysed and discussed. The conclusions on the relative importance of each sub-criterion will be initially explained. Then, the local weights of each sub-criterion will be compared to ones from the same category/criteria (strengths with strengths, weaknesses with weaknesses), and some considerations obtained with the comparisons of global weights will be presented. Through this process, the point is to assess which sub-criteria are likely to play the most significant role, either as beneficial factors or setbacks, in the implementation of UAS within the smart city paradigm in Porto. A similar exercise will be conducted for the strategy prioritization ranking.

Additionally, the intersection between the relative importance of factors and strategies will be explored. Since strategies were defined based solely on factors (without considering their relative importance), this raises the question of whether the pre-defined strategies reflect the significance each sub-criterion justifies, or if more emphasis should have been given to specific factors during strategy development. Based on this, the identified strategies will be analysed with a focus on the most directly relevant factors that informed their creation. Simultaneously, the factors regarded as the most important but not linked to any strategy will also be identified.

Finally, the results obtained from the validation process were presented. These findings reflect the perspective of Speedbird Aero, a drone company based in Porto. From a qualitative perspective, the feedback provided will help to potentially identify other factors/strategies that might play more significant relevant roles than some of the 20 factors/4 strategies initially defined, respectively. From a quantitative perspective, an order for local and global weights and for the strategies were proposed and substantiated. Additionally, and while the focus of this validation was to assess the results from the qualitative and quantitative analyses, brief feedback was gathered regarding practical applications of UAS, which will eventually contribute to the overall assessment of the dissertation's objectives.

4.2 Criteria comparison

In this subsection, a comprehensive analysis and discussion of the mentioned factors will be elaborated. This process will consist of the provision of insights about sub-criteria from both a local perspective - where sub-criteria will be compared with others from the same category - and from a global perspective – discussed throughout the subchapter and finalized with a discussion of key take-aways. Global comparisons will be elaborated based on the results from Table 15, along with a summary of the top five and bottom two sub-criteria.

Table 18 shows the local weights of each Strength.

Table 18 - Local weights obtained for each Strength (S) – source: own elaboration

Strengths	Local weight
S_1 - Porto as a dynamic, collaborative, digital and green ecosystem	0.2151
S_3 – UAS lower environmental impact during operation compared to traditional methods	0.2081
S_2 – Highly educated, trained and experienced professionals in the field	0.2074
S_5 – Cost-effective and affordable operational approach	0.1864
S_4 – UAS operational flexibility	0.1830

As smart city practices are a key area of study within this research framework, and given the fact that Porto exemplifies key four aspects for smart cities – dynamic, collaborative, digital and green – S_1 was perceived to be the most significant positive internal factor within the present focus of study by a large margin. This internal factor can prove to be crucial in the support of UAS implementation, as the openness to change and the overall receptivity of the city towards technology and sustainable practices both support the general goals of both smart cities and UAS. Apart from that, the collaborative mindset of Porto can eventually foster partnerships between smart city initiatives, municipality, authorities, and drone enterprises.

The importance of highly qualified professionals and the lower environmental impact of UAS during operation are almost tied in terms of local importance, as respondents seem to recognize the importance of skilled talent for a successful and safe implementation of UAS, and the potential role of UAS in strengthening a key aspect of smart cities: environmental sustainability. UAS operational flexibility and its cost-effectiveness were two factors considered as 'less important' than others within the smart city framework, with respondents perceiving these two factors as secondary when compared to factors like Porto already possessing key smart city features within the present context.

Table 19 shows the local weights of each Weaknesses.

Table 19 - Local weights obtained for each Weakness (W) – source: own elaboration

Weaknesses	Local weight
W_5 – Inadequate and insufficient current legislative and regulatory landscape for UAS	0.2176
W_2 – Dependence on skilled operators and technicians	0.2110
W_1 – Significant initial investment required for infrastructure	0.2025
W_3 – Technical limitations related to weather dependency	0.1863
W_4 – Amount of time required for implementation	0.1825

Unsurprisingly, and even though important steps have been taken by European authorities to address this issue, the lack of rules and guidelines that are adequate for the large-scale implementation of UAS is perceived as the most significant internal challenge. As highlighted before, this aspect is believed to be the primary obstacle to a high-volume UAS implementation. The absence of a comprehensive regulatory framework severely compromises safety, which can ultimately range from operational incidents to risks that could endanger public welfare.

The dependence on skilled operators and technicians is also recognized as a significant internal challenge for UAS implementation, which emphasizes the importance of operators' certification and extensive training to ensure the safe integration and operation of UAS in smart urban environments, as opposed to conventional means of transportation, like cars or trucks, where similar applications (e.g., delivery of goods) require a degree of specialization that is far more standardized and globally recognized. Remarkably, the significant investment needed for infrastructure requirements is seen as a challenge that deserves attention. While this issue is often perceived as secondary to operational benefits, it emerges as an important concern, potentially indicating the need for increased emphasis to infrastructure funding in cost-effective analysis to ensure the successful implementation and scalability of UAS in urban applications.

Technical limitations related to weather dependency and the "necessary evil" of the time required for implementation were ranked as the least significant challenges from the list. Although it is still considered a notable challenge by literature, weather dependency is an aspect expected to have a decreasing relevance, as technological prospects are encouraging when it comes to addressing this issue. The time required for a comprehensive preparation is also an important setback, despite being an inevitable aspect of the implementation process.

Table 20 shows the local weights of each Opportunity.

Table 20 - Local weights obtained for each Opportunity (O) – source: own elaboration

Opportunities	**Local weight**
O_4 – Job creation and business opportunities	0.2086
O_3 – Experience acquired with UAS implementation in other contexts	0.2038
O_5 – Economic growth as a door for the implementation of unmanned aviation	0.1999
O_1 – EU's efforts to be a pioneer in the implementation of UAS	0.1941
O_2 – Integration of Porto in several European smart city initiatives	0.1935

The results indicate that respondents' overall perception of positive external factors was more balanced, with no single factor being perceived as overwhelmingly more important than others, as the ranked as most and as least important were separated by only 0.0151, contrasting with the perceptions of strengths (0.0321) and weaknesses (0.0351).

The factor directly related to the economic benefits derived from the implementation of UAS is seen as something more advantageous compared to the factor related to the role of economic development as a driver of the implementation of unmanned aviation. Job creation and business opportunities are indeed key within the smart city philosophy, as they are an important component for both economic and social development. The experience gained from the application of unmanned aviation in other contexts is also regarded as a key aspect compared to other opportunities. While the current realities where drones have been implemented differ significantly from the predicted future levels of urban integration, this experience could play a critical role in Porto's efforts, as the city can potentially gather knowledge from projects, particularly those within a European framework (e.g., U-space).

As a result, respondents seem to place greater emphasis on Porto's efforts to diversify its economy and the potential for job creation and business opportunities compared to factors directly connected to European partnerships. Respondents identify European Union's efforts to be a pioneer in the implementation of unmanned aviation and the importance of shared European knowledge in fostering of innovation and sustainability through the concept of smart cities as moderately significant opportunities to be capitalized on.

Table 21 shows the local weights of each Threat.

Table 21 - Local weights obtained for each Threat (T) – source: own elaboration

Threats	Local weight
T_2 – Security aspects and public concerns related to the application of UAS in cities	0.2158
T_1 – Safety aspects and public concerns related to the application of UAS in cities	0.2087
T_4 – Complex and evolving legislative and regulatory landscape	0.1985
T_3 – Privacy issues arising from UAS implementation	0.1958
T_5 – Potential shortage of necessary expertise due to migration of skilled talent	0.1813

Regarding the results presented in Table 21, security and safety aspects, as well as public concerns related to the implementation of UAS in urban environments, are the sub-criteria that concern respondents the most. As an emerging sector, the challenges faced with this implementation are greater and more uncertain than, for example, those encountered in conventional commercial aviation. Respondents' perception of privacy issues is much lower than safety and security concerns, aligning with EASA's findings on public concerns regarding delivery drones. This alignment opens the door for evaluating other potential obstacles that, while not currently viewed as massive public concerns, could still pose significant challenges, such as noise.

Notably, respondents seem to perceive the importance of the complex and evolving nature inherent to the establishment of a legislative framework as a moderately important factor compared to the above-mentioned threats. When comparing the global weights of the closely related internal factor using the data from Table 15, the external factor related to the importance of a robust regulatory framework (0.0503) is perceived as slightly less important than the internal one (0.0529), suggesting respondents are more concerned with the effective ways to deal with immediate legislative obstacles than with future ones.

Interestingly, the potential shortage of necessary expertise due to migration of skilled talent is perceived as the least relevant negative external factor by a large margin, contrasting to the importance respondents have attributed to a similar sub-criterion (i.e., W2 – Dependence on skilled operators and technicians – ranked 9^{th} out of 20 sub-criteria).

Similarly, some interesting remarks can be made based on the overall comparison of SWOT criteria, where each sub-criterion was grouped with others from the same category (internal/external or positive/negative), resulting in four groups of five sub-criteria each: Group A - Strengths, Group B - Weaknesses, Group C - Opportunities, Group D - Threats. The local weights obtained for each SWOT criterion are showcased in Table 22.

Table 22 - Local weights obtained for each SWOT criterion – source: own elaboration

Criterion	**Local weight**
S	**0.2513**
W	**0.2416**
O	**0.2536**
T	**0.2535**

As shown in Table 22, external factors (with local weights of 0.2536 for opportunities and 0.2535 for threats) have been given more emphasis than internal factors (with local weights of 0.2513 for strengths and 0.2416 for weaknesses) by respondents. Another noteworthy takeaway from Table 22 is that positive criteria (strengths and opportunities) outperformed negative criteria (weaknesses and threats), indicating a stronger focus on the benefits, driving forces and potential advantages rather than the challenges and risks.

Finally, Table 23 summarizes the five most important and the two least important sub-criteria in respondents' eyes:

Table 23 - Top 5 and bottom 2 sub-criteria by global weight – source: own elaboration

Sub-criteria (Top 5 / Bottom 2)	**Global weight**
T_2 – Security aspects and public concerns related to the application of UAS in cities	0.0547
S_1 - Porto as a dynamic, collaborative, digital and green ecosystem	0.0540

Sub-criteria (Top 5 / Bottom 2)	Global weight
T_1 – Safety aspects and public concerns related to the application of UAS in cities	0.0529
O_4 – Job creation and business opportunities	0.0529
W_5 – Inadequate and insufficient current legislative and regulatory landscape for UAS	0.0526
...	
W3 – Technical limitations related to weather dependency	0.0450
W4 – Amount of time required for implementation	0.0441

As highlighted by Table 23, respondents rate the fact that the city possesses key characteristics specific to smart cities as the primary factor to be capitalized on. The city's posture towards technology and sustainable practices supports the general goals and philosophy inherent to both smart cities and UAS. The potential for job creation and business opportunities also fits the paradigm of a smart city very well, contributing to the development of smart cities in its economic and social dimensions.

Regarding obstacles and challenges, security and safety aspects, along with public concerns related to the application of UAS in cities, are the two most influential negative factors in the eyes of respondents, posing relevant obstacles to the development of a smart city if not thoroughly addressed. These aspects can only be effectively tackled with a solid regulatory framework, capable of addressing both emerging and current challenges, which explains why the negative internal factor with the highest weight is understandably ranked among the top five sub-criteria.

In contrast, the technical limitations related to weather dependency are not considered a crucial sub-criterion. Similarly, the time estimated for achieving such a level of implementation is not seen as a major setback, as it is deemed essential for ensuring the safe integration of UAS in urban environments, being ranked last among all 20 sub-criteria.

4.3 Strategy prioritization

Table 24 presents the ordered list of strategies by global weight.

Table 24 - Ordered list of strategies by global weight - Source: own elaboration

TOWS matrix strategies	Global weight
SO - Develop partnerships with existing smart city initiatives in Porto to integrate UAS operations	0.6378
ST - Establish a comprehensive safety and security framework to address the complexity and the evolving legislation of urban UAS operations	0.6150
WO - Collaborate with European partners to secure funding and reduce investment costs	0.6119
WT – Use the time to engage with the community and educate and inform about the benefits and safety measures of UAS operations	0.5930

The results indicate that one of the strategies clearly stand out from the other three for a successful implementation of unmanned aviation within the smart city paradigm. The development of partnerships with existing smart city initiatives in Porto has been identified as the leading strategy from the four. As pointed above, this strategy would consist in using existing smart city initiatives to integrate UAS technology by enhancing existing sectors where UAS are expected to play an important role — such as mobility, transportation, and tourism.

This strategy is followed by the establishment of a safety and security framework for urban UAS operations, which would require collaboration between local, national, and European authorities, as well as active engagement from industry and community stakeholders. Previous examples of European investments in technology, innovation and sustainable projects (including in UAS research) have also been recognized as a key strategy, that could prove to be crucial in reducing the financial costs associated with creating the appropriate infrastructure necessary the successful implementation of UAS.

However, respondents perceive the use of the time required for a comprehensive implementation of UAS for the improvement of public acceptance as a secondary strategy, aligning with respondents' perspective of the time needed for the full-scale implementation of unmanned aviation in urban environments – that other aspects demand more emphasis.

4.4 Criteria-strategies intersection

The philosophy of this study focuses on defining a TOWS matrix solely based on the SWOT analysis. An alternative approach could involve supporting the development of the TOWS matrix using respondents' input on the importance of each sub-criterion (i.e.

the results obtained from the application of FAHP for criteria comparison - Table 14), in defining the most relevant strategies. Figure 23 illustrates the path adopted in this research and an alternative path.

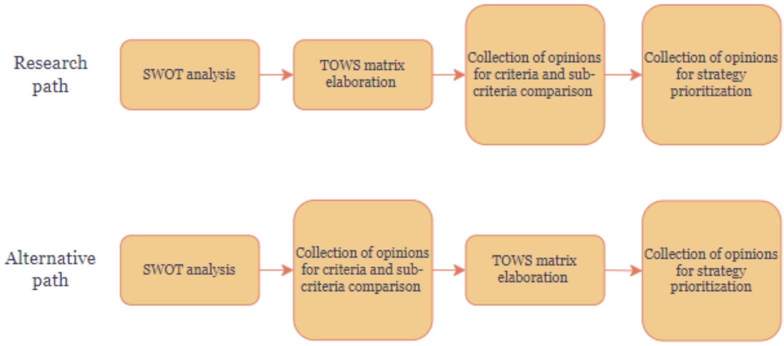

Figure 23 - A summary of the current research path and an alternative path – Source: own elaboration

Due to the possibility of respondents' input playing a role in the definition of the TOWS matrix of strategies, a question about the research path can be raised:

- Do pre-defined strategies accurately reflect the importance each sub-criterion ultimately deserves?

Although not perceived as the pre-defined strategy that should be given the highest priority, the strategy ST – "Establish a comprehensive safety and security framework to address the complexity and the evolving legislation of urban UAS operations" - has a broad scope, and results obtained from criteria comparison suggest a strategy that can effectively address safety and security aspects, which are ranked as the two most prominent threats (1st and 3rd overall), is required. This approach can be effectively supported by leveraging the use of highly qualified personnel (7th out of 20) and capitalizing on the dynamic nature and proactivity of the city (ranked 2nd).

The strategy SO – "Develop partnerships with existing smart city initiatives in Porto to integrate UAS operations" - was identified as the one that should be given the highest priority for UAS implementation. This is supported by the leading sub-criterion of the research: Porto as a dynamic, collaborative, digital and green ecosystem. This strength can be leveraged to capitalize on Porto's inclusion (and high regard) in national and European initiatives that promote smarter practices.

Regarding strategy WO, which aim is to try to overcome weaknesses by taking advantage of opportunities, the pre-defined strategy - "Collaborate with European partners to secure funding and reduce initial investment costs for infrastructure" – seeks to capitalize on a moderately important positive external factor, while trying to address a moderately important challenge, particularly when compared to issues such as inadequate legislation and dependency on skilled operators and technicians. As a result, European's proactivity and pioneering posture towards UAS implementation can be continuously canalized into the development of improved and stronger regulations.

As for strategy WT – "Use the time to engage with the community and educate and inform about the benefits and safety measures of UAS operations", it aims at addressing a very significant threat for the smart implementation of unmanned aviation, while minimizing the effect of a weakness perceived as secondary when compared to others. The fact this strategy is ranked last by a quite considerable margin reflects the respondents' view of this setback - a "necessary evil" in the context of achieving successful UAS integration.

Notably, the results suggest sub-criterion O_4 (Job creation and business opportunities) did not initially receive the emphasis it deserved, as it was ranked 4^{th} out of 20 by respondents, yet it was considered by respondents as the one of the most positive factors related to UAS implementation. Neither of the two proposed strategies that aimed at taking advantage of opportunities directly focus on this external factor. An example of a potential approach could be to leverage the strength of highly educated, trained, and experienced professionals in the field to help build a UAS ecosystem that creates job and stimulates business opportunities. Similarly, regarding negative sub-criteria, results also suggest sub-criterion W_5 (Inadequate and insufficient current legislative and regulatory landscape for UAS) was overlooked. It was ranked in the top 5 of global weights, yet neither of the two proposed strategies that aimed at minimizing or overcoming weaknesses directly address this internal factor. A potential approach to mitigate this issue could be to further leverage the knowledge and experience already gained from the implementation of UAS in various contexts, to take additional lessons and insights to refine the regulatory framework.

4.5 Results validation

In this subchapter, the results from the validation process will be presented and discussed, and a comparison between the findings from the research and the company's perspective will be elaborated. Additionally, insights into the qualitative components of the study will also be provided, including the potential redefinition or addition of factors and strategies based on the company's view of the benefits or needs of the ecosystem. The organization of the subchapter follows the philosophy of subchapters 4.2 and 4.3.

4.5.1 Criteria comparison

Table 25 showcases the ranking obtained from research results and from the vision of the company for internal positive factors.

Table 25 - Ranking of Strengths: research results vs company vision – Source: own elaboration

Strengths	Research results	Company vision
S_1 - Porto as a dynamic, collaborative, digital and green ecosystem	**1st**	**2nd**
S_2 – Highly educated, trained and experienced professionals in the field	**3rd**	**3rd**
S_3 – UAS lower environmental impact during operation compared to traditional methods	**2nd**	**1st**
S_4 – UAS operational flexibility	**5th**	**5th**
S_5 – Cost-effective and affordable operational approach	**4th**	**4th**

As showcased in Table 25, the vision of the company aligns closely to the results obtained from the questionnaire and subsequent analysis, with every sub-criterion being perceived in similar ways except for S_1 and S_3. In particular, the company places greater emphasis on the advantages related to the vehicle itself, which does not change the fact that Porto's possession of key smart city features is recognized as the second most relevant positive internal factor among the five presented above. As a result, the company recognizes the lower environmental impact during operation as the primary inherent advantage of UAS implementation in any context. This also aligns with one of the most common attributes of a modern smart city.

Regarding the strengths related to the cost-effectiveness of UAS in operational contexts and to UAS operational flexibility, the company believes that, given the current early stage of the whole process, these factors do not yet correspond to tangible benefits, which is the reason behind S_4 and S_5 being ranked in the last two places of the ranking.

In Table 26, the comparison between the research results and from the company vision for weaknesses can be seen.

Table 26 - Ranking of Weaknesses: research results vs company vision - Source: own elaboration

Weaknesses	Research results	Company vision
W_1 – Significant initial investment required for infrastructure	**3rd**	**2nd**
W_2 – Dependence on skilled operators and technicians	**2nd**	**4th**
W_3 – Technical limitations related to weather dependency	**4th**	**5th**
W_4 – Amount of time required for implementation	**5th**	**3rd**
W_5 – Inadequate and insufficient current legislative and regulatory landscape for UAS	**1st**	**1st**

Regarding internal negative factors, the company's vision appears to differ significantly from the research results when compared to the same exercise for strengths.

Despite this, both methods concluded that the inadequate and insufficient current legislative and regulatory landscape for UAS constitutes the most relevant weakness in the application of drones in urban environments. The company also emphasized that this weakness is particularly notable on a global scale, not just in the city of Porto. In this regard, Speedbird Aero proposes the creation of a new sub-criterion, which would address operational limitations related to national infrastructure and regulation (e.g., airspace segregation) impacting a possible harmonized implementation.

Speedbird Aero also highlights the significant initial investment required for infrastructure as a major obstacle. This economic concern extends beyond infrastructure requirements with the company proposing the addition of a sub-criterion that considers the substantial investment required in new certifiable high robustness products (research and development), or alternatively, the coverage of both points under W_1. The time required for a full-scale implementation of UAS is also seen as a significant setback, mostly due to the multidisciplinary nature involved.

Opposingly, they believe the high dependence on skilled operators and technicians is currently not a key weakness based on their experience and on the present reality, and that the technical limitations related to weather dependency should not be seen as a weakness, especially when compared to the impact of this factor in other countries. They also state that Portugal is highly regarded as a potential place for testing purposes, given that its weather conditions are more favourable than in most European countries.

Similarly, Table 27 contains the comparison between the research results and the company vision for opportunities.

Table 27 - Ranking of Opportunities: research results vs company vision - Source: own elaboration

Opportunities	Research results	Company vision
O_1 – EU's efforts to be a pioneer in the implementation of UAS	**4th**	**1st**
O_2 – Integration of Porto in several European smart city initiatives	**5th**	**4th**
O_3 – Experience acquired with UAS implementation in other contexts	**2nd**	**5th**
O_4 – Job creation and business opportunities	**1st**	**3rd**
O_5 – Economic growth as a door for the implementation of unmanned aviation	**3rd**	**2nd**

Although respondents' perception of opportunities was relatively balanced, with no sub-criterion standing out as particularly important or unimportant, there was an evident contrast between the vision of respondents and of the company. The most evident disagreements consist lies in the perception of the importance of European partners (institutions and smart city initiatives), with the company viewing them in much higher regard than the respondents do. Another remarkable disagreement is the perception of the experience acquired with the implementation of UAS in other contexts - while valuable insights can be still gathered from some past experiences, none of these contexts present the same level of challenge in the safety of pedestrians and in the coexistence between manned and unmanned aviation.

The company has also proposed the addition of two new sub-criteria. One is closely related to O1, with the difference that it would be a national momentum that would be leveraged. As a result, this strategy would capitalize on Portugal's current drive to position itself as a pioneer in the implementation of UAS. This is strongly supported by the Technology Roadmap for Aeronautics in Portugal, developed by Aeronautics, Space and Defence (AED) Cluster Portugal [169]. Additionally, a new opportunity sub-criterion should be added to consider Portugal's efforts in setting goals for the industrialization of technological products and their internationalization, as well as ways to facilitate the implementation of new technologies (e.g., creating sandboxes). This is strongly substantiated by "Zonas Livres Tecnológicas" (ZLT) of Matosinhos and Marinha - ZLT Infante D. Henrique.

Table 28 showcases the ranking obtained from research results and from the vision of the company for external negative factors.

Table 28 - Ranking of Threats: research results vs company vision - Source: own elaboration

Threats	Research results	Company vision
T_1 – Safety aspects and public concerns related to the application of UAS in cities	**2nd**	**2nd**
T_2 – Security aspects and public concerns related to the application of UAS in cities	**1st**	**3rd**
T_3 – Privacy issues arising from UAS implementation	**4th**	**4th**
T_4 – Complex and evolving legislative and regulatory landscape	**3rd**	**1st**
T_5 – Potential shortage of necessary expertise due to migration of skilled talent	**5th**	**5th**

In contrast to what was observed with external positive factors, there is a general agreement between respondents and the company regarding threats, with the most notable exception being the perception of safety and security aspects, as well as public concerns. Speedbird Aero views safety aspects as more crucial than security, particularly in an industry that is still in its early stages of development. While they acknowledge that privacy issues arising from UAS implementation may pose a setback, they believe these concerns will not significantly hinder the process, as the public is more focused on the potential benefits of drones being integrated into their daily lives. The perception of T5 aligns with the observation written for W2 – their experience suggests this has not been a concrete challenge.

However, and above all the already mentioned sub-criteria, the company believes there are two primary threats. The first is effectively T4, while the second is a new sub-criterion that would rank between T4 and T1. This new threat would consist of considering the high need for investments in products and infrastructure to compete internationally, which may exceed the capacity of the local economy.

As shown in Table 22, external factors have been given more emphasis than internal factors. Speedbird Aero was asked about the possible reason behind this feeling among respondents. According to the company, this is a high-tech industrial sector that focuses on multi-market goods and services, which demands a significant amount of investment. Since it is an emerging market, there isn't a clear worldwide regulatory framework (harmonization). Furthermore, most of the businesses that entered this market years ago were from the technology sector and lacked aviation experience. Consequently, there appeared to be a widespread misunderstanding regarding the time and financial resources necessary to develop and certify such products. As a result, after many years of intensive capital injection and failure of milestones, they have caused fear among investors and a general lack of investment. This negative trend is evident in a series of announcements about companies in the Innovative Air Mobility (IAM) sector undergoing judicial recovery processes or shutting down entirely. This situation reinforces the sentiment among stakeholders that the risks associated with the uncertainty of the broader market context outweigh those associated to the capabilities of companies and the local ecosystems.

Finally, Table 29 summarizes the top eight most important sub-criteria in the company's eyes:

Table 29 - Top 8 sub-criteria - research results vs company vision – Source: own elaboration

Sub-criteria – Company vision (Top 8)	**Research results**	**Company vision**
S_3 – UAS lower environmental impact during operation compared to traditional methods	**6th**	**1st**
O_1 - EU's efforts to be a pioneer in the implementation of UAS	**13th**	**2nd**
O_4 – Job creation and business opportunities	**4th**	**3rd**
T_4 – Complex and evolving legislative and regulatory landscape	**11th**	**4th**
W_1 – Significant initial investment required for infrastructure	**15th**	**5th**
W_5 – Inadequate and insufficient current legislative and regulatory landscape for UAS	**5th**	**6th**
T_1 – Safety aspects and public concerns related to the application of UAS in cities	**3rd**	**7th**
T_2 – Security aspects and public concerns related to the application of UAS in cities	**1st**	**8th**

In line with the local comparison of strengths, the company highlights the low environmental impact during operation as the most crucial aspect for the successful implementation of UAS, particularly within the smart city paradigm. Respondents, on the other hand, have placed more emphasis on Porto combining essential attributes for smart cities and its potential for job creation and business opportunities. Nonetheless, the attribute of environmental sustainability was ranked as the third most important positive factor by respondents. As a result, there is a clear consensus among both on the high importance of this factor and on the key role of job creation and business opportunities as a driving force for this implementation.

This table also reinforces that there is a consensus regarding the overall perception of safety, security and legislative obstacles as some of the most significant obstacles to the large-scale implementation of UAS, with the company being slightly more concerned with the predicted evolving nature of regulatory frameworks, whereas respondents are more focused on current challenges.

4.5.2 Strategy prioritization

Table 30 presents the ordered list of strategies as perceived by respondents and the company's eyes.

Table 30 - Ordered list of strategies by global weight (research results vs company vision) - Source: own elaboration

TOWS matrix strategies	Research results	Company vision
SO - Develop partnerships with existing smart city initiatives in Porto to integrate UAS operations	**1st**	**4th**
ST - Establish a comprehensive safety and security framework to address the complexity and the evolving legislation of urban UAS operations	**2nd**	**1st**
WO - Collaborate with European partners to secure funding and reduce investment costs	**3rd**	**2nd**
WT – Use the time to engage with the community and educate and inform about the benefits and safety measures of UAS operations	**4th**	**3rd**

Table 30 highlights a notable agreement in the order of implementation ST—SO—WT but also reveals a significant divergence regarding the SO strategy. The development of partnerships with existing smart city initiatives in the city for UAS implementation is rated as the highest priority for respondents, but the lowest for the company.

Considering the perspectives from both respondents and the company and considering the initially defined strategies from the TOWS matrix, it is therefore possible to conclude the first strategy to be implemented would be ST, based on the establishment of a comprehensive safety and security framework to address the evolving legislation of urban UAS operations. This is also evidenced by both parts' feelings towards the most directly related sub-criteria.

Besides that, three key strategies have been proposed by the company. In line with the conclusion obtained from the prevalence of external factors over internal ones, primarily associated with a negative feeling of risk toward the uncertainty of the broader market context overshadowing confidence in the capabilities of companies and the local ecosystems, the company suggests developing technological solutions (products and services) and business models that demonstrate the economic, social and environmental viability of such implementations. Building on the national momentum highlighted above and the already observed positive impact on advancing implementation efforts, the company also proposes strengthening local collaborations. Additionally, Speedbird Aero also advocates community involvement to create employment opportunities and enhance business viability, enabling them to be part of this emerging economic sector.

4.5.3 Practical applications

To illustrate practical applications and align with one of the objectives of this dissertation, the company was asked to provide an order of implementation. The prioritization was based on the concepts B2B (business-to-business) and B2C (business-to-costumer):

1. B2B/B2C Surveillance
2. B2C Emergency Response
3. B2B Health (e.g., hospitals and lab-to-lab logistics)
4. B2B Inspection
5. B2C Healthcare (e.g., medication delivery)
6. B2C Multimodal Generic Delivery

Notably, all these applications have been identified as key in the fulfilment of several smart city components highlighted in subchapter 2.4, particularly those related to smart transportation, smart services, smart health, and smart infrastructure. This underscores the role of UAS as a transformative enabler in urban ecosystems. By addressing both market needs and societal challenges, these applications highlight the multifaceted value of integrating UAS into smart city frameworks.

4.6 Conclusion

In Chapter 4, the results obtained for the case study were analysed and discussed. The main findings associated with each portion of this analysis can be summarized as follows:

- Factors – respondents identified Porto's position as a dynamic, collaborative, digital, and green ecosystem as the most significant positive factor for UAS implementation in the city, supported by the increasing amount of job and business opportunities. The lack of a comprehensive regulatory framework emerges as one of the most critical challenges, along with safety and security aspects and public concerns. Overall, positive criteria outweigh negative ones, which ultimately emphasizes Porto's potential to integrate UAS into its urban environment. The validation process revealed that the company generally agrees with these findings, particularly regarding negative factors. However, they believe other positive factors could be more crucial than the ones mentioned above, such as the lower environmental impact of UAS and the EU's proactive efforts to pioneer unmanned aviation implementation. Additionally, respondents have put more emphasis on external factors, with the company believing that is due to a series of events, starting with the widespread misunderstanding about the time and financial resources needed to develop and certify such products and culminating in the closure of companies in the IAM sector, which led stakeholders to believe that the risks associated with the uncertainty of the broader market outweigh the factors related to the capabilities of companies and local ecosystems;

- Strategies – the strategy focused on using strengths to take advantages of opportunities was considered the one that should be given the highest priority for respondents. Establishing a safety and security framework to address the complexity and evolving nature of urban UAS operations legislation, along with the collaboration with European partners and entities to secure funding, ranked closely behind. Meanwhile, using the time required for the full-scale implementation of unmanned aircraft to improve public acceptance was identified as a secondary priority. The company that performed the validation process agrees with the order ST-WO-WT, however, it perceives the strategy ranked first by respondents as the least relevant. As a result, the establishment of a comprehensive safety and security framework to address the evolving legislation of urban UAS operations was concluded to be the most immediate step. Furthermore, the company proposed three additional strategies that they believe could be crucial for the successful implementation of UAS, leveraging factors such as national momentum and addressing the possibility of risks outweighing the capabilities of the local ecosystem.

The concluding remarks of this dissertation will be presented in the next chapter.

Chapter 5 – Conclusion

5.1 Dissertation synthesis

This dissertation is divided into five chapters: introduction, literature review, case study, results analysis, and conclusion.

In Chapter 1, the motivation for conducting this research was presented, along with the dissertation object and objectives. A summary of the methodology and the dissertation structure were also provided.

Chapter 2 provided the necessary foundations for conducting an informed study, by dissecting the concept of smart cities, their main characteristics, key components and globally recognized examples. UAS were then introduced, with the role of UAM being highlighted as the biggest driving force for the implementation of these technologies in urban environments, alongside the main associated challenges. A connection between UAS and smart cities was subsequently established. This chapter has concluded with the presentation of the main theoretical concepts required for an informed strategic planning analysis.

Chapter 3 focused on the specific case of Porto. First, a scenario description was provided, mentioning the technologic, economic, demographic, and social reasons that make Porto an important choice for evaluating the implementation of UAS within the smart city paradigm. Additionally, a brief explanation of current applications of UAS in Porto and a brief overview of the operational context regulating UAS operations under the open category was given. A qualitative analysis - SWOT - was conducted to assess the implementation of UAS in Porto, by defining and explaining 20 internal and external sub-criteria/factors, based on literature findings. Subsequently, a TOWS matrix was developed by analysing the intersections of these factors. A quantitative analysis followed and included the application of the FAHP. This process aimed at ranking the perceived importance of the sub-criteria/factors and strategies by ideal order of prioritization, based on the input from respondents across various areas of expertise.

In Chapter 4, the conclusions regarding the relative importance of each sub-criterion were discussed. Based on the results from the previous chapter, the sub-criteria most likely to play the most significant role – whether as driving forces or obstacles - were presented. Additionally, conclusions on the perceived importance of each of the four pre-defined strategies were outlined. Since these strategies were defined based solely on factors (without considering their relative importance as perceived by respondents), an intersection between factors and strategies was examined to understand which factors where potentially overlooked or overestimated. The interpretation and discussion of results was successfully supported by a validation process performed by Speedbird Aero, a company from the UAS sector and located in Porto, which has provided valuable insights within this context.

Chapter 5 contains the closing remarks of this dissertation. A synthetises of the key aspects of the dissertation will be elaborated, supported by an analysis of the fulfilment of each of the four initially proposed objectives. The limitations and prospects of future research will also be discussed.

5.2 Concretization of objectives

The following objectives were defined in the introduction:

1. Understand in which ways UAS contribute to the development of a smart city;
2. Evaluate the status regarding the use of UAS in European cities, with a focus on the chosen case study (Porto);
3. Assess the steps that can be taken in Porto for UAS application, in alignment with European goals;
4. Establish priorities for the smart implementation of UAS in Porto, considering the surrounding context.

Objective number 1 was achieved by linking the two core concepts of this dissertation – UAS and smart cities. This bridge was successfully built by associating each current and future application of unmanned aircraft to the respective smart city component. While a city can only be classified as 'smart' if all its components are fulfilled, UAS have proven to make a meaningful contribution towards achieving this status. Effectively, in addition to providing the required basis for a successful case study, chapter 2 effectively fulfilled objective 1 and provided valuable help to fulfil objective 2.

The fulfilment of objective 2 began in chapter 2 and was completed in chapter 3. The main challenges associated with UAS and UAM discussed highlight the fact that the process is still at a very early stage of implementation, with manned aviation expected to set the stage for the implementation of eVTOL vehicles in urban environments. A specific operational aspect regarding in-force drone operation regulations - the city's geozones for open category operations – was also presented, with the overall reality of Porto regarding the implementation of UAS being similar to that of other major urban environments under EASA's jurisdiction – the set of guidelines required for safe UAS operations, which depend on ensuring the coexistence between manned and unmanned aviation, are still being developed. Additionally, and even though manned aviation is expected to be the pioneer in UAM initiatives, the process of certification and licensing of UAS operators has already begun.

Objective 3 was fulfilled throughout chapter 3 and can be divided into two stages. In the first stage, factors that are predicted to have great influence – either as driving forces or setbacks – were identified, which encompass a range of economic, social, legal, environmental and demographic aspects. A list of 20 sub-criteria, categorized into internal/external and positive/negative factors based on the framework of a SWOT analysis, was elaborated. For each sub-criterion, a description of its predicted significance in the reality of a high-volume implementation of UAS in the city of Porto was presented. In the second stage, concrete steps/strategies were developed based on the intersection of the 20 sub-criteria, and applying the concept of a TOWS matrix. The validation process has complemented the fulfilment of this objective, as it provided a clear order of implementation for practical applications, all of which proven to be crucial within the smart city framework in subchapter 2.4.

Objective 4 was fulfilled in chapter 4, which leveraged results from chapter 3 to establish an order of prioritization for strategies. Additionally, the results obtained from the comparison of local and global weights of sub-criteria, combined with the validation process, have proved Porto's potential to be a successful case of the high-volume UAS implementation within the smart city framework and provided key insights and findings that can help redefine and adjust the focus of specific strategies. They offer a much clearer understanding of the positive aspects to capitalize on and the negative aspects that need to be addressed, while strongly considering the perspective of a company operating in the field and based in the city under study.

5.3 Limitations

Although the objectives of these dissertation were effectively fulfilled, some limitations that might have an influence in the results can be identified.

Qualitatively, and while the identified sub-criteria accurately represent internal and external factors related to the implementation of UAS within the smart city framework in Porto, a key limitation inherent to the nature of SWOT analysis arises – subjectivity. Even though the identified benefits and challenges of the full-scale implementation of UAS in urban environments were based on an extensive literature review, questions may be raised regarding why certain sub-criteria was selected over others that were ultimately excluded, particularly when they are unrelated to each other in terms of field. Moreover, more than 5 sub-criteria for each SWOT category could have been identified, but this would likely make the expert input process overly exhaustive and reduce engagement. Ideally, and while this action would not eliminate all subjectivity and bias, all sub-criteria would be picked through an expert panel from different fields of expertise.

Another factor that could have improved the accuracy in the results obtained would be to consider the level of expertise of each respondent, either through external evaluation of professional experience or through self-assessment on their level of expertise, given that the importance of each sub-criterion and the ranking of TOWS strategies are elaborated based on expert input using mathematical methods. Assessing the level of knowledge of the city could also prove to be beneficial, though such assessment would only impact respondents' perception on very few of the identified sub-criteria, as the large majority focus on aspects transversal to a national or even European context, not being exclusive to Porto's reality.

5.4 Future research

Considering the current trends of UAS implementation in urban environments and the approach adopted in this work, it is believed to provide a solid foundation for many paths for future research to be created. The most immediate step would be to delve deeper into the identified sub-criteria/factors, by exploiting the benefits derived from positive factors and mitigating the negative ones through the development and adoption of new strategies.

Although this represents a very specific case, and factors that influence this implementation are highly dependent on social, economic, and geopolitical contexts, this dissertation is believed to have produced valuable insights that could serve as a source of inspiration for similar strategic planning analyses in other urban environments. If a similar approach to that pursued in this work is adopted, addressing some the above-mentioned limitations – such as the relatively low number of identified factors and the lack of consideration for varying levels of expertise among respondents – would be important. An "expert panel" approach to the qualitative analysis, including participants with different levels and from various fields of expertise, could promote active discussions around key factors and improve accuracy in the process.

A SWOT analysis usually evaluates general solutions and serves as a guiding framework to the specific parts. Consequently, another proposed approach would involve a more tailored examination of the identified factors, as deeper analysis is required to determine their specific impact with greater precision. For example, given that this dissertation aims to offer a 'smart' approach to the problem, with the improvement of citizens' quality of life as the top priority, it becomes essential to assess the public perspective of UAS among the citizens of Porto, especially given the findings of this dissertation. The crucial role of public acceptance in the successful implementation of new technologies, together with the importance of public concerns around safety and security of UAS operations identified by both EASA's study on the societal acceptance of UAM (broad perspective) and by this dissertation (focused perspective), provide strong justification for further analysis on the public acceptance of the high-volume implementation of UAS in the city.

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Appendix 1 – Electronic Survey and Example Calculation

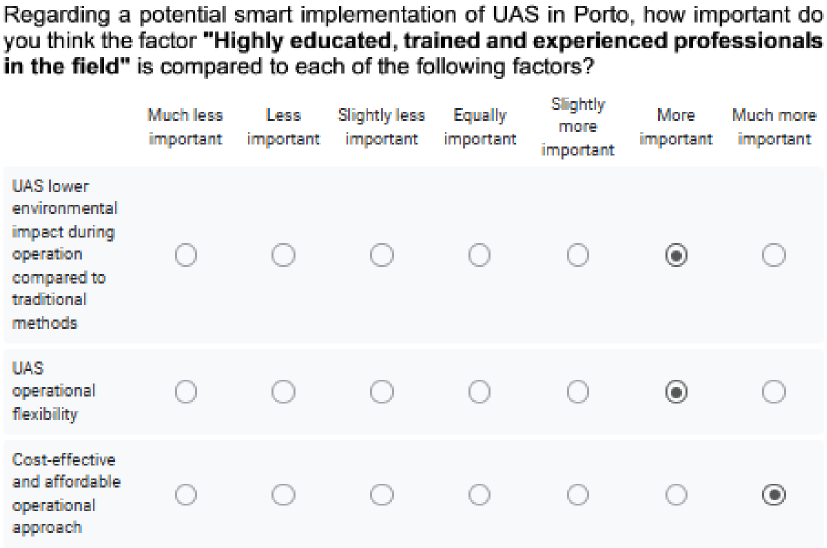
a) Pairwise comparison

Regarding a potential smart implementation of UAS in Porto, how important do you think the factor **"Porto as a dynamic, collaborative, digital and green ecosystem"** is compared to each of the following factors?

<u>Note:</u> *If you select "More important" in the first line, you are indicating that you believe that the factor "Porto as a dynamic, collaborative, digital and green ecosystem" is more important than the factor "Highly educated, trained and experienced professionals in the field"*

	Much less important	Less important	Slightly less important	Equally important	Slightly more important	More important	Much more important
Highly educated, trained and experienced professionals in the field	○	○	○	◉	○	○	○
UAS lower environmental impact during operation compared to traditional methods	○	○	○	○	○	○	◉
UAS operational flexibility	○	○	○	○	○	○	◉
Cost-effective and affordable operational approach	○	○	○	○	○	○	◉

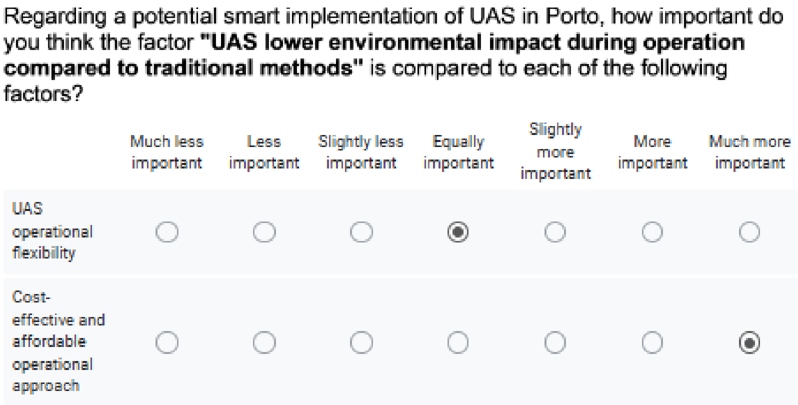
Figure 24 - Pairwise comparison of sub-criteria: example of a respondent's answer (Part I) – Source: own elaboration



Regarding a potential smart implementation of UAS in Porto, how important do you think the factor **"Highly educated, trained and experienced professionals in the field"** is compared to each of the following factors?

	Much less important	Less important	Slightly less important	Equally important	Slightly more important	More important	Much more important
UAS lower environmental impact during operation compared to traditional methods	○	○	○	○	○	●	○
UAS operational flexibility	○	○	○	○	○	●	○
Cost-effective and affordable operational approach	○	○	○	○	○	○	●

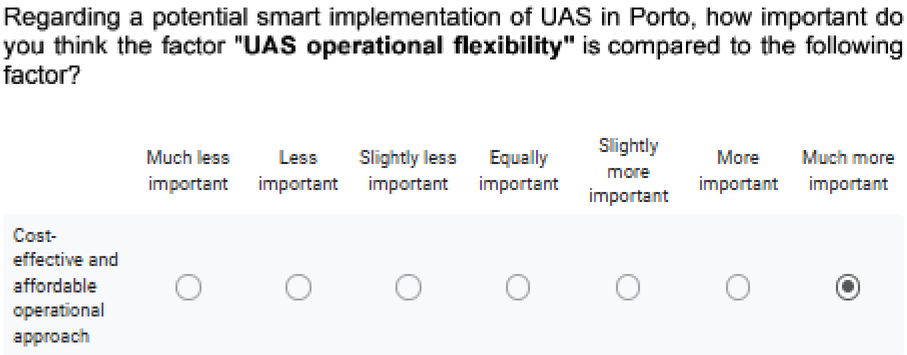
Figure 25 - Pairwise comparison of sub-criteria: example of a respondent's answer (Part II) – Source: own elaboration



Regarding a potential smart implementation of UAS in Porto, how important do you think the factor **"UAS lower environmental impact during operation compared to traditional methods"** is compared to each of the following factors?

	Much less important	Less important	Slightly less important	Equally important	Slightly more important	More important	Much more important
UAS operational flexibility	○	○	○	●	○	○	○
Cost-effective and affordable operational approach	○	○	○	○	○	○	●

Figure 26 - Pairwise comparison of sub-criteria: example of a respondent's answer (Part III) – Source: own elaboration



Regarding a potential smart implementation of UAS in Porto, how important do you think the factor **"UAS operational flexibility"** is compared to the following factor?

	Much less important	Less important	Slightly less important	Equally important	Slightly more important	More important	Much more important
Cost-effective and affordable operational approach	○	○	○	○	○	○	●

Figure 27 - Pairwise comparison of sub-criteria: example of a respondent's answer (Part IV) – Source: own elaboration

Answer no. **1**	S1	S2	S3	S4	S5
S1	N/A	Equally important	Much more important	Much more important	Much more important
S2		N/A	More important	More important	Much more important
S3			N/A	Equally important	Much more important
S4				N/A	Much more important
S5					N/A

Linguistic variables	Triangular fuzzy number	Triangular fuzzy reciprocal number
Equally important	(1/2, 1, 3/2)	(2/3, 1, 2)
Slightly more important	(1, 3/2, 2)	(1/2, 2/3, 1)
More important	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Much more important	(2, 5/2, 3)	(1/3, 2/5, 1/2)

Answer no. **1**	S1	S2	S3	S4	S5
S1	(1,1,1)	(0.5,1,1.5)	(2,2.5,3)	(2,2.5,3)	(2,2.5,3)
S2	(0.667,1,2)	(1,1,1)	(1.5,2,2.5)	(1.5,2,2.5)	(2,2.5,3)
S3	(0.333,0.4,0.5)	(0.4,0.5,0.667)	(1,1,1)	(0.5,1,1.5)	(2,2.5,3)
S4	(0.333,0.4,0.5)	(0.4,0.5,0.667)	(0.667,1,2)	(1,1,1)	(2,2.5,3)
S5	(0.333,0.4,0.5)	(0.333,0.4,0.5)	(0.333,0.4,0.5)	(0.333,0.4,0.5)	(1,1,1)

Figure 28 - Conversion of the respondent's answers into numeric variables – Source: own elaboration

4,042731	5,483213	7,106256
3,885822	5,252373	6,995678
3,967245	5,272896	7,005955
3,522142	4,567294	6,234446
3,668569	4,646552	6,400871

$$\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right)$$

0,029636	0,039647	0,052393

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right)$$

	l	m	u
S1	0,1198	0,2174	0,3723
S2	0,1152	0,2082	0,3665
S3	0,1176	0,2091	0,3671
S4	0,1044	0,1811	0,3266
S5	0,1087	0,1842	0,3354

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1}$$

Figure 29 - Application of Chang's method (Part I) - Source: own elaboration

S1	S2	1
S1	S3	1
S1	S4	1
S1	S5	1
S2	S1	0,964231
S2	S3	0,996742
S2	S4	1
S2	S5	1
S3	S1	0,967376
S3	S2	1
S3	S4	1
S3	S5	1
S4	S1	0,850651
S4	S2	0,886184
S4	S3	0,881983
S4	S5	0,985785
S5	S1	0,866633
S5	S2	0,90165
S5	S3	0,897648
S5	S4	1

$$V(S_2 \geq S_1) = \begin{cases} 1 & if\ m_2 \geq m_1 \\ 0 & if\ l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & otherwise \end{cases}$$

Figure 30 - Application of Chang's method (Part II) - Source: own elaboration

d'(S1)	1
d'(S2)	0,964231
d'(S3)	0,967376
d'(S4)	0,850651
d'(S5)	0,866633

$$d'(A_i) = min\, V(S_i \geq S_k)$$

d(S1)	0,215105
d(S2)	0,207411
d(S3)	0,208087
d(S4)	0,1830
d(S5)	0,186417

$$d(A_i) = \frac{d'(A_i)}{\sum_{i=1}^{n} d'(A_n)}$$

Figure 31 - Application of Chang's method (Part III) - Source: own elaboration

Each factor can be categorized into four different groups based on whether they are internal or external, and positive or negative:

GROUP A

- Porto as a dynamic, collaborative, digital and green ecosystem
- Highly educated, trained and experienced professionals in the field
- UAS lower environmental impact during operation compared to traditional methods
- UAS operational flexibility
- Cost-effective and affordable operational approach

GROUP B

- Significant initial investment required for infrastructure
- Technical limitations related to weather dependency
- Dependence on skilled operators and technicians
- Amount of time required for implementation
- Inadequate and insufficient current legislative and regulatory landscape for UAS

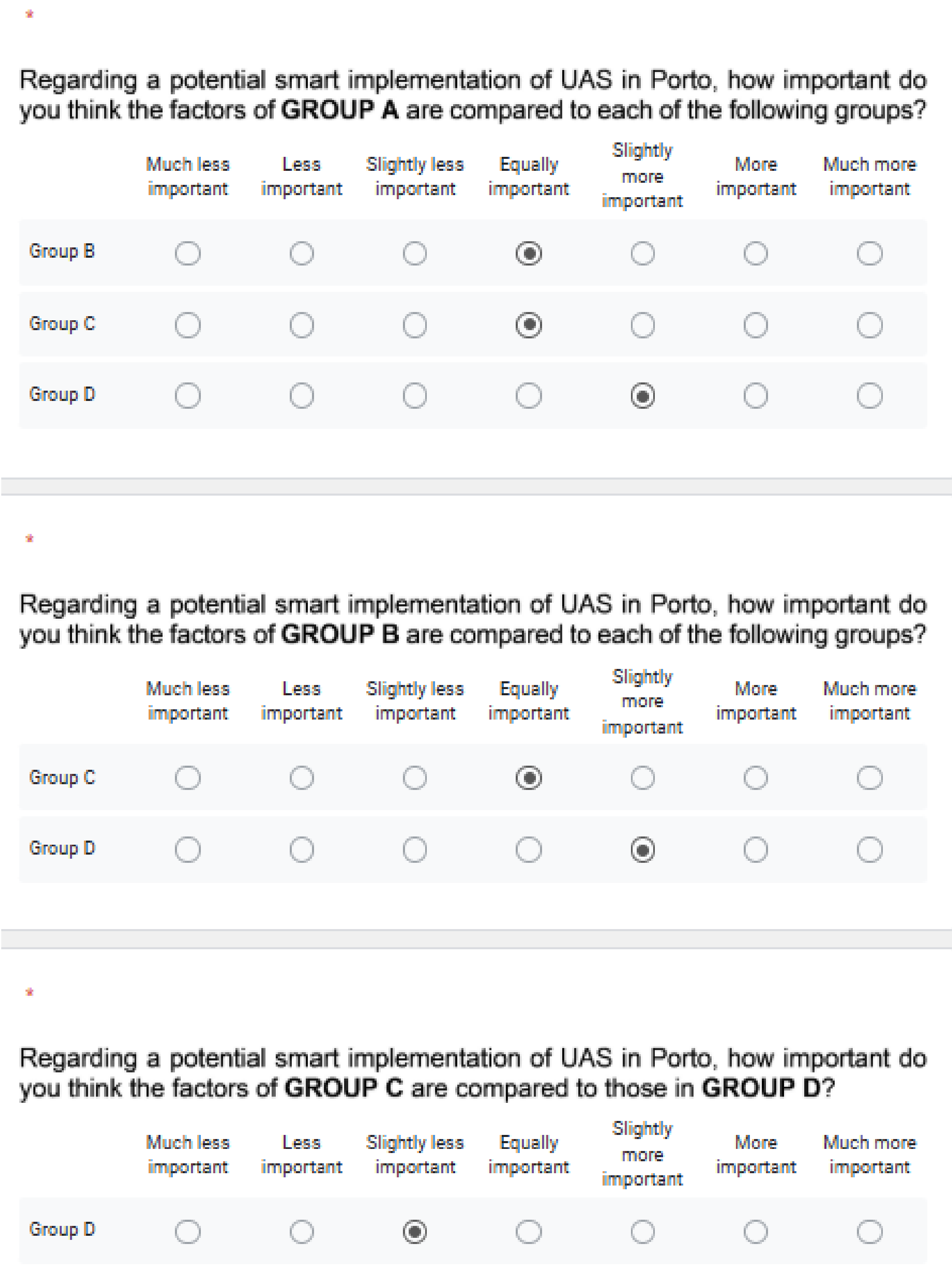
GROUP C

- EU's efforts to be a pioneer in the implementation of UAS
- Integration of Porto in several European smart city initiatives
- Experience acquired with UAS implementation in other contexts
- Job creation and business opportunities
- Economic growth as a door for the implementation of unmanned aviation

GROUP D

- Safety aspects and public concerns related to the integration of UAS in cities
- Security aspects and public concerns associated with urban UAS operations
- Privacy issues arising from UAS implementation
- Complex and evolving legislative and regulatory landscape
- Potential shortage of necessary expertise due to migration of skilled talent

Figure 32 - Pairwise comparison of SWOT criteria (groups) - Source: own elaboration



*

Regarding a potential smart implementation of UAS in Porto, how important do you think the factors of **GROUP A** are compared to each of the following groups?

	Much less important	Less important	Slightly less important	Equally important	Slightly more important	More important	Much more important
Group B	○	○	○	(x)	○	○	○
Group C	○	○	○	(x)	○	○	○
Group D	○	○	○	○	(x)	○	○

*

Regarding a potential smart implementation of UAS in Porto, how important do you think the factors of **GROUP B** are compared to each of the following groups?

	Much less important	Less important	Slightly less important	Equally important	Slightly more important	More important	Much more important
Group C	○	○	○	(x)	○	○	○
Group D	○	○	○	○	(x)	○	○

*

Regarding a potential smart implementation of UAS in Porto, how important do you think the factors of **GROUP C** are compared to those in **GROUP D**?

	Much less important	Less important	Slightly less important	Equally important	Slightly more important	More important	Much more important
Group D	○	○	(x)	○	○	○	○

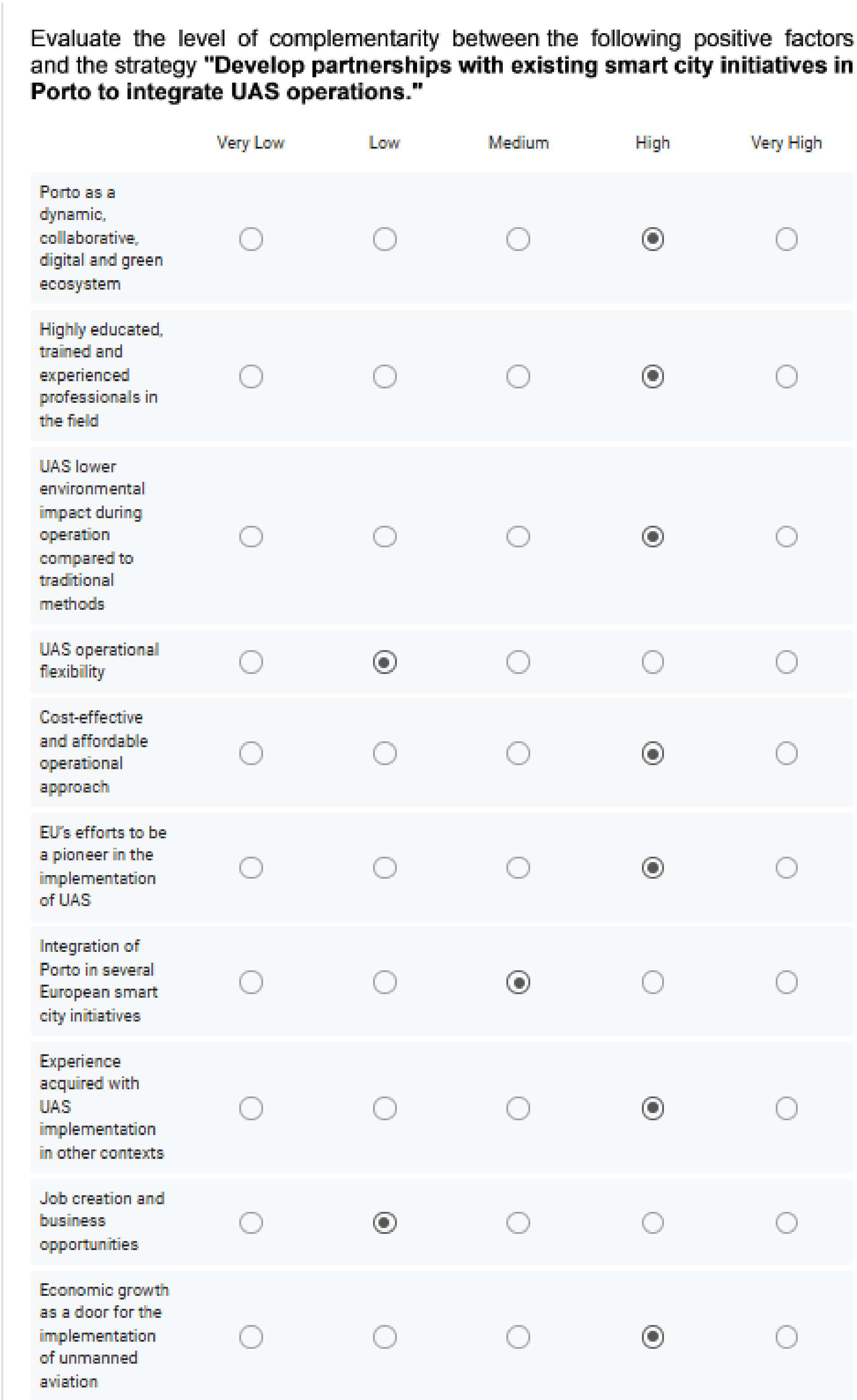
Figure 33 - Pairwise comparison of SWOT criteria: example of a respondent's answer – Source: own elaboration

	LW-SC	LW-C	GW-SC
d(S1)	0,2151	0,2513	0,0540
d(S2)	0,2074		0,0521
d(S3)	0,2081		0,0523
d(S4)	0,1830		0,0460
d(S5)	0,1864		0,0468
d(W1)	0,2025	0,2416	0,0489
d(W2)	0,2110		0,0510
d(W3)	0,1863		0,0450
d(W4)	0,1825		0,0441
d(W5)	0,2176		0,0526
d(O1)	0,1941	0,2536	0,0492
d(O2)	0,1935		0,0491
d(O3)	0,2038		0,0517
d(O4)	0,2086		0,0529
d(O5)	0,1999		0,0507
d(T1)	0,2087	0,2535	0,0529
d(T2)	0,2158		0,0547
d(T3)	0,1958		0,0496
d(T4)	0,1985		0,0503
d(T5)	0,1813		0,0460

$$(GW)_{SC} = (LW)_{C} \times (LW)_{SC}$$

Figure 34 - Global weights of each SWOT sub-criterion - Source: own elaboration

b) Importance of sub-criteria for each strategy



Evaluate the level of complementarity between the following positive factors and the strategy **"Develop partnerships with existing smart city initiatives in Porto to integrate UAS operations."**

	Very Low	Low	Medium	High	Very High
Porto as a dynamic, collaborative, digital and green ecosystem	○	○	○	●	○
Highly educated, trained and experienced professionals in the field	○	○	○	●	○
UAS lower environmental impact during operation compared to traditional methods	○	○	○	●	○
UAS operational flexibility	○	●	○	○	○
Cost-effective and affordable operational approach	○	○	○	●	○
EU's efforts to be a pioneer in the implementation of UAS	○	○	○	●	○
Integration of Porto in several European smart city initiatives	○	○	●	○	○
Experience acquired with UAS implementation in other contexts	○	○	○	●	○
Job creation and business opportunities	○	●	○	○	○
Economic growth as a door for the implementation of unmanned aviation	○	○	○	●	○

Figure 35 - Complementarity between strategies and sub-criteria: example of a respondent's answer (Part I) – Source: own elaboration

Evaluate the potential contribution of the strategy **"Develop partnerships with existing smart city initiatives in Porto to integrate UAS operations"** in mitigating the effects of each of the following negative factors:

	Very Low	Low	Medium	High	Very High
Significant initial investment required for infrastructure	○	●	○	○	○
Technical limitations related to weather dependency	○	○	●	○	○
Dependence on skilled operators and technicians	○	○	○	●	○
Amount of time required for implementation	○	○	●	○	○
Inadequate and insufficient current legislative and regulatory landscape for UAS	○	●	○	○	○
Safety aspects and public concerns related to the application of UAS in cities	○	○	○	●	○
Security aspects and public concerns related to the application of UAS in cities	○	○	○	●	○
Privacy issues arising from UAS implementation	○	○	●	○	○
Complex and evolving legislative and regulatory landscape	○	○	●	○	○
Potential shortage of necessary expertise due to migration of skilled talent	○	○	●	○	○

Figure 36 - Complementarity between strategies and sub-criteria: example of a respondent's answer (Part II) – Source: own elaboration

Answer no. 1	SO
S1	High
S2	High
S3	High
S4	Low
S5	High
O1	High
O2	Medium
O3	High
O4	Low
O5	High
W1	Low
W2	Medium
W3	High
W4	Medium
W5	Low
T1	High
T2	High
T3	Medium
T4	Medium
T5	Medium

Linguistic markings	Triangular fuzzy number
Very Low (VL)	(0, 0, 0.25)
Low (L)	(0, 0.25, 0.5)
Medium (M)	(0.25, 0.5, 0.75)
High (H)	(0.5, 0.75, 1)
Very High (VH)	(0.75, 1, 1)

Answer no. 1	SO
S1	(0.5,0.75,1)
S2	(0.5,0.75,1)
S3	(0.5,0.75,1)
S4	(0,0.25,0.5)
S5	(0.5,0.75,1)
O1	(0.5,0.75,1)
O2	(0.25,0.5,0.75)
O3	(0.5,0.75,1)
O4	(0,0.25,0.5)
O5	(0.5,0.75,1)
W1	(0,0.25,0.5)
W2	(0.25,0.5,0.75)
W3	(0.5,0.75,1)
W4	(0.25,0.5,0.75)
W5	(0,0.25,0.5)
T1	(0.5,0.75,1)
T2	(0.5,0.75,1)
T3	(0.25,0.5,0.75)
T4	(0.25,0.5,0.75)
T5	(0.25,0.5,0.75)

Figure 37 - Conversion of the respondent's answers into numeric variables – Source: own elaboration

$$M = (l, m, u)$$

	SO			BNP
S1	0,49149	0,7342	0,93514	0,72028

$$BNP = l + \frac{(u - l) + (m - l)}{3}$$

Figure 38 - BNP calculation: example - Source: own elaboration

Appendix 2 – Results Validation – Relevant Documentation

speedbird .aero

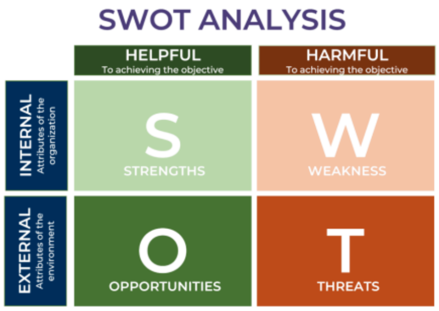
COMPANY DESCRIPTION

Speedbird Aero, a global leader in drone logistics with approximately 60 employees, operates with a presence in the United States and two branches—established in Brazil (2018) and Portugal (2024). The company's origins trace back to 2016, when co-founders Manoel Coelho and Samuel Salomão, while working at a leading telemedicine company in the United States, identified a critical gap in healthcare logistics. Coelho, serving as Chief Revenue Officer, and Salomão, as Head of Software, realized that while telemedicine effectively addressed initial diagnostic needs, it fell short in providing seamless follow-up services, such as local sample collection, rapid laboratory deliveries, and the swift dispatch of emergency medical supplies. Although their telemedicine employer was encouraged to develop a drone-based solution, it ultimately deemed the market too early for investment. This unmet need became the foundation for Speedbird Aero, established in Brazil in 2018 with the mission to revolutionize logistics through drone technology.

The company set out to tackle logistical challenges in congested urban centers and remote regions with limited infrastructure. Speedbird Aero has since developed an innovative, proprietary ecosystem of hardware and software, enabling the management of autonomous drone fleets for the fast and secure transport of packages. Over the years, the company has solidified its position as a leader in drone logistics, achieving more than 31,000 commercial flights and expanding its expertise across diverse industries. Its cutting-edge technology operates Beyond Visual Line of Sight (BVLOS) in eight countries, with products engineered to meet the rigorous standards like EASA Light-UAS and certified for UN3373 medical transport. Speedbird's portfolio includes three specialized aircraft designed for aerial logistics, featuring advanced capabilities such as automated payload release systems, winch-based delivery solutions, and proprietary software tailored to support a wide range of operational use cases.

Credentials: https://drive.google.com/file/d/1yruTmnPowQUMoxnVS9oclxROMtEwrW_0/view

Figure 39 - Company description - Source: Speedbird Aero



NOTE: The local and global classification does not refer to the geographic scope of the market but rather to the grouping of SWOT criteria, where: local compares and classifies subcriteria within the same group (e.g., S) and global compares all SWOT subcriteria.

Internal - Attributes of the organization

S - Strengths

RESEARCH RESULTS

1. S1 - Porto as a dynamic, collaborative, digital and green ecosystem
2. S3 – UAS lower environmental impact during operation compared to traditional methods
3. S2 – Highly educated, trained and experienced professionals in the field
4. S5 – Cost-effective and affordable operational approach
5. S4 – UAS operational flexibility

COMPANY VISION

1. S3 – UAS lower environmental impact during operation compared to traditional methods
2. S1 - Porto as a dynamic, collaborative, digital and green ecosystem
3. S2 – Highly educated, trained and experienced professionals in the field
4. S5 – Cost-effective and affordable operational approach
5. S4 – UAS operational flexibility

W - Weaknesses

RESEARCH RESULTS

1. W5 – Inadequate and insufficient current legislative and regulatory landscape for UAS
2. W2 – Dependence on skilled operators and technicians
3. W1 – Significant initial investment required for infrastructure
4. W3 – Technical limitations related to weather dependency
5. W4 – Amount of time required for implementation

COMPANY VISION

1. W5 – Inadequate and insufficient current legislative and regulatory landscape for UAS

Comment 1: This subcriterion (W5) should make it clear that this is a weakness at a global level.

Comment 2: A new weakness subcriterion should be added to consider operational limitations related to national infrastructure and regulation (e.g., airspace segregation) impacting a possible harmonized implementation.

2. W1 – Significant initial investment required for infrastructure

Comment: A new weakness subcriterion should be added to consider the significant investment required in new certifiable high robustness products (R&D). Or, W1 should cover both points.

3. W4 – Amount of time required for implementation
4. W2 – Dependence on skilled operators and technicians
5. W3 – Technical limitations related to weather dependency

External - Attributes of the environment

O - Opportunities

RESEARCH RESULTS

1. O4 – Job creation and business opportunities
2. O3 – Experience acquired with UAS implementation in other contexts
3. O5 – Economic growth as a door for the implementation of unmanned aviation
4. O1 – EU's efforts to be a pioneer in the implementation of UAS
5. O2 – Integration of Porto in several European smart city initiatives

COMPANY VISION

1. O1 – EU's efforts to be a pioneer in the implementation of UAS

Comment 1: A new opportunity subcriterion should be added to consider Portugal's momentum to invest efforts to be a pioneer in the implementation of UAS. Or, O1 should cover both points. The Technology Roadmap for Aeronautics in Portugal, developed by AED, substantiates this. https://drive.google.com/file/d/1D22Gk52YF3cHGXLfAePlsZCXDMeQpDVW/view?usp=sharing

Comment 2: A new opportunity subcriterion should be added to consider Portugal's momentum in setting goals for industrialization of technological products and internationalization, and means to facilitate the implementation of new technologies (e.g., creating sandboxes). The "Zonas Livres Tecnológicas" of Matosinhos and Marinha (ZLT Infante D. Henrique) substantiate this. If it existed, it would be classified in that position (between the current 1 and 2).

2. O5 – Economic growth as a door for the implementation of unmanned aviation
3. O4 – Job creation and business opportunities
4. O2 – Integration of Porto in several European smart city initiatives
5. O3 – Experience acquired with UAS implementation in other contexts

T - Threats

RESEARCH RESULTS

1. T2 – Security aspects and public concerns related to the application of UAS in cities
2. T1 – Safety aspects and public concerns related to the application of UAS in cities
3. T4 – Complex and evolving legislative and regulatory landscape
4. T3 – Privacy issues arising from UAS implementation
5. T5 – Potential shortage of necessary expertise due to migration of skilled talent

COMPANY VISION

1. T4 – Complex and evolving legislative and regulatory landscape

Comment: A new threat subcriterion should be added to consider the high need for investments (products and infrastructure) to compete internationally - which may be beyond the limits of the local economy. If it existed, it would be classified in that position (between the current 1 and 2).

2. T1 – Safety aspects and public concerns related to the application of UAS in cities
3. T2 – Security aspects and public concerns related to the application of UAS in cities
4. T3 – Privacy issues arising from UAS implementation
5. T5 – Potential shortage of necessary expertise due to migration of skilled talent

Q&A

1. In general, do the factors identified in the SWOT analysis reflect the local reality? Are there any subcriteria that you consider more or less relevant?

See comments above.

2. Do you consider the identified Forces (S) sufficient to justify the adoption of UAS in Porto? And are the Weaknesses (W) listed the biggest challenges in the company's view?

See comments above.

3. Do the Opportunities (O) subcriteria correspond to expectations and perceived advantages? Do the identified Threats (T) cover the main associated risks?

See comments above.

4. Do you consider that "security" threats (and respective public perception) may constitute a greater risk than "safety" threats (and respective public perception)?

No, the opposite.

Figure 40 - Results validation: Support Document (Part I) - Source: Speedbird Aero

5. In general, respondents gave greater importance to external factors (opportunities and threats) than to internal factors (strengths and weaknesses). What could be the reason?

This is a high-tech industrial sector focused on multi-market products and services, which requires a high level of investment. As an emerging market, there is no well-defined regulatory framework at a global level (harmonization).

In addition, most of the companies that started in this market years ago had no experience in aviation, coming from the technology industry. Thus, with a misconception presumably about the effort (time and cost) required to develop and certify this type of product. In this sense, after many years of intensive capital injection and failure of milestones, they have caused fear among investors and a general lack of investment.

The negative impact can be easily verified by a cascade of announcements about several companies in the Innovative Air Mobility (IAM) sector undergoing judicial recovery processes or closing down completely. Thus, validating the sentiment of stakeholders that the risk becomes greater due to the uncertainty associated with the general market context than that associated with the capabilities of the company and the local ecosystem.

6. Are the weights obtained for the subcriteria (local and global) aligned with the company's practical perception?

See the local evaluation above and the global one below.

GLOBAL

	RESEARCH RESULTS	COMPANY VISION
1	External / Threat T2 – Security aspects and public concerns related to the application of UAS in cities	Internal / Strength S3 – UAS lower environmental impact during operation compared to traditional methods
2	Internal / Strength S1 – Porto as a dynamic, collaborative, digital and green ecosystem	External / Opportunity O1 – EU's efforts to be a pioneer in the implementation of UAS
3	External / Threat T1 – Safety aspects and public concerns related to the application of UAS in cities	External / Opportunity O4 – Job creation and business opportunities
4	External / Opportunity O4 – Job creation and business opportunities	External / Threat T4 – Complex and evolving legislative and regulatory landscape
5	Internal / Weakness W5 – Inadequate and insufficient current legislative and regulatory landscape for UAS	Internal / Weakness W1 – Significant initial investment required for infrastructure
6	Internal / Strength S3 – UAS lower environmental impact during operation compared to traditional methods	Internal / Weakness W5 – Inadequate and insufficient current legislative and regulatory landscape for UAS
7	Internal / Strength S2 – Highly educated, trained and experienced professionals in the field	External / Threat T1 – Safety aspects and public concerns related to the application of UAS in cities
8	External / Opportunity O3 – Experience acquired with UAS implementation in other contexts	External / Threat T2 – Security aspects and public concerns related to the application of UAS in cities
9	Internal / Weakness W2 – Dependence on skilled operators and technicians	External / Threat T3 – Privacy issues arising from UAS implementation
10	External / Opportunity O5 – Economic growth as a door for the implementation of unmanned aviation	Internal / Strength S5 – Cost-effective and affordable operational approach
11	External / Threat T4 – Complex and evolving legislative and regulatory landscape	Internal / Weakness W4 – Amount of time required for implementation
12	External / Threat T3 – Privacy issues arising from UAS implementation	External / Opportunity O5 – Economic growth as a door for the implementation of unmanned aviation
13	External / Opportunity O1 – EU's efforts to be a pioneer in the implementation of UAS	Internal / Strength S1 – Porto as a dynamic, collaborative, digital and green ecosystem
14	External / Opportunity O2 – Integration of Porto in several European smart city initiatives	Internal / Strength S4 – UAS operational flexibility
15	Internal / Weakness W1 – Significant initial investment required for infrastructure	Internal / Strength S2 – Highly educated, trained and experienced professionals in the field
16	Internal / Strength S5 – Cost-effective and affordable operational approach	External / Opportunity O3 – Experience acquired with UAS implementation in other contexts
17	Internal / Strength S4 – UAS operational flexibility	External / Opportunity O2 – Integration of Porto in several European smart city initiatives
18	External / Threat T5 – Potential shortage of necessary expertise due to migration of skilled talent	External / Threat T5 – Potential shortage of necessary expertise due to migration of skilled talent
19	Internal / Weakness W3 – Technical limitations related to weather dependency	Internal / Weakness W3 – Technical limitations related to weather dependency
20	Internal / Weakness W4 – Amount of time required for implementation	Internal / Weakness W2 – Dependence on skilled operators and technicians

PART II – STRATEGIES (overall weight)

RESEARCH RESULTS

1. SO – Develop partnerships with existing smart city initiatives in Porto to integrate UAS operations

2. ST – Establish a comprehensive safety and security framework to address the complexity and the evolving legislation of urban UAS operations

3. WO – Collaborate with European partners to secure funding and reduce initial investment costs for infrastructure

4. WT – Use the time to engage with the community and educate and inform about the benefits and safety measures of UAS operations

COMPANY VISION

1. ST – Establish a comprehensive safety and security framework to address the complexity and the evolving legislation of urban UAS operations

Strategy to Add: Create technological solutions (products and services) and business models that prove the viability (environmental, economic and social) of this type of implementation.

2. WO – Collaborate with European partners to secure funding and reduce initial investment costs for infrastructure

Strategy to Add: In the same direction highlighted above (momentum), local collaborations at the national level are having a positive impact on driving implementation. Therefore, they should be considered here.

3. WT – Use the time to engage with the community and educate and inform about the benefits and safety measures of UAS operations

Strategy to Add: It is also important to involve the community in order to increase employment opportunities and business viability, enabling them to be part of the new economic sector.

4. SO – Develop partnerships with existing smart city initiatives in Porto to integrate UAS operations

Q&A

7. Overall, do the strategies identified in the TOWS analysis reflect the local reality? Are the strategies comprehensive enough to address key local challenges and opportunities?

Yes, see comments above.

8. Are the strategies identified for implementing UAS in the Port viable and aligned with the company and sector objectives?

Yes, see comments above.

9. In the present context, do you consider that developing partnerships with "smart city" initiatives should be a priority in relation to using implementation time to improve public acceptance?

No, the opposite.

10. Do you consider that the strategies are correctly ordered by importance? Would they change any priorities based on practical experience or local needs?

See comments above.

PART III – GENERAL OBSERVATIONS

Q&A

11. In your opinion, what will be the first large-scale practical applications of UAS to be implemented in Porto?

Implementation in the following order: B2B / B2C Surveillance, B2C Emergency Response, B2B Health (Hospitals and Lab-to-Lab), B2B Inspection, B2C Healthcare (e.g. medication delivery), B2C multimodal generic delivery.

12. In the context of consolidating the status of a smart city, are there any other observations or recommendations that you consider important for the successful implementation of UAS in Porto?

There are several aspects associated with intelligent mobility design and implementation that are still missing for a successful implementation or in early stages, for example, a robust network for data collection and analysis. It is necessary to put together the key-players from industries like telecommunications, energy, transport, urbanisation, sustainability, etc. to build an ecosystem around this technology (UAS) to enable implementation, acceptance and scalability.

Figure 41 - Results validation: Support Document (Part II) - Source: Speedbird Aero)

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Declaração de Autorização

A **Speedbird Aero** autoriza a utilização de informações e dados fornecidos no âmbito da dissertação intitulada ***Enhancing Smart City Capabilities with the Integration of Unmanned Aircraft Systems: Unlocking Porto's Potential***, de autoria de João Gonçalo Lopes Barateiro, estudante do Mestrado Integrado em Engenharia Aeronáutica na Universidade da Beira Interior.

Esta autorização abrange a utilização das informações fornecidas para fins académicos e a sua inclusão na dissertação que será apresentada publicamente.

Porto, 29 de janeiro de 2025

O/A Representante da Empresa

Manoel Coelho

Speedbird Aero Europe

Figure 42 - Declaration of authorization for publication - Source: Speedbird Aero

Appendix 3 – Articles Submitted to Scientific Journals and Conferences with Double-Blind Review

A - Article Submitted to the International Congress on Engineering UBI – ICEUBI 2024

Enhancing Smart City Capabilities With The Integration Of Unmanned Aircraft Systems: The Case Of Porto

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Abstract

The increasing number of urban residents presents growing challenges that require innovative and efficient solutions. Cities are looking for smarter approaches, which involve the optimization of resource usage and the improvement of public services, with the aim of enhancing the quality of life and overall satisfaction of residents through sustainable practices. Current and emerging innovative technologies provide effective tools for addressing urban challenges. Unmanned Aircraft Systems (UAS) present a valuable solution, due to their versatility, flexibility, efficient data collection methods, and lower environmental impact compared to other technologies. UAS have been extensively studied as they offer a wide range of urban applications, such as monitoring, traffic management, and infrastructure inspection. In the near future, they are also

expected to start carrying passengers and delivering goods in Europe, contributing to the development of Urban Air Mobility (UAM), a priority among the European Union's sustainable urban mobility initiatives. This work proposes the application of a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis to qualitatively evaluate the implementation of UAS in Porto, supported by the Fuzzy Analytical Hierarchical Process (FAHP) to prioritize strategies for implementation, with the primary goal of pinpointing initiatives that would position Porto closer to the leading smart cities in Europe.

B - Article Submitted to the Journal of Airline and Airport Management (JAIRM)

Unmanned Aircraft Systems in Urban Environments: A Smart City Approach for Porto

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Abstract

Purpose: With the increasing urban population, the need for smarter solutions to address urban problems has become imperative. UAS have already proven their potential in this context, due to their versatility, lower environmental impact compared to traditional tools, and efficient data collection capabilities. Consequently, this study aims at selecting a specific case study to evaluate the benefits and constraints of introducing UAS into that city (Porto), and to identify strategies for their adoption and a prioritization order.

Design/methodology/approach: The study began with a literature review and an analysis of Porto's multidimensional reality, leading to the definition of sub-criteria expected to influence UAS implementation and strategy development. Respondents from different fields of expertise were engaged to use linguistic variables for pairwise comparison of sub-criteria and to assess the complementarity between the sub-criteria and strategies. Several quantitative methodologies enabled the establishment of ranking for sub-criteria importance and a prioritization order for strategies. The results were validated by a company located in Porto and specialized in the UAS sector.

Findings: Results indicate that the main advantages and driving forces include Porto's possession of several features typical of smart cities, the potential for the UAS industry to stimulate job creation and develop business opportunities, and their higher environmentally friendliness compared to many conventional transportation methods. However, the legislative framework governing UAS operations remains insufficient and inadequate, which poses serious safety and security concerns that could hinder rapid and effective advancements in the implementation process.

Originality/value: This study aims at enhancing practical applicability by providing potential concrete insights for urban planning, supported by the collaboration with a company working in the UAS sector. This approach offers a realistic perspective on the main benefits and challenges, contributing to the definition of executable strategies for the adoption of UAS in smart cities.

Keywords: Smart City, Quality of Life, Sustainability, UAM, UAS, IAM, SWOT, FAHP