Architecture Definition of Urban Air Mobility Addressing Situation Awareness, Security, Safety Culture, and Sustainability

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by

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Abstract

Urban Air Mobility (UAM) is a concept that envisions the integration of electric Vertical Takeoff and Landing (eVTOL) aircraft into the airspace above cities, offering innovative solutions for passenger transport. This doctoral dissertation explores the socio-technical dimensions of UAM, employing an enterprise architecture (EA) methodology and using the Unified Architecture Framework (UAF) to address the complexities and challenges associated with its systematic implementation. The research focuses on four socio-technical concerns: situation awareness, security, safety culture, and sustainability, all examined through a System-of-Systems (SoS) approach.

The research begins by exploring the concept of situation awareness (SA) in UAM operations, highlighting the unique demands placed on pilots and air traffic controllers as they navigate dense urban environments. The author investigates SA in the UAM ecosystem and addresses it as a collective competence. Security is another socio-technical concern, and the dissertation assesses both cyber and physical security risks. The research proposes a comprehensive security model tailored to the UAM context, addressing systems, data, and personnel vulnerabilities. Resilient principles applied during security controls and processes are particularly emphasized, showcasing its potential in developing robust security strategies.

Safety culture within UAM is investigated with an emphasis on just culture. The research underscores the importance of fostering open communication and accountability to enhance safety performance in the UAM novel operation. It also considers the challenges of building trust and achieving consensus in the highly dynamic and distributed operational environment of UAM, proposing strategies for effective safety oversight.

Sustainability is explored through eco-efficiency principles, focusing on the environmental and social impacts of UAM. The author evaluates the potential benefits and drawbacks of eVTOL operations, including their greenhouse gas emissions, resource efficiency, and social equity implications. It highlights the need for a balanced approach incorporating real-world data and community engagement to ensure that UAM contributes positively to sustainable urban development.

The dissertation's findings combine the architecture conceptualization process and model visualizations based on the architecture elaboration process. UAF views are evaluated and validated through expert discussions and stakeholder consultations. The study concludes with practical recommendations for policymakers, industry stakeholders, and researchers, advocating for interdisciplinary collaboration and adaptive governance to navigate the complexities of UAM. By providing a holistic examination of UAM's socio-technical challenges, this doctoral research contributes insights and frameworks to guide the safe, secure, and sustainable integration of UAM into urban transportation systems.

The dissertation is organized into eight chapters. In Chapter 1, the author introduces the thesis, providing an overview of the research context, problem analysis, research objectives, questions, methods, resources, contributions, limitations, delimitations, and the thesis structure. In Chapter 2 the author conducts a literature review presenting relevant information about UAM, evaluating work related to UAM ConOps, situation awareness, security, safety culture, and sustainability. This chapter identifies gaps in current knowledge and provides theoretical foundations on multiple topics involved in the research. Chapter 3 describes the research methods used for UAM as a SoS, including the rationale for the methodology applied, the foundations and principles substantiating the methodology, the standards and processes used during the study, the modeling framework, validation methods, and the model strategy used to develop the research results.

Results are presented in Chapter 4 to Chapter 8. In Chapter 4, Situation Awareness Concern in the UAM SoS, the author presents the results of the architecture conceptualization and elaboration addressing UAM SoS's concerns regarding situation awareness, including UAM enterprise views and key findings from the analysis. Chapter 5 Security Concern in the UAM SoS, details the architecture conceptualization and elaboration addressing UAM security concerns, considering UAM cyber and physical security threats and including UAM enterprise views and key findings from the analysis. Chapter 6, Safety Culture Concern in the UAM SoS, discusses the architecture conceptualization and elaboration addressing UAM safety culture concerns, considering UAM safety management perspectives and including UAM enterprise views and findings from the analysis. Chapter 7, Sustainability Concern in the UAM SoS, elaborates on the architecture conceptualization and elaboration addressing UAM sustainability concerns, considering UAM's

environmental and social impacts and including UAM enterprise views and critical findings from the analysis.

Finally, in Chapter 8, the author discusses the results and stakeholder engagement in each concern, highlights the contribution of EA visualization with different enterprise viewpoints and perspectives, summarizes answers to each research question, and provides recommendations for future work in the field of UAM.

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First and foremost, I would like to express my deepest gratitude to my advisor, Nishimura-sensei. Your guidance, patience, and unwavering belief in my work have been invaluable throughout this journey. Your ability to listen and understand every new topic I brought to the research has been remarkable. I sincerely appreciate that you introduced me to the UAF and encouraged me when I struggled to see the potential contributions of my work. Your timely words of encouragement, even with the language barrier, had a significant impact on my research and motivation. Your vision for what brings value to research, coupled with your provision of the best resources and financial support, has made this achievement possible. I am proud to be part of SDM. **ありがとうございます**.

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To my parents, thank you for being my role models and for your continuous encouragement and motivation. Your dedication to science and lifelong learning has always inspired me to strive for excellence. Your investment and belief in my education have driven my pursuit of this doctoral degree. Thank you, Dad, for always believing that the cost of ignorance is much higher than the cost of knowledge. Thank you, Mom, for being a woman in science, stubborn, and capable of standing up for yourself. My feeling of being prepared and authorized to be wherever I want comes

from your example. I admire you both profoundly for your hard work in achieving your doctoral degrees. I am proud to join you among our family's doctors now. To my sister Mariana, thank you for your advice, encouragement, and joy. You are about to start this journey, and I hope to be as supportive as you are.

Lastly, to my family – Ivan, my partner in this life, and my daughters, Malu and Camila – thank you for your support and understanding. Throughout this journey, I have endeavored to balance my professional and personal responsibilities. I hope I have succeeded in your eyes. Your patience and tolerance, especially during times when I had to prioritize my studies over family activities, mean the world to me. Malu and Camila, I hope my journey serves as an example of the importance of continuous learning. I have tried to show you how happy I was being a student and learning, often telling you with excitement when I had to go to school, just like you. Sometimes, sharing the same space in our house made my reading and writing time more challenging, but it was also a blessing. Thank you for your patience and understanding. The sense of accomplishment is even greater knowing I could be fully present at home, caring for you both, doing house chores, and studying for this degree. Thank you for being my constant source of joy and motivation.

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This achievement is as much yours as it is mine. Thank you all for being part of this journey.

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List of Abbreviations

AAM	Advanced Air Mobility
ACCA	Accounting Center of China Aviation
AGL	Above Ground Level
ANAC	Agencia Nacional de Aviação Civil
ATC	Air Traffic Control
ATM	Air Traffic Management
CAA	United Kingdom Civil Aviation Authority (CAA)
CNS	Communication, Navigation, and Surveillance
ConOps	Concept of Operations
CRM	Crew Resource Management
CSP	Communication Service Provider
EA	Enterprise Architecture
EASA	European Union Aviation Safety Agency
ELCC	Environmental Life Cycle Costs
eVTOL	Electric Vertical Takeoff and Landing
FAA	Federal Aviation Administration
FATOs	Final and Take-Off Areas
GHG	Greenhouse Gas
HSI	Human Systems Integration
IA	Innovative Air Mobility
IAM	Innovative Air Mobility

IAS	Innovative Aerial Services
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
JAXA	Japan Aerospace Exploration Agency
MSP	Meteorological Service Provider
NIST	National Institute of Standards and Technology
OEM	Original Equipment Manufacturer
PSU	Provider of Services to UAM
RAAML	Risk Assessment and Analysis Modeling Language
RE	Resilience Engineering
SA	Situation Awareness
SMS	Safety Management Systems
SOP	Standard Operational Procedure
SoS	System of Systems
SP	Special Publication
SysML	Systems Modeling Language
UAF	Unified Architecture Framework
UAM	Urban Air Mobility
UML	UAM Maturity Level
UTM	Unmanned Traffic Management
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions

xTM	Extensible Traffic Management

CHAPTER 1

Introduction

Urban Air Mobility (UAM) is a conceptual ecosystem currently undergoing active development and extensive discussion through public and private initiatives. At its core, UAM envisions a future where electric Vertical Takeoff and Landing (eVTOL) aircraft provide an innovative solution for passenger transportation within urban areas. While promising transformative benefits, this concept also presents many challenges and uncertainties that span the realms of safety, security, social dynamics, and environmental impact — each of which carries profound implications for urban communities and society.

Navigating socio-technical complexities is far from simple and demands a comprehensive, systemic approach. Addressing the intricacies of safety, security, social, and environmental impact necessitates a comprehensive perspective considering urban life and mobility's diverse and interrelated facets. This chapter sets the stage for this thesis by delving into the context and definition of the problem. It also presents the objectives and questions guiding the research exploration. Methods and resources summarize how the research undertakes the challenges within its scope. Furthermore, this Chapter describes the unique contributions this research makes to the field while acknowledging its inherent limitations. Lastly, it provides a glimpse into the structure of the thesis, offering a roadmap for the reader to navigate the subsequent Chapters.

1.1 Background and Context

Urban Air Mobility (UAM) for passenger-carrying operations is expected to impact urban transportation by potentially reducing congestion and passenger delay (Graydon et al., 2021). Vehicles capable of vertical take-off and landing are being developed for an expected flexible air travel demand. UAM intends to integrate manned (piloted) and unmanned (uncrewed) aerial vehicles transporting people or cargo in an urban or suburban environment. Control and navigation

of such aerial vehicles can be handled by a pilot, a controller from a remote location, onboard automation, or a ground-based centralized automated system (FAA, 2020).

The concept of operations for Urban Air Mobility (UAM) proposes an integrated approach to add operational complexity through phases in UAM operations. A network of strategically positioned vertiports and skyports is envisioned throughout urban areas to make this concept a reality. These hubs would serve as the departure and arrival points for eVTOLs, effectively functioning as modern-day airports. Figure 1.1 illustrates the envisioned future with the UAM passenger transportation services, a projection created by EmbraerX, manufacturer of the eVTOL project called Eve (Air Service Australia & Embraer, 2020).

Figure 1.1: Projection of Urban Air Mobility for Passenger Transportation (Air Service Australia & Embraer, 2020)

Crucially, UAM operates with a strong focus on flexibility and on-demand service. Passengers can take an eVTOL ride through a smartphone app or digital platform, and these electric aircraft will promptly transport them to their chosen destinations. UAM's vision extends beyond standalone air travel. It aims to seamlessly integrate with existing transportation modes, such as ground-based transit systems. Passengers would have the convenience of transitioning between eVTOLs and other forms of transportation to complete their journeys (FAA, 2020). To manage the complex traffic of eVTOLs in urban airspace, advanced traffic management systems, including Unmanned

Traffic Management (UTM) systems, are proposed. These systems would coordinate the movement of eVTOLs, ensuring safe separation and efficient routing.

The massive discussion about implementing UAM operations is currently the highest challenge for the air transportation market. The UAM System of Systems (SoS) comprises a significant number of stakeholders, including service operators, service providers, lawmakers, human operators, and the public. Integrating systems and human interactions among UAM components in urban space builds a complex ecosystem. In addition, the safety-critical aspects of passenger transportation add even more complexity to the UAM SoS. Numerous concepts of operations are being explored throughout industry and research domains aiming for a safe operation for society and efficient transportation for the industry (FAA, 2020; FAA, 2022; Air Service Australia & Embraer, 2020). The foreseen UAM's highly integrated operation is characterized by technological nuances and novel advancements, introducing significant uncertainties. However, these complexities also present rich investigation, analysis, and exploration opportunities. By thoroughly examining these factors, we can work towards minimizing unintended consequences and supporting architectural decisions toward safe UAM operations.

1.2 Research Topics and Definitions

The research addresses different problem types for UAM operations. Safety, security, and sustainability are broad domains that include multiple subtopics or aspects. To provide a clear understanding of the research objectives, methods, and results, it is essential to begin by explaining the basic definitions and meanings associated with each topic. These foundational concepts serve as the building blocks for the research, enabling a deeper exploration of the challenges and opportunities that UAM presents as it integrates into urban transportation systems.

EASA (2023) defines UAM as "a new safe, secure and more sustainable air transportation system for passengers and cargo in urban environments, enabled by new technologies and integrated into multimodal transportation systems. The transportation is performed by electric aircraft taking off and landing vertically, remotely piloted or with a pilot on board." This definition was selected because it offers a comprehensive and concise summary of the various aspects of UAM and

effectively encapsulates the key elements of UAM. Regardless, other UAM definitions are similar among different authorities and industries, which was presented in 2.2 during the literature review.

The research addresses two socio-technical concerns within the safety topic: Situation Awareness (SA) and Safety Culture. Mica Endsley has significantly influenced the understanding of Situation Awareness, making her a central figure in this field. According to Endsley (1988), SA refers to the perception of environmental elements within a specific volume of time and space, the comprehension of their meaning, and the projection of their future status. SA is crucial in understanding how human or automated operators interact and make decisions in dynamic and complex systems like UAM. This definition was selected because of its relevance to managing the complexities of dynamic urban airspaces. The concept of SA helped focus the research on how operators maintain awareness and make decisions in the UAM environment. It guided the analysis of system elements and interactions within UAM operations, emphasizing the importance of harmonizing human capability, system interface, and operational procedures.

Safety Culture is defined by the International Civil Aviation Organization (ICAO) as "the enduring value, priority, and commitment placed on safety by every individual and every group at every level of the organization. Safety culture reflects the individual, group, and organizational attitudes, norms, and behaviors related to the safe provision of air navigation services" (ICAO, 2018). ICAO is a specialized agency of the United Nations that plays a central role in setting international aviation standards and regulations. Countries adopt its guidelines and standards worldwide, making it a cornerstone of global aviation safety and security. Moreover, its definition was essential in shaping the research's focus on organizational and human factors. It emphasized the need to evaluate how attitudes, norms, and behaviors within UAM organizations contribute to or detract from safety.

The National Institute of Standards and Technology (NIST) defines security as protecting systems from unauthorized access and cyber threats and ensuring data integrity, availability, and confidentiality. This definition summarizes the security risks to which protection is intended. The NIST definition and its framework (NIST, 2018) informed the research by emphasizing the need to consider physical and cybersecurity threats, guiding the analysis toward identifying vulnerabilities, and proposing measures to secure UAM operations.

According to the Brundtland Commission's report in 1987, sustainability is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This definition underscores the importance of balancing economic growth, environmental protection, and social equity in the context of UAM development. Understanding and evaluating the environmental and societal impacts of UAM lay the ground for the broader UAM sustainability topic. Furthermore, Brundtland's work emphasized the need to balance economic, environmental, and social considerations in UAM development, ensuring that UAM contributes positively to sustainable urban mobility.

The extraction of meaning from each definition guided the analysis of each problem and provided tailored perspectives and insights for the UAM as an ecosystem. By integrating these definitions, the research method was bounded by a systemic approach that considers the technical, operational, human, organizational, social, and environmental dimensions of UAM while discerning the specificities of each problem's nature. The literature review in Chapter 2 presents more details about definitions and discussions on UAM's context.

1.3 Problem Analysis

The advent of Urban Air Mobility (UAM) represents a transformative shift in the way we envision transportation systems within urban areas. UAM transportation emerged as a potential solution to alleviate congestion, reduce travel times, and offer a more sustainable and efficient mode of transportation. However, the implementation and operation of UAM systems introduce a new layer of complexity to urban environments, with multifaceted implications for safety, security, public perception, and the overall urban landscape (Graydon et al., 2020).

The UAM ecosystem is conceptualized as a dynamic and evolving web of technologies, regulations, infrastructures, and human behaviors. Its complexity stems from the convergence of various domains, including aviation, urban planning, technology development, and public policy (Air Service Australia & Embraer, 2020). This amalgamation gives rise to uncertainties and impacts that radiate across multiple socio-technical dimensions, such as human factors, technology, organizational structure, and social and environmental interactions.

Traditional urban transportation systems were primarily ground-based, but UAM introduces the dimension of airspace. Integrating these systems while ensuring safety and efficiency is a complex task (FAA, 2022). Moreover, the UAM ecosystem encompasses a multitude of stakeholders, from vehicle manufacturers to regulators, each with unique interests and concerns. Understanding the interconnectedness of these elements is crucial.

Safety is paramount in UAM, given its operation in densely populated urban environments. The integration of autonomous or semi-autonomous eVTOLs introduces new safety considerations. These include collision avoidance in crowded airspace, vehicle reliability, and emergency response (Ribeiro et al., 2017). Ensuring the safety of passengers and urban residents is non-negotiable for the public integrity and the UAM transportation business. Another similar concern is Security in UAM, which extends beyond physical threats to cybersecurity (Jordan et al., 2022). The increasing reliance on digital systems for vehicle control, communication, and navigation opens doors to potential vulnerabilities (Cenk Erturk et al., 2020). Safeguarding against cyberattacks and ensuring the integrity of UAM operations is a pressing challenge (Maxa et al., 2019).

The impact of UAM extends beyond safety concerns, encompassing questions of airspace management, noise pollution, community acceptance, and socioeconomic disparities (Vascik et al., 2018; Bauranov & Rakas, 2019). Thus, the UAM ecosystem is not just about technology; it is a complex interplay of human, technical, regulatory, and environmental factors that necessitate a holistic understanding (Thipphavong et al., 2018).

UAM relies on cutting-edge technologies such as electric propulsion, autonomy, and advanced air traffic management (FAA, 2020). These innovations bring immense potential but also demand rigorous testing and validation. The transition from traditional aviation to electric and autonomous operations introduces a learning curve for industry stakeholders and the public. The UAM landscape is also marked by uncertainty. Technological advancements are ongoing, and regulatory frameworks are evolving. Predicting how UAM will integrate into existing transportation systems and urban environments remains challenging. Ensuring that UAM can adapt to unforeseen developments and scale effectively is essential.

Finally, at the heart of the UAM challenge lies the delicate balance between fostering innovation and safeguarding the public's interests. The very novelty of UAM introduces uncertainty that requires careful analysis. Issues related to safety and security are paramount, as integrating aerial

vehicles into urban environments demands robust systems to prevent accidents, mitigate risks, and ensure the safety of both passengers and ground occupants (Cohen et al., 2021). Therefore, the dissertation problem statement is as follows:

> "Urban Air Mobility (UAM) offers a revolutionary opportunity to transform urban transportation by alleviating congestion, reducing travel times, and promoting sustainability. However, integrating UAM into densely populated urban areas presents significant challenges, particularly related to socio-technical concerns such as safety and security. The advent of new technologies, such as eVTOL vehicles, coupled with a heavy reliance on digital systems for control and communication, exacerbates the complexity of these challenges. If these issues are not adequately addressed, they could result in catastrophic incidents, eroding public trust and hindering the widespread adoption of UAM technologies. Conversely, effectively addressing these challenges could ensure the safe and efficient integration of UAM, delivering significant benefits to urban populations through improved mobility and reduced environmental impact.
>
> To achieve the successful and safe implementation of UAM, addressing specific socio-technical concerns like situational awareness, security, safety culture, and eco-efficiency is essential. Each of these concerns requires a carefully crafted strategy tailored to the specific context and nature of the problem. Given the diversity of stakeholders — operators, regulators, service providers, and urban communities— balancing these imperatives demands meticulous planning, interdisciplinary cooperation, and adaptive management. This complexity highlights the necessity of adaptive and context-sensitive approaches to ensure the safe and sustainable integration of UAM into urban environments."

1.4 Research Objectives

The purpose of this research is to systematically explore the UAM ecosystem, recognizing that it functions as a complex, interconnected network with interdependencies that require a comprehensive approach. The UAM landscape is addressed as a whole and explored as an enterprise, acknowledging its components' broad and interconnected nature. Addressing the opportunities and challenges within this landscape necessitates the application of concepts, principles, procedures, and tools that enable more informed architecture-related decisions, developing more effective architectures, and formulating better architecture strategies. By

elaborating on enterprise architecture, this research aims to uncover insights that allow decision-makers to enhance UAM's safety, security, and sustainability.

Specifically, the research objectives (RO) are as follows:

RO1→ To systematically frame UAM socio-technical concerns: The research will systematically frame and explore key socio-technical concerns, including situation awareness, security, safety culture, and sustainability within the UAM ecosystem, utilizing architecture-related definitions as a foundational resource to gain a comprehensive understanding of their behavior and implications for UAM operations within urban environments;

RO2→ To communicate with multiple stakeholders and support decision-makers: The research will develop architecture perspectives and viewpoints that can effectively engage and address the interests of various stakeholders, including the public, industry, and policymakers. Therefore, the research aims to provide decision-makers with valuable insights and recommendations to navigate society's challenges and opportunities that UAM poses.

1.5 Research Questions

To direct the course of the research, the following research questions have been formulated:

RQ1→ What identifies the problem space for situation awareness, security, safety culture, and sustainability in Urban Air Mobility (UAM), and how can the solution space meet the diverse interests of different stakeholders?

RQ2→ How does Situation Awareness behave as a collective cognitive process distributed at different UAM ecosystem levels, and how does it compromise the UAM safe operation?

RQ3→ Which security controls and processes are necessary for the UAM ecosystem to manage cyber, physical, and personnel security risks?

RQ4→ How can the UAM ecosystem develop and maintain a safety culture that fosters trust and accountability among front-line workers?

RQ5→ What are the social, economic, and environmental impacts of integrating UAM into urban environments, and to what extent can UAM operation be eco-efficient for passenger transportation?

RQ6→ How can different UAM ecosystem viewpoints and perspectives inform decision-makers, and what recommendations can be provided to balance diverse stakeholder interests while ensuring safety, security, and eco-efficiency?

Figure 1.2 depicts the relationship between the research purpose, objectives, and questions.

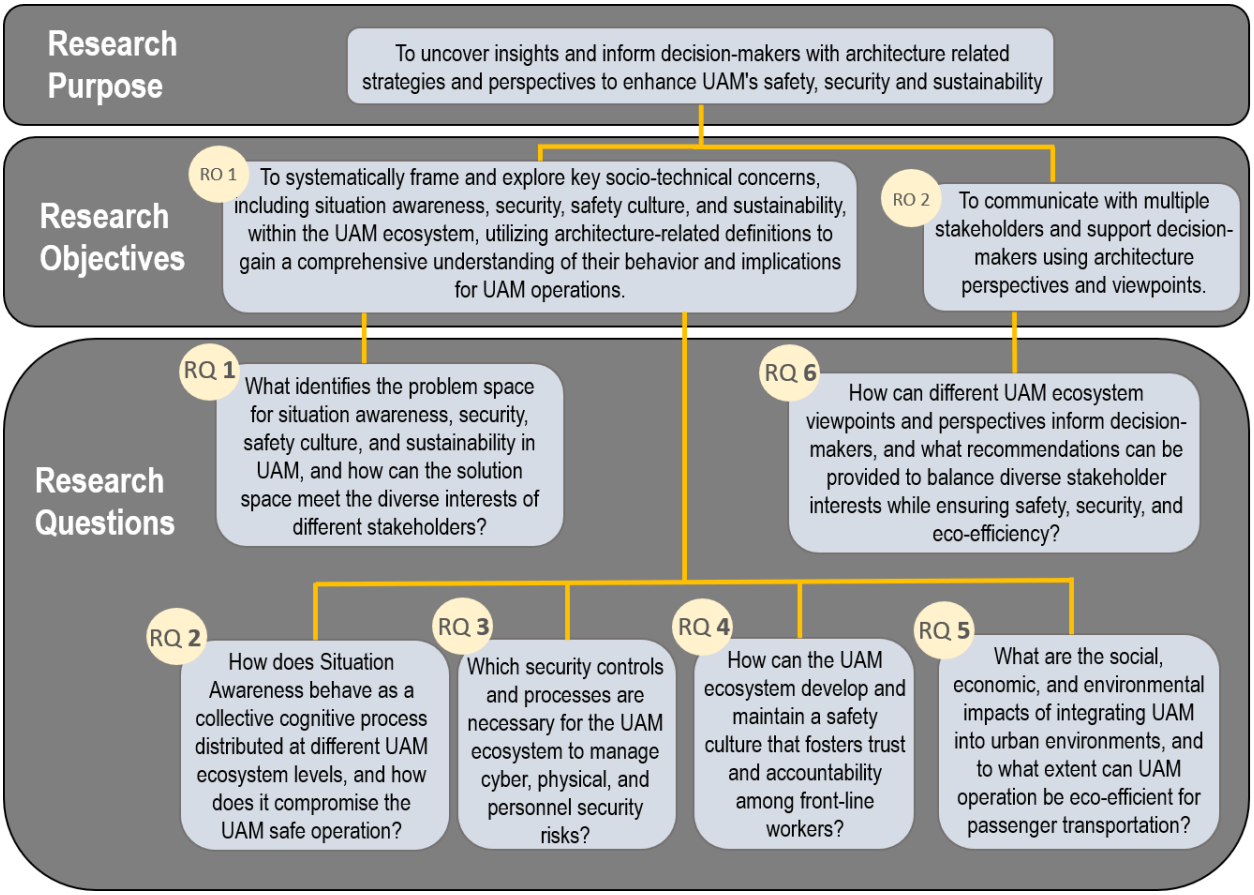

Figure 1.2: Research Purpose, Objectives, and Questions

In the following Chapters, the dissertation will investigate these research questions, exploring the intricacies of the UAM ecosystem and seeking to provide valuable insights for its sustainable integration into urban spaces.

1.6 Research Methods and Resources

To address the first research objective – "To systematically frame UAM socio-technical concerns" – and to answer questions RQ1 to RQ5, the research employs literature review and enterprise architecture (EA) processes as core methods. The initial step involves a comprehensive review of existing literature, including theoretical foundations and available data on general aviation and urban mobility, to identify relevant insights that can be reflected in the UAM context. This review helps to understand the problem space for each concern covered in this study by drawing on established knowledge and evidence.

Building on this foundation, the socio-technical systems approach comprehends complex systems by examining the interaction between people, technology, and organizational structures. Complementing the socio-technical approach is the application of EA principles, which provide a structured framework for analyzing and designing the UAM SoS. These principles ensure that all aspects of the ecosystem are considered, from operational processes to technological infrastructure and regulatory requirements to human factors. By applying EA processes and considering the socio-technical systems theory, we can create comprehensive models that capture the complexity of UAM and provide a clear blueprint for addressing its socio-technical concerns.

The effectiveness of the research method depends on the quality of the resources available. To frame UAM's socio-technical concerns, the research relies on the literature as a primary resource. To be more specific, relevant theoretical foundations (related to each concern), the UAM Concept of Operation (ConOps) released by industry and government entities, and existing findings about general aviation and urban mobility are also used.

UAM is not an actual operation at the present date. Therefore, the UAM ConOps (FAA, 2020; Air Service Australia & Embraer, 2020; FAA, 2022) is the leading operational data resource. Understanding the UAM ConOps is vital to comprehend the mission principles and operational complexity of UAM systems. This resource serves as the schema for future UAM functions, including aspects such as airspace management, vehicle characteristics, and urban integration.

Data from existing operations complete the primary resources in terms of information input. As a well-established industry, commercial and general (non-military, non-commercial) aviation provides a wealth of historical data and lessons learned that can be applied to the nascent UAM

sector. This data includes operational procedures, safety standards, accident reports, and system performance from traditional aviation. It offers a valuable foundation for assessing the safety and security aspects of UAM systems and their socio-technical concerns. In addition, mobility in urban areas also provides valuable inputs to understand the specificity of implementing aerial services within cities. Data about routes, environment, accessibility, and passenger transportation services are essential to address future UAM challenges.

To achieve the second research objective – "To communicate with multiple stakeholders and support decision-makers using ecosystem perspectives and viewpoints" – and to answer RQ6, the research uses the EA modeling methodology (processes and model framework) and validation methods. In the research, EA processes are tailored to address the research problem using a comprehensive view of the UAM ecosystem and incorporating various stakeholders, technologies, processes, and regulations. This modeling approach provides a structured representation of the UAM landscape, facilitating communication and decision-making. Validation methods are used to improve the research model views' quality and assess effective communication with stakeholders and decision-makers, which involves engaging in meaningful discussions. The research explored dialogues with experts to present findings and perspectives. These discussions are crucial for validating the analyses and recommendations and gaining diverse insights and viewpoints.

It relies on two primary resources for effective communication and decision support: the Unified Architecture Framework (UAF) Version 1.2 and the modeling tool Magic System of Systems (SoS) Architect from Dassault Systems (Dassault Systems, 2022). UAF is a comprehensive modeling framework designed for system architecture. It provides a standardized way to represent and communicate complex systems, making it a valuable tool for Enterprise Architecture modeling. The Magic SoS Architect tool, enhanced with the UAF plug-in, was used to elaborate the UAM SoS model. This software empowers the research to create visual representations of the UAM ecosystem, fostering effective communication with stakeholders and decision-makers.

Finally, expert consultations were used as a resource. The work engaged experts from various domains, including modeling, systems engineering, UAM navigation, security, cybersecurity, safety management, accident investigation, green technologies, and commercial piloting. Their

insights and expertise are not just valuable but integral to validating models, enriching discussions, and accurately addressing the UAM ecosystem's complex socio-technical concerns.

Figure 1.3 illustrates the relationship between methods and resources according to the research objectives. More details about the research methodology can be found in Chapter 3.

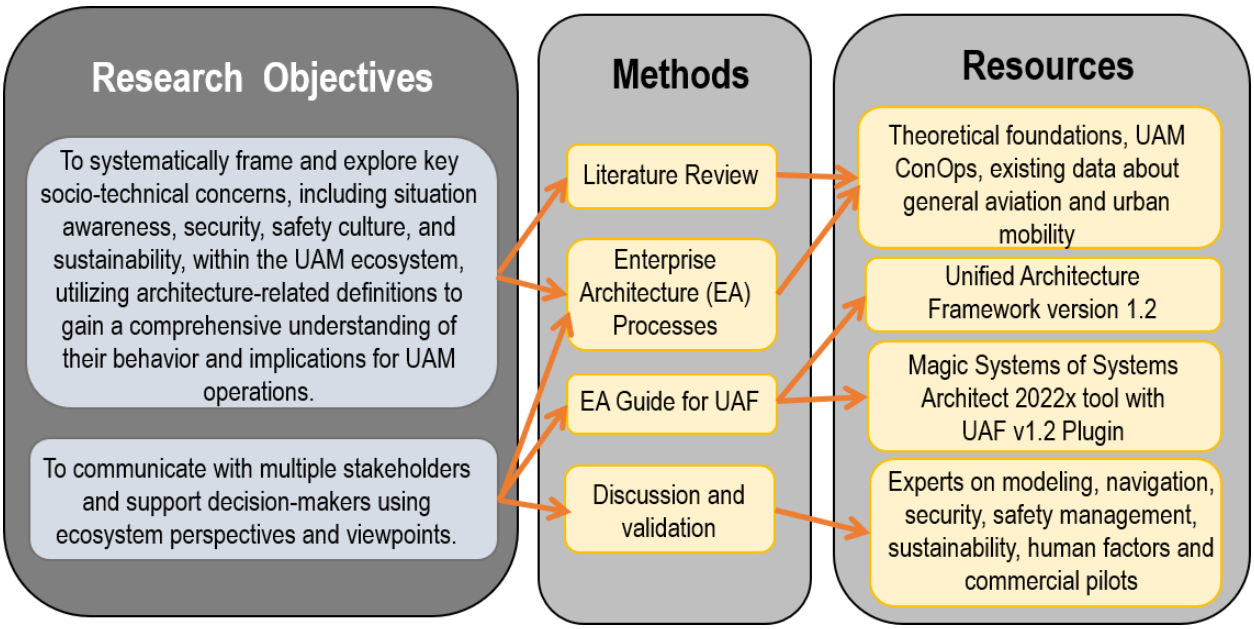

Figure 1.3: Research Objectives, Methods, and Resources

1.7 Research Contribution

This thesis contributes to the understanding of UAM by providing enterprise architecture views with multiple perspectives to address the research objectives. The contribution can be characterized into three main types:

1. Comprehensive Analysis: For all the socio-technical concerns included in this research, it is performed a comprehensive analysis of the UAM ecosystem by integrating various agents, including technological, regulatory, environmental, and human aspects;
2. Impact Assessment and Recommendations: For the socio-technical concerns included in this research, a thorough examination of their impacts was conducted, focusing on different dimensions based on each concern's specific nature. The operational, environmental, cultural, and social impact analysis was performed at different moments to craft the

solution according to the problem addressed. Human integration was placed at the core of the research, addressing various human-related aspects across all concerns. This included understanding human limitations in the SA problem, engaging operators in security processes, analyzing organizational culture in the context of safety management, and exploring how passengers and society can benefit from sustainable UAM practices. Strategies and recommendations were proposed to enhance safety, security, and sustainability, drawing from the insights gained through the research;

3. Stakeholder Engagement: For all the socio-technical concerns included in this research, views, and perspectives were developed that facilitate meaningful engagement with diverse stakeholders, fostering a more inclusive and informed discourse on UAM.

1.7.1 Research Originality

Unlike many studies that concentrate on isolated aspects of UAM, this research takes a systemic approach by integrating a diverse range of socio-technical concerns, including elements of the operational, regulatory, environmental, and human systems integration dimensions. This comprehensive integration ensures the analysis transcends individual domains, offering a SoS perspective on UAM. By integrating and coordinating architectural views to address different challenges, this research provides a broader and more comprehensive analysis than other studies (See 2.7 for more information about the literature gap).

Furthermore, diagrams, modeling structures, and enterprise-level perspectives offer a clear and structured visualization of the findings, making the human-centered analysis more accessible and understandable. This visual approach, coupled with a focus on practical applications, distinguishes this research from more abstract or purely theoretical studies.

In summary, this analysis sets itself apart by delivering a comprehensive, human-centered, and transdisciplinary approach that addresses multiple socio-technical concerns, fosters stakeholder engagement, and contributes both theoretically and practically through advanced systems engineering and enterprise architecture modeling.

1.7.2 Research Contribution Organization

The research contribution can also be classified into pragmatic and well-defined outcomes. For each research question listed in 1.5, the knowledge contribution (numbers 1 to 6) is mapped in this

dissertation structure and academic publications. Figure 1.4 correlates the RQ1 to 6 into knowledge contributions (1 to 6) and locations of those findings.

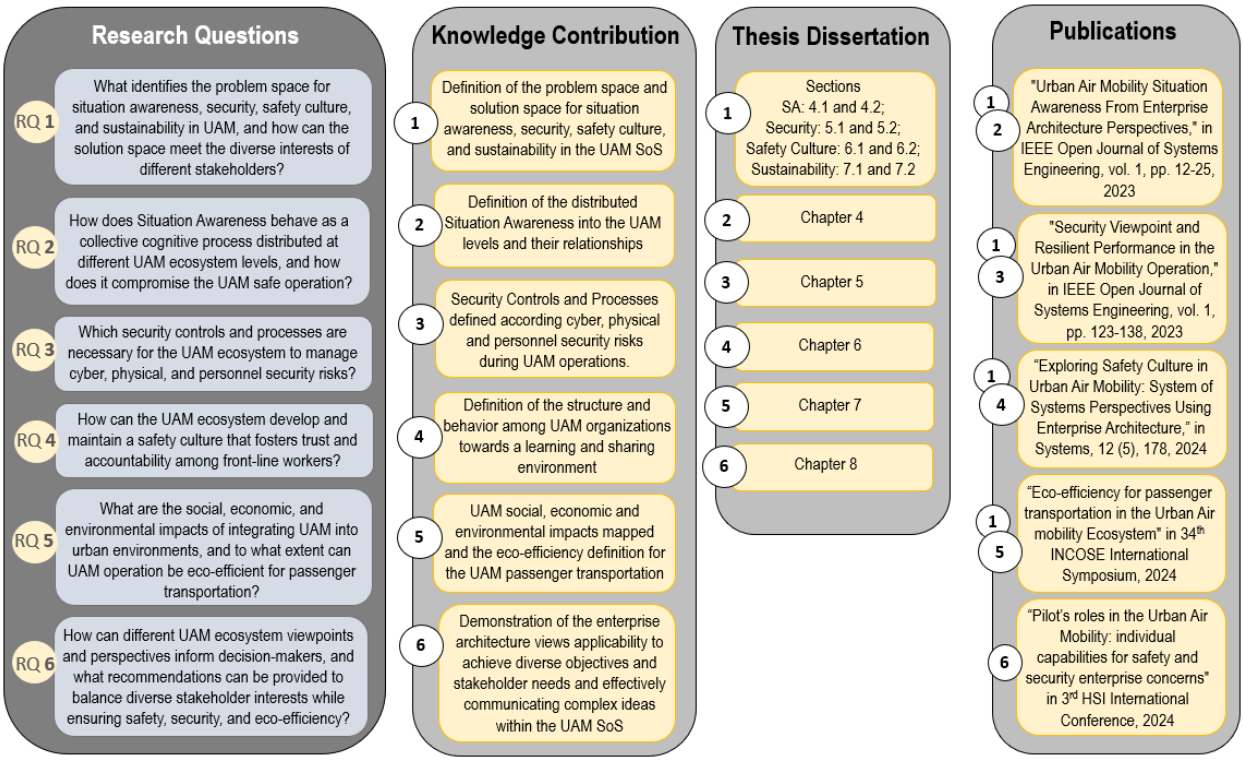

Figure 1.4: Research Knowledge Contribution and Related Publication

A collection of diagrams and modeling structures is part of the research contribution. SoS modeling is a concept within the Systems Engineering (SE) field, but it often extends beyond the traditional boundaries of SE. It can be considered a transdisciplinary topic because it involves integrating and coordinating multiple complex systems to achieve a common goal (INCOSE, 2023). Exploring complex systems with enterprise architecture models can contribute to the state of the art of systems engineering, complex systems science, and interdisciplinary research. Moreover, since UAM is the operational subject of this research, practical views and operational recommendations are valuable for the stakeholders.

In this sense, knowledge contribution #6 results from all architecture elaboration and visualization from Chapters 4 to 7 and is summarized in Chapter 8. In addition, a dedicated and individual perspective was elaborated upon, considering the enterprise-level concerns. The pilot's roles and capability elaboration extend the work done at the SoS level, shifting the perspective while

maintaining coherence and consistency. This work has been published and is presented in APPENDIX A.

1.7.3 Academic Publications

In this thesis dissertation, all results and findings, including model representations, will be presented. The research also includes other academic publications used to fulfill the requirements for the Systems Engineering PhD degree. These publications are structured around socio-technical concerns and are represented in model viewpoints. The complete information on all publications is below:

1. R. Hoffmann, H. Nishimura and R. Latini, "Urban Air Mobility Situation Awareness from Enterprise Architecture Perspectives," in *IEEE Open Journal of Systems Engineering*, vol. 1, pp. 12-25, 2023, doi: 10.1109/OJSE.2023.3252012;
2. R. Hoffmann, D. Pereira and H. Nishimura, "Security Viewpoint and Resilient Performance in the Urban Air Mobility Operation," in *IEEE Open Journal of Systems Engineering*, vol. 1, pp. 60-76, 2023, doi: 10.1109/OJSE.2023.3327524;
3. R. Hoffmann, H. Nishimura and P. Gomes, "Exploring Safety Culture in Urban Air Mobility: System of Systems Perspectives Using Enterprise Architecture," *Systems* 2024, 12 (5), 178, doi: 10.3390/systems12050178;
4. R. Hoffmann, F. Silva and H. Nishimura, "Evaluating the Eco-Efficiency of Urban Air Mobility: Understanding Environmental and Social Impacts for Informed Passenger Choices," in *34th Annual INCOSE International Symposium*; 34 (1), pp. 967-984, doi: 10.1002/iis2.13189
5. R. Hoffmann, H. Nishimura, and R. Calhau, "Pilot's roles in the Urban Air Mobility: individual capabilities for safety and security enterprise concerns," in *3rd Human System Integration (HIS) International Conference*, 2024.

1.8 Research Limitations and Delimitations

While aiming to contribute significantly to the understanding and development of UAM with a socio-technical perspective, this research has limitations and delimitations. Acknowledging these

boundaries and potential constraints is essential to provide a transparent and honest assessment of the research.

1.8.1 Limitations

Limitations refer to external factors or constraints that affect the research process and may compromise the study's validity or generalizability. The prominent limitation is the reliance on modeling, which inherently simplifies the complex UAM ecosystem. Models are abstractions that may not fully represent the reality of UAM operations. Therefore, the findings should be interpreted as insights and approximations rather than absolute truths. Still on the modeling subject, the research uses the UAF. Like any modeling framework, the results are subject to the assumptions and simplifications inherent in the chosen resource. Moreover, the UAF has a metamodel (ISO/IEC, 2022) with a defined ontology and semantics. Although the architect has some freedom to create elements, views, and relationships, most of the modeling effort follows the established rules in the language specification and guides (OMG, 2022a; OMG, 2022b).

Complexity is another aspect that brings limitations. UAM is a complex and evolving SoS. Despite efforts to explore it holistically, the dynamic nature of UAM may result in some aspects being beyond the scope of this research. On top of a complex ecosystem, UAM is a *conceptual* operation. Data availability relies on conceptual studies and proposals for an imagined future. There is no actual data, only extrapolations and reasonable assumptions. The quality and availability of data related to UAM, especially in security, safety, and sustainability, can result in limitations. The research may rely on existing data sources with their own limitations or gaps.

Moreover, there are interdisciplinary challenges. Integrating multiple disciplines, methods, and subjects, as this research does, can be challenging. The interdisciplinary approach might introduce complexities that require trade-offs in depth and breadth. Since the ecosystem perspective proposes a *whole visualization*, there are more perspectives than those developed by this research.

Finally, the validation of architectural views and definitions is limited by the scope and diversity of stakeholder involvement. Since only a subset of the broader UAM community was engaged, the validation reflects these participants' specific experiences and expertise, potentially overlooking broader perspectives. This limitation affects the comprehensiveness of the validation process,

particularly in capturing the full range of interdisciplinary and emerging viewpoints within the UAM ecosystem. As a result, the findings should be seen as a valuable but partial contribution to the ongoing development of UAM architectures.

1.8.2 Delimitations

Delimitations, on the other hand, are the deliberate choices made by researchers to establish the boundaries and parameters of their study, ensuring it remains manageable and focused. The first boundary in the research's scope is temporal. The research primarily focuses on the present and near-future state of UAM. Notably, air transportation was considered via an eVTOL vehicle with a pilot onboard. Also, the scope focuses on passenger transportation with on-demand or scheduled flights. The research context does not attempt to predict or address issues beyond a certain timeframe, as the UAM landscape may evolve considerably in the long term.

Regarding geographic aspects, the study centers on UAM in urban settings and may not fully encompass the unique challenges and opportunities of UAM in rural or less densely populated regions. The contribution aims to be as agnostic as possible without focusing on a specific city or route. However, it is important to mention that the UAM operation will heavily depend on the local environment, such as urban topography, weather, community, and local regulation.

Moreover, vehicle design and project definitions of a real location and operation were not considered to maintain a broader applicability of the findings. This approach allows the research to focus on generalized principles and frameworks that can be adapted to various contexts rather than being constrained by the specifics of a single case study. By not limiting the study to a particular geographic location, operational scenario, or vehicle design, the research aims to develop flexible insights and recommendations that can be applied across different UAM environments. This choice ensures that the conclusions drawn are relevant for strategic decisions and also adaptable to the evolving landscape of urban air mobility, where different cities, technologies, and operational models may present unique challenges and opportunities.

The research does not encompass an exhaustive analysis of the regulatory landscape. The UAM regulatory dynamics are currently a complicated matter in the international community, and there is still no clear understanding and agreement for operational details. The research recognizes the regulation authority as a crucial agent to most of the analysis, but operational requirements for

certification are not discussed. Instead, it offers a broad understanding of how regulations intersect with socio-technical concerns in UAM and recommendations for a safer operation.

Consequently, this research intentionally does not address UAM governance as a SoS, a complex area requiring separate and specialized analysis. Exploring UAM governance would involve a detailed examination of coordination, control, and legal frameworks among independent systems, which falls beyond the scope and expertise of this study.

Despite these limitations and delimitations, the research aims to make valuable contributions to the UAM field by exploring its complexities, emphasizing socio-technical concerns, and utilizing an integrated systemic approach. The insights gained are expected to provide a foundation for further research and facilitate the development of safer, more secure, and sustainable UAM systems.

1.9 Structure of the Thesis

Chapter 1, Introduction, provides an overview of the research context, problem analysis, research objectives, questions, methods, resources, contributions, limitations, delimitations, and the thesis structure. Chapter 2, Literature Review, presents the literature relevant to UAM, evaluating work related to UAM ConOps, situation awareness, security, safety culture, and sustainability. It identifies gaps in current knowledge and provides theoretical foundations on multiple topics involved in the research. Chapter 3, Research Methods used for UAM as a SoS, describes the research methodology, including the rationale for the methods applied, the foundations and principles substantiating the methodology, the standards and processes used during the study, the modeling framework, validation methods, and the model strategy used to develop the research results. The EA processes described in Chapter 3 are employed and referenced in each of the results' Chapters. Similarly, the UAF metamodel presented in the methodology is the base for the architecture visualization presented in the results. In addition, validation methods at the end of Chapter 3 are explained and tailored with contextual information for each concern presented in the results Chapters.

Results are presented in Chapter 4 to Chapter 8. Chapter 4 Situation Awareness Concern in the UAM SoS, presents the results of the architecture conceptualization and elaboration addressing

UAM SoS's concerns regarding situation awareness, including UAM enterprise views and key findings from the analysis. The results of this chapter have also been published in the IEEE Open Journal of Systems Engineering (Hoffmann et al., 2023a). Chapter 5, Security Concern in the UAM SoS, details the architecture conceptualization and elaboration addressing UAM security concerns, considering UAM cyber and physical security threats and including UAM enterprise views and key findings from the analysis. The results of this chapter have also been published in the IEEE Open Journal of Systems Engineering (Hoffmann et al., 2023b). Chapter 6 Safety Culture Concern in the UAM SoS, discusses the architecture conceptualization and elaboration addressing UAM safety culture concerns, considering UAM safety management perspectives and including UAM enterprise views and findings from the analysis. The results of this chapter have also been published in the Systems Journal (Hoffmann et al., 2024a). Chapter 7, Sustainability Concern in the UAM SoS, elaborates on the architecture conceptualization and elaboration addressing UAM sustainability concerns, considering UAM's environmental and social impacts and including UAM enterprise views and critical findings from the analysis. Most of the results in this chapter have also been published in the INCOSE International Symposium (Hoffmann et al., 2024b).

Finally, Chapter 8, Conclusion, discusses the results and stakeholder engagement in each concern, highlights the contribution of EA visualization with different enterprise viewpoints and perspectives, summarizes answers to each research question, and provides recommendations for future work in the field of UAM. Findings and views of Chapters 4 to 7 are inputs of the conclusion.

APPENDIX A presents the results of the UAM pilot's perspective when addressing enterprise-level concerns. The content of this section was published at the INCOSE Human System Integration Conference (Hoffmann et al., 2024c) and reinforces the argument presented in section 8.1 by illustrating the utility of using EA views from different perspectives.

Figure 1.5 shows the sections and their relationships in presenting the research. The diagram intends to help the reader understand the thesis structure. The activities during the research were not sequential. Multiple iterations and updates to the analysis and findings were performed. Therefore, sequential flow (dotted lines) represents the order in which Chapters and sections are presented in this document. The input and output of parts are equally representative. Not all relationships are depicted in the activity diagram, but only the relevant ones. Although the original intention of this diagram was to conceptualize the thesis structure, it was immensely useful for the

author’s mental visualization of the thesis. It also supported the consistency between sections and information.

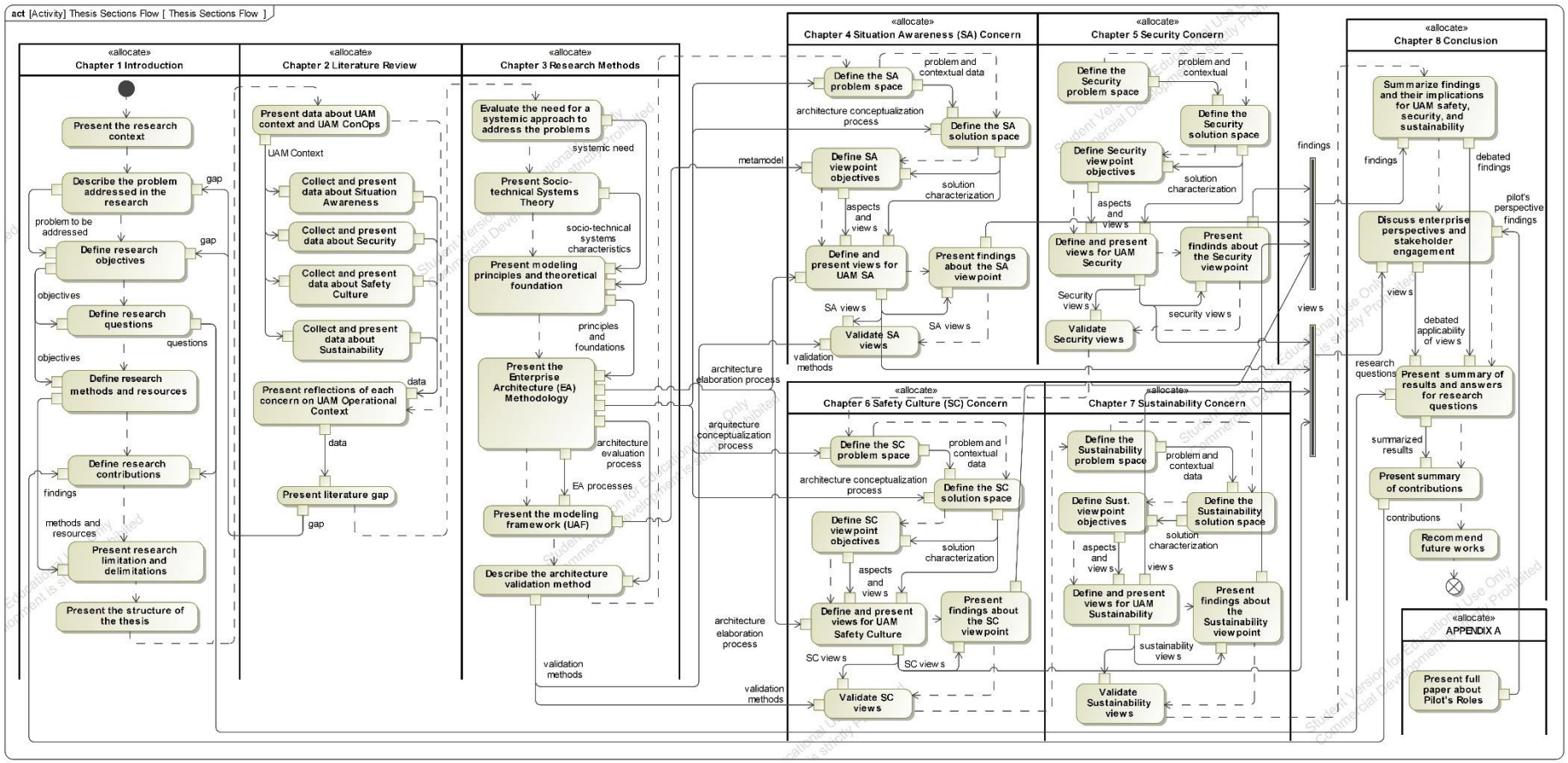

Figure 1.5: Thesis Section Flow

CHAPTER 2

Literature Review

This chapter aims to collect relevant data about the topics covered by the research. It starts with describing the context of the research and the problems raised by previous works. How researchers approached those problems is also meaningful for the methods proposed in this dissertation. Ultimately, this section aims to identify important unanswered questions in the research field. This chapter is divided into seven subsections to help readers understand the dissertation research. The introduction explains the literature review's scenario and the author's chosen path. Then, the narrative unfolds with the presentation of pertinent data concerning the UAM Concept of Operations, Situation Awareness, Security, Safety Culture, and Sustainability. Lastly, key ideas are synthesized, and the existing literature gap is presented.

2.1Introduction

The emergence of UAM represents a conceptual frontier in urban transportation, with most existing research being inherently theoretical and exploratory. Given the nascent stage of UAM development, much of the literature draws from analogous operations in aviation, urban planning, and other existing enabling systems. As UAM is mainly aspirational at this point, the body of work surrounding it is anticipatory and relies on parallels with established sectors. This literature review, therefore, delves into the concept of operations theoretical foundations and exploratory insights related to UAM, emphasizing the conceptual nature of the technology and its alignment with established frameworks in aviation, urban planning, and other pertinent domains. By analyzing this theoretical landscape, the review aims to provide a foundational understanding of UAM's socio-technical considerations, acknowledging the speculative nature of current discourse and its

reliance on analogous systems to envision the potential implications and challenges of UAM operations.

The topics explored in this research include knowledge from safety, human factors, security, resilience, and sustainability disciplines. Integrating knowledge and methods from different disciplines, using a real synthesis of approaches, makes this study an interdisciplinary endeavor. The abstraction level of the ecosystem perspective is intentional in exploring the comprehensiveness of the research problem. Socio-technical concerns often cross the different layers of the ecosystem. Understanding each of the concerns requires investigating behaviors in different abstraction levels.

The literature review was organized following the research method. Different viewpoints are being proposed as a framed way of visualizing each concern. Hence, the literature review effort first started with understanding the operational context of UAM and then four dedicated steps to investigate each topic. The topics presented below represent the chronological order in which the research happened. The author chose the topics according to personal interests. Although there is one viewpoint to each concern, the topics are not separated nor independent. Safety, security, and sustainability often converge into common goals. Likewise, the literature review demonstrated that previous work has explored similar topics, overlaying some concepts from different issues.

The following sections present the narrative literature review performed in the research. It aims to identify key ideas, challenges, debates, and gaps in the literature. Scientific databases, including Scopus, IEEE Xplore, ACM Digital Library, Elsevier, and Google Scholar, were used to find relevant literature. Industry material like white papers and commercial and operational data about UAM were also used when publicly available. Governmental and regulatory data often result from multidisciplinary work and are good sources for UAM as an ecosystem. This is the case with the Concept of Operations (ConOps) released by NASA (NASA, 2021), FAA (FAA, 2020; FAA, 2023), JAXA (JAXA, 2023), UBER (UBER Elevate, 2016) and EmbraerX (Air Service Australia & Embraer, 2020), as described below.

2.2 Literature Review on UAM Concept of Operations

The advent of UAM represents a transformative shift in the way we envision transportation systems within urban areas. UAM transportation emerged as a potential solution to alleviate congestion, reduce travel times, and offer a more sustainable and efficient mode of transportation. However, the implementation and operation of UAM systems introduce a new layer of complexity to urban environments, with multifaceted implications for safety, security, public perception, and the overall urban landscape.

Before going into more details about UAM, it is worth naming a broader notion used by NASA, FAA, JAXA, and others (FAA, 2020; Air Service Australia & Embraer, 2020; FAA, 2022; JAXA, 2023; NASA, 2023): Advanced Air Mobility (AAM). It represents a spectrum of innovative and technological advancements in aviation, such as electric aircraft, increasingly automated operations, and enhanced airspace management. The UAM is a subset of AAM, explicitly focusing on air-taxi services within densely populated cities and their outskirts (NASA, 2023). The European Union Aviation Safety Agency (EASA) defined the terms Innovative Air Mobility (IAM) and Innovative Aerial Services (IAS) (EASA, 2024). They are similar to the AAM concept and envision the safe, secure, and sustainable air mobility of passengers and cargo enabled by new-generation technologies integrated into a multimodal transportation system.

This subsection aims to collect and present information about the UAM operation relevant to the concerns explored in this work. The systemic approach adopted in this research aims to connect and contextualize systems, systems elements, and environments to understand the complexity of UAM socio-technical concerns. System context describes the system relationships and environment resolved around a selected system-of-interest (SoI) (Flood & Carson, 1993). Operational contextual data provides a comprehensive view of the environment in which a problem exists. The characteristics of the UAM ecosystem, such as operational distribution, geographical information, socio-economic conditions, regulatory frameworks, technological capabilities, stakeholder dynamics, and future stages, partially define the operational contextual information.

Moreover, understanding the UAM operational landscape is crucial for developing targeted solutions that address the core challenges, not just the symptoms. By collecting and examining the data, underlying factors, contributing variables, and systemic issues that may influence socio-

technical concerns can be perceived. In addition, having the whole operational picture facilitates the stakeholder's identification. Consequently, problem and solution analysis can be more meaningful for stakeholder engagement and collaboration. By sharing relevant data and insights, stakeholders can participate in problem definition, contribute diverse perspectives, and co-create solutions. Lastly, understanding the problem's operational implications helps formulate strategies that mitigate risks and maximize positive outcomes. In summary, operational contextual data is crucial for understanding a problem comprehensively, identifying root causes, assessing impacts, engaging stakeholders, and refining problem definitions iteratively. It provides the foundational knowledge and insights needed to define problem spaces accurately and develop informed strategies for effective problem-solving.

UAM operation has not entered into service yet. Therefore, operational data for UAM is formed by conceptual frameworks, preliminary regulatory definitions, and projected operational scenarios. Information about the operating environment, including air traffic (and airspace), ground infrastructure, flight conditions, terrain features, and aircraft, is crucial to understanding the UAM ecosystem. Although most of the conceptual definitions of UAM are confluent among governmental and regulatory bodies, there are some differences in taxonomy and terms. Similarities and differences among different locations and UAM concepts have been evaluated by Wiedemann et al. (2024).

Following is an overview of the UAM use cases, airspace definitions, operational definitions, ground infrastructure, traffic management, aircraft types, phases, and UAM system actors.

2.2.1 Use cases definition

A use case for UAM refers to a specific scenario or situation in which UAM technology and services are utilized to address transportation needs within urban areas. These use cases typically highlight the practical applications and benefits of UAM systems, showcasing how they can improve mobility, efficiency, and accessibility in urban environments. Examples of UAM use cases extracted from JAXA ConOps (JAXA, 2023), pages 9-10, are divided into two categories:

A. Passenger Carrying

- Airport Shuttle: Providing transportation services for passengers to and from airports, facilitating their onward journey.

- Intra-Urban: Catering to passenger transportation needs within urban areas.
- Suburban Routes: Connecting urban centers with suburban or remote areas for passenger transport.
- Entertainment and Tourism: Offering excursion flights around recreational facilities and tourist destinations.
- Routes Connecting Remote Islands or Mountainous Areas: Connecting passengers between remote islands and the mainland, among islands, and between mountainous and urban regions.
- Emergency Medical Transport (EMT): Transporting doctors and patients for emergencies during disasters or sudden illnesses over urban and rural areas.

B. Cargo Transport

- Emergency Transport of Goods: Transporting essential goods in the event of a disaster.
- Inter-Facilities: Conveying goods or products between facilities owned by a company or organization.
- Cargo Delivery (Sea and Mountainous Areas): Transporting cargo across sea routes and within mountainous regions, including remote medical care.
- Cargo Delivery (Urban Areas): Transporting cargo within urban areas.

In addition to the mentioned scenarios, AAM is anticipated to encompass use cases where companies independently introduce and use these services for their specific needs. Furthermore, there is a vision for private ownership and individual utilization for personal purposes in the future.

The NASA whitepaper (Doo et al., 2021) also explored more UAM use cases. Different use cases are described to identify areas of potential interdisciplinary collaborations. For instance, fighting wildfires, logistics of natural disasters and humanitarian crises, law enforcement, and public safety. Each use case involves different considerations: infrastructure requirements, regulatory aspects, passenger safety, environmental impacts, and economic feasibility. UAM stakeholders, including industry players, regulators, city planners, and communities, collaborate to develop and implement use cases that demonstrate the value and potential of UAM technology in addressing urban transportation challenges.

For this research, the use case considered from the ecosystem viewpoint is *passenger transportation*. There are no specifics concerning types of passenger-carrying modes nor the reason why people are being transported. The rationale behind this research definition is the critical aspect of safety that passenger transportation means for UAM operations and services. Commercial aviation transporting passengers is the highest safety standard required by regulatory bodies. Protecting the public (passenger and non-passenger) is a priority of safety programs from FAA, ICAO, EASA, and others.

2.2.2 Airspace definitions

The International Civil Aviation Organization (ICAO) defined in 1990 the current airspace classification scheme (IATA, 2014). These classes are primarily defined based on flight rules and the interactions between aircraft and air traffic control (ATC). In essence, the ICAO airspaces allocate the responsibility for avoiding other aircraft either to ATC (if separation is provided) or the aircraft commander (if not).

Classes A to E are categorized as controlled airspace, while Classes F and G are deemed uncontrolled airspace. Additionally, there are special airspaces that impose restrictions on pilot operations in certain areas, such as Prohibited areas, Restricted areas, Warning Areas, MOAs (military operation areas), Alert areas, and Controlled firing areas (CFAs), all identified on flight charts.

Each class has rules and definitions regarding airspace separation, clearance authorization, traffic information, and flight rules. Aircraft may operate under visual flight rules (VFR) or instrument flight rules (IFR), with an intermediate form known as special visual flight rules (SVFR). When conducting operations in the airspace, a UAM aircraft will comply with the Air Traffic Services (ATS) requirements of the applicable airspace class. NASA (2023) assumes that UAM operations will be conducted in all classes of airspace except Class A (only instrumented flight is allowed in this class). The FAA (2023) provides some UAM scenarios to depict future UAM operations using corridors and flights within airspace class B.

2.2.3 Operational definitions and Interoperability

The most recent UAM ConOps released by the FAA, 2023, expects that in the initial UAM operations, new aircraft types will be certified to fly within the current regulatory and operational

environment. In other words, UAM aircraft will need to comply with applicable air traffic regulations regarding VFR and IFR while operating in either Visual Meteorological Conditions (VMC) or Instrument Meteorological Conditions (IMC), like any current air operation. Consistent with today's operations, the UAM operation will be subject to the flight's environmental conditions.

In the future, with a higher frequency (i.e., tempo) of UAM operations, airspace regulation will evolve and use UAM-dedicated corridors through collaborative technologies and techniques. In ground-level terms, UAM aircraft are expected to use UAM corridors situated above 400 feet, maintaining a typical cruising altitude ranging from 1,500 to 4,000 feet above ground level (AGL) (FAA, 2020; Air Service Australia & Embraer, 2020). Other airspace users, like drones or Unmanned Aircraft Systems (UAS), are expected to share the low-altitude airspace.

Figure 2.1 represents the operating environment regarding other aerial vehicles, airspace classes, and UAM corridors (according to FAA). In low-altitude space where UAM will share with other vehicles like UAS, it is expected to be controlled by Unmanned Traffic Management (UTM). In the US, this area is below 400 feet (FAA, 2020), and in Korea and Japan (JAXA, 2023) is 500 feet. The interoperability details can vary slightly among regulatory bodies and locations, but all concepts of operations foresee interactions with UAS operations.

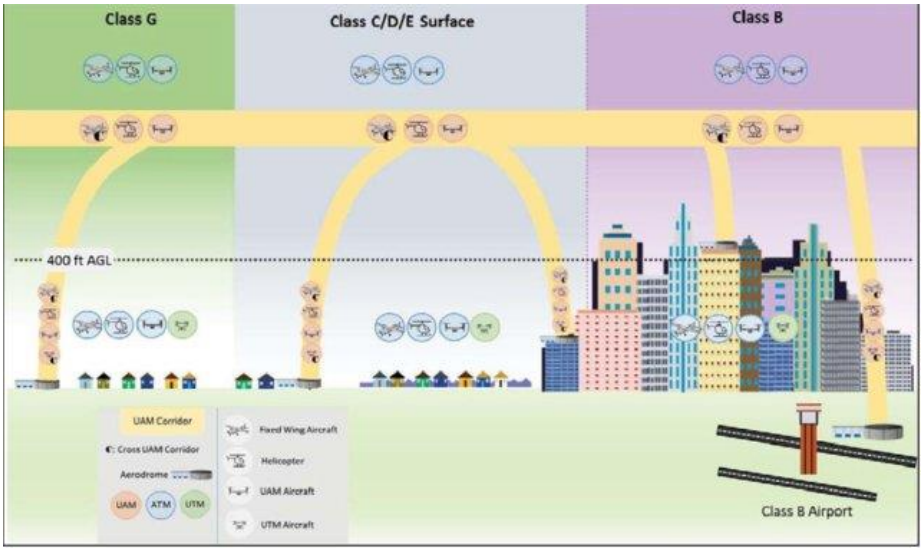

Figure 2.1: UAM Operating environment according to FAA ConOps (FAA, 2022)

Next, to follow the increased operational tempos, new operational rules and infrastructure with highly automated management systems will enable remotely piloted and autonomous aircraft to operate safely. More information about future phases of UAM is described in 2.2.7.

2.2.4 Ground infrastructure

The ground infrastructure for UAM encompasses a range of considerations to support the safe, efficient, and scalable operation of UAM vehicles within urban and suburban environments. There are four main elements to consider about UAM ground infrastructure: take-off and landing areas, UAM vehicle maintenance and charging areas, ground control and communication systems, and integration with ground transportation.

Vertiports (also named UAM aerodrome, skyports, or vertistops) serve as essential infrastructure for UAM vehicles to take off, land, and conduct passenger boarding and disembarkation. These facilities may be located on rooftops, in urban centers, near transportation hubs, or strategically within communities to facilitate seamless integration into the transportation network (Uber Elevate, 2016; Air Service Australia & Embraer, 2020).

UAM vehicles, especially electrically powered ones, require reliable and accessible charging or refueling infrastructure. Charging stations equipped with fast-charging capabilities and renewable energy sources can support the rapid turnaround of UAM operations and promote sustainability (Air Service Australia & Embraer, 2020). Similarly, dedicated maintenance and service centers are crucial for inspecting, maintaining, and repairing UAM vehicles. These centers ensure the airworthiness and reliability of UAM fleets with skilled technicians, spare parts inventory, and advanced diagnostic equipment (Hill et al., 2020; Uber Elevate, 2016).

Ground control stations with advanced communication systems enable real-time monitoring, command, and control of UAM operations. These systems facilitate airspace management, route planning, weather monitoring, collision avoidance, and emergency response coordination (NASA, 2023; Hill et al., 2020). Urban Air Traffic Management (UATM) systems and Unmanned Traffic Management (UTM) services are integral for managing UAM traffic. More information about UATM and UTM is presented in 2.2.5.

Integrating UAM services with existing public transportation networks, such as rail, bus, and metro systems, enhances passengers' connectivity and multimodal mobility options. Seamless

intermodal transitions, ticketing integration, and last-mile connectivity solutions contribute to a comprehensive urban transportation ecosystem (Hill et al., 2020). Metropolitan planning organizations, along with state and local governments, might integrate UAM infrastructure planning into broader transportation and utility planning initiatives to guarantee comprehensive coverage and sufficient capacity. FAA (2023) believes that engaging with communities and establishing strategic links to broader transportation planning endeavors are essential for optimizing the advantages offered by UAM services.

In summary, the UAM ground infrastructure relies on vertiport services and operations. Vertiport systems and services will provide maintenance, battery charging, aerodromes, ground mobility integration, and communication and control. Vertiport operators will control and manage their operations and define the services provided by their vertiports and to whom they are provided. The Vertiport Operator is responsible for ground safety, security such as access control, and supervision of charging and refueling. However, these responsibilities may be held by the AAM operator or other third party (JAXA, 2023). The vertiport operator will provide information regarding the operational status of the vertiport, including the availability of takeoff and landing strips, personnel, and charging facilities (Hill et al., 2020).

Lastly, Air Service Australia & Embraer (2020) states that "vertiport capacity will significantly affect the capacity of the overall UATM system." Moreover, JAXA (2023) considers that the capacity of a vertiport is highly dependent on the number of airfields (or vertipads), time of occupancy of the airfield (on arrival and departure), departure and arrival routes, and airspace requirements like noise reduction and special procedures. EASA (2022) published the first vertiport design guidelines and proposed requirements to meet the vertiport capacity expectations.

2.2.5 Traffic Management

Air traffic management (ATM) systems are needed to ensure safe separation, deconfliction with other airspace users, and compliance with airspace regulations (FAA, 2022). The current ATM system has been constructed to fulfill the needs of the existing airspace users. UAM operations will add operational challenges to managing air traffic. Urban terrain, obstacles, and radiofrequency can cause interference in Communication, Navigation, and Surveillance (CNS) systems. Plus, the UAM vehicles will be diversified in performance, automation, and pilot capability (Air Service Australia & Embraer, 2020).

Based on the foundational principles of ATM, a novel traffic management approach is necessary to effectively handle UAM traffic with safety, efficiency, reliability, and security. The UATM is part of the UAM ecosystem concept of operations and "is a collection of systems and services (including organizations, airspace structures, and procedures, environment, and technologies) that support the integrated operation of UAM vehicles in low-level airspace" (Air Service Australia & Embraer, 2020).

Initially, UAM aircraft are expected to operate within the requirements of the current ATM operating environment under existing procedures and standards. As the UAM industry matures, various aircraft with varying levels of automation (including piloted, partially automated, and fully autonomous operations) are expected to operate within low-level airspace. Increased density of operations, development of automation/autonomy, and the diversity of airspace users in the UATM Service Area (UASA) are expected to require additional capabilities to the current ATM system (JAXA, 2023).

The FAA envisions the introduction of a cooperative operating environment known as Extensible Traffic Management (xTM), which complements the traditional provision of Air Traffic Services (ATS) for future passenger or cargo-carrying operations and flights (FAA, 2023). In addition, a dedicated ConOps for Unmanned Aircraft System (UAS) Traffic Management (UTM) provides examples of how piloted UAM aircraft would interact with UAS (FAA, 2022).

There are differences in nomenclatures and details about UATM structure and services among existing ConOps. However, the evolutionary path and the need for new technologies and automation levels are a common approach (FAA, 2020; Air Service Australia & Embraer, 2020; FAA, 2023; JAXA, 2023). The integrated environment is also a key attribute to achieving a mature UATM. An information exchange service connecting ATM (existing systems), UTM (unmanned systems), and UATM (UAM systems) is necessary for Air Service Australia & Embraer (2020) and JAXA (2023). UATM Operator (or Provider of Services to UAM in NASA, 2023) is responsible for managing the provision of information services associated with airspace operations to the UAM Operator. In addition, the Communication Service Provider (CSP), Surveillance Service Provider (SSP), and the Meteorological Service Provider (MSP) are considered Supplemental data service providers (SDSP) and are essential services to support UATM (FAA, 2023).

2.2.6 Types of aircraft

Electric vertical take-off and landing (eVTOL) aircraft, utilizing distributed electric propulsion (DEP), sustainable energy sources, innovative aviation materials, artificial intelligence (AI), 5G networks, and other cutting-edge technologies, has emerged as a promising UAM vehicle. Unlike conventional aircraft, eVTOL relies on electric power for vertical take-off, hovering, and landing, making it ideally suited for on-demand, point-to-point transportation requirements within the Advanced Air Mobility (AAM) sector.

More than 150 companies are developing eVTOL vehicles (Doo et al., 2021), and there are more than 500 different models (Vertical Flight Society, n.d.). Below is a brief overview of different types of eVTOL configurations and their main operation characteristics.

A. **Multicopter:** Multicopters, or multirotors, are wingless aircraft. They operate by utilizing three or more electric-powered rotors that rotate around a nearly vertical axis, providing the main lift and propulsion. The rotation speed of each rotor blade generates thrust and counter-torque, influencing the aircraft's attitude based on factors like rotor positioning, rotation direction, and rotor pitch. However, the cruise phase of these aircraft is limited by high battery drainage, restricting them to short-distance journeys.
B. **Lift + Cruise**: The Lift + Cruise concept integrates multirotors for vertical take-off and landing, fixed wings for cruise, and propellers for thrust. During take-off and landing, multirotors create upward thrust, while in cruise mode, forward-facing propellers on the wings generate lift for level flight. This configuration enhances energy efficiency during cruise compared to traditional multirotor AAM aircraft, making it suitable for longer distances.
C. **Vectored Thrust**: In the Vectored Thrust concept, fixed wings support cruise, and a unified electric propulsion system serves both vertical take-off/landing and cruising. During take-off and landing, vertically positioned propellers generate lift, and during cruise, these propellers tilt to provide forward thrust, with additional lift generated by the wings. This design is well-suited for longer distances and has the potential for higher cruise speeds compared to other concepts.

Table 2.1 summarizes various existing designs suitable for Urban Air Mobility (UAM). Diverse configurations may be employed based on the specific mission, such as cargo transport versus passenger transport, leading to varying operational needs for each configuration.

Table 2.1: Sample of ongoing eVTOL designs extracted from the Vertical Flight Society (n.d.)

Aircraft (Manufacturer)	Configuration	Range	Capacity	Cruise Speed	Country	Entry into Service
EH-216 (Ehang)	Multicopter	35 Km	2 pax	100 km/h	China	2025
SKYDRIVE (SkyDrive)	Multicopter	15 Km	2 (+ pilot)	100 km/h	Japan	2026
Volocity (Volocopter)	Multicopter	65 Km	1 (+ pilot)	90 km/h	Germany	2024
Midnight (Archer)	Vectored Thrust	80 Km	4 (+ pilot)	241 km/h	USA	2025
VX4 (Vertical Aerospace)	Vectored Thrust	161 Km	4 (+ pilot)	241 km/h	UK	2025
Lilium Jet	Vectored Thrust	250 Km	5 (+ pilot)	250 km/h	Germany	2024
CityAirbus NextGen (Airbus)	Lift + Cruise	80 Km	3 (+ pilot)	120 km/h	France	2025
Eve (EmbraerX)	Lift + Cruise	96 Km	4 (+ pilot)	150 km/h	Brazil	2026
Cora (Wisk Aero)	Lift + Cruise	100 Km	2 pax	180 km/h	USA	Unknown

2.2.7 UAM Evolution Strategy and UAM Phases

Traditional urban transportation systems were primarily ground-based, but UAM introduced the dimension of airspace. Integrating these systems while ensuring safety and efficiency is complex (FAA, 2022). At the heart of the UAM challenge lies the delicate balance between fostering innovation and safeguarding the public's interests. The novelty of UAM introduces a level of uncertainty that requires careful analysis. Integrating aerial vehicles into urban environments demands robust systems, processes, and organizations, which raises the complexity level of UAM operations (Cohen et al., 2021).

"UAM implementation is an evolutionary developmental approach starting with low-complexity, low-operational tempo operations and building toward an environment of higher operational tempo and the introduction of UAM airspace structure to mitigate an otherwise higher level of complexity." This statement from FAA ConOps (FAA, 2020) expresses the strategy to deal with complexity in the UAM ecosystem and operations. The progressive approach to understanding and

planning for UAM implementation offers numerous benefits. Initially focusing on simpler operations (lower complexity), where technological demands and services are less strict, allows for a streamlined implementation using existing capabilities that meet performance standards without needing a complete regulatory and operational overhaul. UAM operations will evolve alongside new technologies and automation, both on the ground and in the air, fostering advanced interactions within the ATM environment through integrated systems capable of automated data exchange (FAA, 2020).

UAM operations will also accommodate diverse UAM demands, business models, applications, and technologies while ensuring safe, efficient, and secure operations that coexist harmoniously with other airspace activities (e.g., manned aircraft, UTM). This approach aims to minimize disruption to the existing ATM system and uphold fair and equitable airspace access (FAA, 2020). This concept will mature to encompass increasingly complex operations in heavily populated environments and more heavily utilized airspace. The second version of the FAA ConOps (FAA, 2023) provides more details about the initial UAM, midterm, and mature state operations.

Goodrich & Theodore (2021) described the NASA UAM framework according to maturity levels. Six UAM Maturity Levels (UML) are mapped into three states: initial, intermediate, and mature. The NASA UAM Coordination and Assessment Team (UCAT) was established to identify key obstacles related to vehicle technology, airspace integration, and community acceptance within the UAM ecosystem. Through collaboration with various stakeholders, such as civil aviation authorities, aircraft developers, operators, and academia, the UCAT developed the UAM maturity level (UML) scale. This framework categorizes the evolutionary phases expected in UAM transportation, envisioning a future where UAM becomes as ubiquitous as automobiles are today. The UML scale, primarily designed for passenger-carrying scenarios, outlines different technological and economic advancement levels required for UAM system progression. However, it acknowledges uncertainties and varying timelines for achieving higher maturity levels, emphasizing that actual progress may differ from projections due to evolving factors influencing UAM adoption.

Figure 2.2 depicts the framework and the UML scale. Aircraft, airspace, and community evolve according to the UAM states. The Airspace Research Roadmap of 2023 explored airspace

progression considering the maturity levels (NASA, 2023). More technical details and discussions for the UML-4 were proposed by Hill et al. (2020).

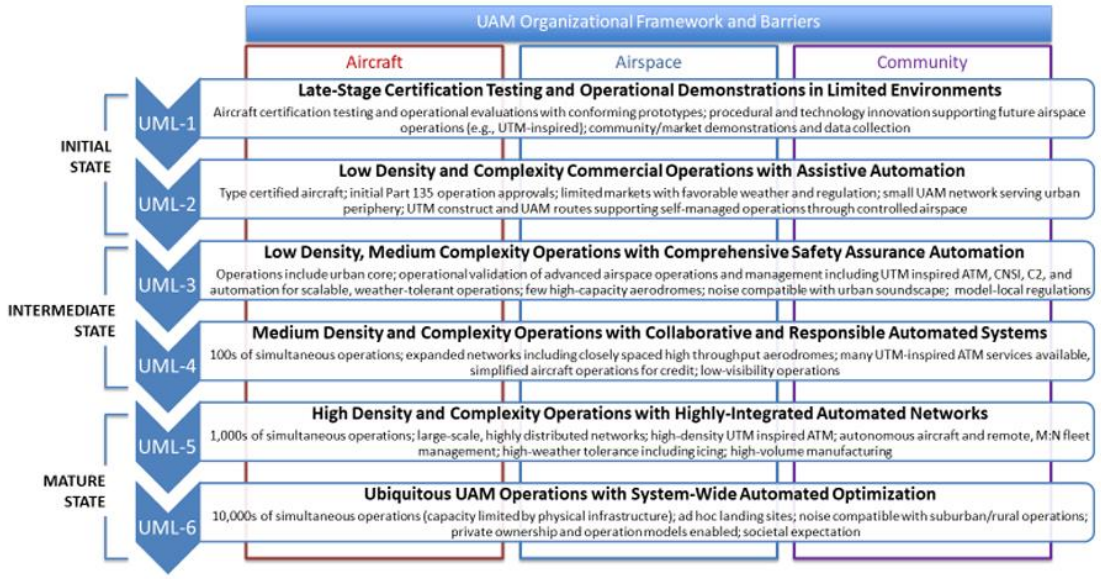

Figure 2.2: Description of UAM UMLs defined by NASA (Hill et al., 2020)

Air Service Australia & Embraer (2020) have similar considerations about the UAM evolution. Three horizons are proposed to express the maturity path according to operation demand and UTM evolution. Horizon 1 expects low-density operation and existing UTM capabilities, horizon 2 with medium-density operation and a mix of existing UTM and new UATM capabilities, and finally, horizon 3 with high-density operation and piloted and autonomous vehicles.

JAXA (2023) considers four phases to introduce the AAM operation according to the definitions of aviation authority (JCAB). Phase 0 (zero) will occur before the UAM commercial services in Japan, which will be dedicated to trials and proof-of-concept flights. Phase 1 is the initial introduction (low-density) of commercial operations with piloted and VRF flights. Phase 2 is medium to high-density operations with piloted flights (on board and remotely). Phase 3 is scaled up and high-density with autonomous operations.

In summary, the phased approach to UAM implementation, as described by various authorities and stakeholders, provides a structured roadmap to manage the complexities and challenges of urban air mobility. This evolutionary strategy, which begins with simpler, low-density operations and gradually progresses to more complex, high-density, and autonomous operations, allows for

incremental advancements in technology, regulatory frameworks, and public acceptance (FAA, 2020; FAA, 2023; Uber Elevate, 2016; Air Service Australia & Embraer, 2020; Doo et al., 2021; Hill et al., 2020). The roadmap to advance UAM operations in phases is necessary to coordinate different sectors that need discussion, analysis, preparation, development, and regulatory definitions (NASA, 2023; Hill et al., 2021). The complex landscape and the various challenges to advancing UAM affect multiple stakeholders. Thus, continuous collaboration among civil aviation authorities, industry stakeholders, and communities will be crucial to achieving their common goal: ensuring safe, efficient, and equitable integration of UAM into urban environments (FAA, 2022; Ribeiro et al., 2017; NASA, 2023; FAA, 2023; EASA, 2024; Uber Elevate, 2016; Air Service Australia & Embraer, 2020; Doo et al., 2021; Hill et al., 2020).

2.2.8 UAM as a System of System (SoS)

SoS is defined as "a set of systems or system elements that interact to provide unique capability that none of the constituent systems can accomplish on its own" (ISO/IEC/IEEE, 2019b). SoS is a concept increasingly used to understand and manage complex systems in various domains (Cook & Pratt, 2021) and, more specifically, to characterize the UAM ecosystem (NASA, 2023; Shivaprakasha et al., 2021). According to Maier (2018), an SoS can be identified by four foundational characteristics: Operational and managerial independence of the components, Geographical distribution, Emergent behavior, and evolutionary development. Table 2.2 describes the SoS characteristics (Maier, 2018) and their reflections on the UAM context (based on FAA, 2020 and Air Service Australia & Embraer, 2020).

Notes about Table 2.2: a) Maier originally proposed the term 'emergent behavior' in his foundational work on SoS. However, recent discussions have increasingly preferred the term 'unintended consequence,' particularly following contributions from systems thinking scholars like Donella Meadows (Meadows, 2008). This shift reflects a growing emphasis on understanding the behaviors that arise from complex system interactions and the unexpected and often unplanned outcomes that can result from these interactions. b) The characteristic "Operational and Managerial independence of the components" was divided into two lines to facilitate understanding the UAM as an SoS.

Table 2.2: SoS Characteristics in the UAM Context

System-of-Systems Characteristics	Description	UAM Context
Operational Independence of the Components	Each system within an SoS can operate independently and provide useful services even when detached from the larger system.	Various components, such as eVTOL vehicles, vertiports, air traffic management systems, and communication networks, each function autonomously. For instance, an eVTOL vehicle can operate independently, but its integration into the UAM framework enhances its utility and efficiency.
Managerial Independence of the Components	Different systems within an SoS are managed independently, potentially by different organizations.	UAM involves multiple stakeholders, including vehicle manufacturers, vertiport operators, municipal authorities, and regulatory bodies, each managing their systems independently while contributing to the overall UAM ecosystem.
Geographical Distribution	The systems are often dispersed over large geographic areas.	UAM infrastructure, such as vertiports and air corridors, spans across urban and suburban regions, necessitating distributed management and coordination.
Emergent Behavior (Unintended Consequences)	The interactions among individual systems lead to behaviors that are not present in any single system.	Integrating eVTOL operations with urban infrastructure and air traffic management can create new mobility, efficiency, and service patterns that are emergent UAM SoS properties.
Evolutionary Development	SoS evolves over time, with individual systems being added, modified, or removed.	The UAM ecosystem is expected to evolve through phases, starting with piloted eVTOLs and gradually incorporating more advanced autonomous operations. This evolutionary development requires adaptable frameworks and regulatory approaches.

Furthermore, other aspects of the UAM ecosystem suggest that the SoS approach is more suitable for this research. Firstly, integration and interoperability among systems are crucial for successful SoS operations (DeLaurentis & Crossley, 2005). Effective UAM requires seamless integration between eVTOLs, vertiports, communication networks, and air traffic management systems. For example, interoperability standards ensure that different eVTOLs can communicate with air traffic control systems and vertiport infrastructure.

Secondly, SoS are marked by high complexity and interdependence among their constituent

systems (DeLaurentis & Crossley, 2005). The complexity in UAM arises from the need to manage airspace dynamically, coordinate between multiple stakeholders, and ensure safety and efficiency. Each system's performance affects the others, such as how air traffic management impacts eVTOL scheduling and vertiport operations.

Lastly, SoS taxonomy and methods emphasize the need for adaptation and flexibility in response to changing requirements and environments, according to Keating (2015). It relates to UAM systems because they must adapt to varying traffic densities, weather conditions, and technological advancements. For instance, as autonomous flight technologies mature, the UAM ecosystem must incorporate these advancements without disrupting existing operations. More details about the systems engineering principles and methodologies applied to SoS are described in Chapter 3.

2.2.9 UAM SoS Assumptions and Boundaries for the Research

The UAM SoS can incorporate multiple definitions across operational scenarios, boundaries, scope, and phases. As a future operation, there is no actual data and operating infrastructure. Therefore, all the operational considerations presented in the previous sections, based on released ConOps, are assumptions for the study. Thus, the research assumes that the UAM SoS will operate with system constituents that govern and provide airspace management and integration, UAM transportation services, UAM ground services, mobility integrated services, and regulatory and local administration.

Regarding the UAM life cycle, the study focuses on the utilization stage. The problems and solutions are discussed by envisioning the active operation of UAM transportation and all the enabling and constituent systems that support such operation.

The other relevant definition for the UAM SoS in this research is the UAM phase according to the evolutionary strategy described in 2.2.7. The study focuses on the earlier phases of UAM operations. This distinction is especially valid in terms of vehicle operation. In other words, the results consider piloted eVTOL vehicles, with the pilot on board controlling it. While the research particularly considers piloted operation, it does not impose limitations on other aspects that characterize UAM phases, such as operational tempo and infrastructure for airspace management and ground services. The results can be applicable for the UAM initial and intermediate stages, or Horizon 1 and 2 per Air Service Australia & Embraer (2020), for traffic and operational complexity

levels.

The pilot onboard eVTOLs was motivated by the criticality of having a human operator in the loop and the proximity to the near future scenario. Also, the piloted operation is crucial for addressing certain concerns within the research. For instance, when examining situational awareness and security, it is essential to recognize the pilot's specific role and responsibilities as a critical element of the enterprise. Having a pilot onboard is also a way of staying close to the current civil aviation operational standards and, therefore, having less incertitude and assumptions during the investigation.

Conversely, in discussions on safety culture, the pilot is viewed as another front-line staff member, making their presence less distinctive in this context. Similarly, for sustainable operations, the presence of a pilot does not significantly alter the outcomes. It is important to note that this research does not encompass autonomous operations or their specific challenges. However, the findings from this study are still valuable for future phases of UAM.

Concerning the use case, the study focused on UAM passenger transportation. The preference to investigate SoS concerns when UAM vehicles are transporting people is justified by safety purposes. Offering aerial transportation for the public requires the most critical safety standards considering the existing civil aviation industry. Ensuring the safety of the public, passengers, and urban areas is a priority for governments and regulatory bodies.

The UAM SoS elements in this research are categorized and analyzed as components and fragments of the overall ecosystem. Different concerns may incorporate system components from different perspectives. Depending on the aspect under consideration, the same SoS element can enable specific capabilities for each viewpoint. Ultimately, the research provides a comprehensive overview of the UAM ecosystem, integrating these diverse elements to offer a broader understanding of the system's structure and functioning. This approach ensures that while the research is focused on the piloted phase of UAM, it also lays the groundwork for future studies and applications in more advanced, autonomous phases of urban air mobility.

2.2.10 UAM SoS Constituent Systems

Naming constituent systems, system elements, or entities in the UAM ecosystem is essential for understanding the results in Chapters 4 to 7. This section will list, name, and provide more

information on the UAM stakeholders and constituent systems inspired by the system actors defined by NASA (2023). The list below includes airspace systems, ground systems, and society entities.

A. Airspace Systems

- Aerodrome community: parties involved in providing and operating the physical infrastructure needed to support aircraft take-off, landing, and ground handling. Example: Vertiport Operator and Vertiport manager;
- Airspace User: Organization operating the aircraft around urban areas on relatively short-haul flights. Example: UAM Operator, Fleet manager, Pilot in Command (PIC), UAS Operator;
- ATM Service Provider: Organizations and personnel (e.g., controllers, engineers, technicians) engaged in the provision of Air Traffic Management services to the Airspace Users. Example: Air Traffic Control (ATC), Provider of Services to UAM (PSU), PSU Operator, Communication Service Provider (CSP), Meteorological Service Provider (MSP);
- Regulatory Authority: responsible for the overall performance of the aviation industry, in which aviation safety is the most significant concern. Examples: ICAO (special agency of the United Nations), FAA (United States agency), EASA (European Union agency), JCAB (Japanese agency), ACCA (Chinese agency), and ANAC (Brazilian agency), among others.

B. Ground Systems

- Ground Support: organization and personnel involved in ground activities necessary to support UAM aircraft, like maintenance, repair, refueling, battery charging, and general logistics. Examples are the Vertiport Operator, the Vertiport manager, the Service Providers, and the Third Party organizations.
- Urban Planners and Local Authority: responsible for integrating UAM infrastructure into urban planning to optimize traffic flow and reduce congestion. Example: Local Government Officials and Urban Planners.

C. Society

- UAM Passenger: individuals using UAM for regular commutes to work or school, professionals using UAM for quick and efficient travel between meetings or business locations.
- Urban Residents: people living in areas impacted by UAM operations, especially near vertiports or flight paths.
- Community Groups: local organizations that may have concerns about noise, safety, and environmental impacts of UAM.

2.3 Literature Review on Situation Awareness

This section introduces the concepts and theoretical background of *Situation Awareness (SA)*. Then, relevant findings about SA and reflections on the UAM operational context are presented. The objective is to provide relevant information necessary to create the problem space and develop the solution presented in Chapter 4.

2.3.1 Situation Awareness

Since early aviation history, the pilot's awareness of what is happening around him has been challenging once his ability to predict problems and perform corrective actions could prevent accidents and save his life. Situation Awareness comes from the military operation as a strategy of gaining awareness of the enemy before the enemy does the same. The definition of situation awareness was first elaborated on the concern of having a separation between the human understanding of the system status and the actual system status (Woods, 1988). SA is also important in many other domains, although it sometimes receives different names. For instance, in the world of air traffic management, air traffic controllers generally refer to SA as the picture, a mental representation of the situation they base their decisions on (Endsley, 2004a). The healthcare and automotive industries are also interested in SA as autonomous systems that play a substantial role in user operations.

The concept of SA also received attention from the Socio-Technical Systems agenda, in which Human Systems Integration (HSI) became an essential asset for safety-critical systems. In complex

social-technical systems where several agents simultaneously operate at different levels and environments, user and system interactions must be considered when safety is a performance goal.

According to Endsley's (1995) model, SA comprises three levels. Level 1 SA is called Perception and represents the first step in achieving SA. The user observes the environment and perceives relevant elements' status, attributes, and dynamics. The set of information to achieve SA for each domain and job type is different. A pilot must perceive the aircraft's attention-getting elements, such as airspace traffic, ground terrain, vehicle system status, warning lights, and sound alerts. In the cockpit, the pilot must keep up with all relevant systems, flight data, navigational data, and communication inputs. An air traffic controller needs to perceive the traffic and the information that comes along with each vehicle's path using displays and communication headsets.

Level 2 SA is called Comprehension and involves integrating and interpreting critical information. The second step in achieving good SA is understanding what the data perceived means concerning relevant goals and objectives. The user then integrates many pieces of data acquired in the previous step to build a set of information and understand its importance and meaning to fully comprehend the scenario. After observing a set of information in the cockpit, the pilot needs to process the meaning of the data regarding the operation and access its criticality to understand the scenario. Approximately 19% of SA errors in aviation involve problems with Level 2 SA (Jones & Endsley, 1996). When people can see or hear the necessary data (Level 1 SA), it does not mean they are able to understand the meaning of that information correctly. Developing an understanding of the many pieces of data perceived is reasonably demanding. It requires a good knowledge base or mental model to assemble and interpret disparate data pieces (Endsley, 1995).

The third step is Level 3 SA and is called Projection. It represents the ability to predict the near future considering the elements perceived in level 1 after understanding (level 2) what they mean concerning the mission goal. A pilot can only achieve Level 3 SA by having a good understanding of the situation, the functioning and dynamics of the vehicle, and the operational environment they are working with. Although there is a dependency relation between those levels, the process of acquiring SA is not linear; they instead represent ascending levels of SA (Endsley, 2015). The idea of a simple 1-2-3 progression (data-driven) is not an efficient processing mechanism in a complex and dynamic system, where expertise and goal-driven processing come into play (Endsley, 2004b).

In aviation, SA is crucial in human information processing and essential in pilots' decision-making

processes. Crew and air traffic controllers work actively to project the aircraft's movement and anticipate problems well in advance. By constantly projecting ahead, they are capable of developing a ready set of strategies and responses to events. This allows them to be proactive, avoid many undesirable situations, and also provide a fast response when various events occur. Acquiring and maintaining appropriate levels of SA is critical in aviation environments as it affects all decisions and actions taking place in flights and air traffic control (Nguyen et al., 2019). Accident statistics indicate that the flight crew is the cause of 70% of air accidents or incidents (Helmreich & Foushee, 1993), and many occurrences are due to loss of SA (Endsley, 1995; Jones & Endsley, 1996; FAA, 2004).

Currently, the aviation industry has handled SA through human factor requirements, mainly focused on the cockpit during vehicle design and certification phases and with crew resource management during operation. According to the United Kingdom Civil Aviation Authority (CAA), the definition of Crew Resource Management (CRM) is "A management system which makes optimum use of all available resources (equipment, procedures, and people) to promote safety and enhance the efficiency of flight operations." (CAA, 2023). Used by airlines on the flight crew and other roles in critical safety positions, the CRM aims to enhance flight safety through operational practices and training. According to FAA AC-120-51E, CRM training covers five subjects: situation awareness, communication skills, teamwork, task allocation, and decision-making within a comprehensive framework of standard operating procedures (SOP) (Woods, 1988). General aviation has evolved over the past century, learned from accidents, and has well-established safe operational procedures. In this context, situation awareness for general aviation is part of a training and preparation phase and relies on flight decks with mature design and proven human factor features.

2.3.2 Situation Awareness Reflections on UAM Operational Context

Despite the stage and infrastructure capacity to handle the UAM traffic control and management, it is expected to interact more with UAM vehicles and other airspace users. UAM flight profile also affects this interaction in the take-off or landing flight phases. The flight range and time of each flight phase depend on the vehicle design. However, UAM flights' concept expects to transport passengers on short trips, which means more take-off and landing interactions during an operational period. The communication workload of the pilot with other airspace users and traffic

controllers is expected to be higher than the current general aviation operation. The ability of UAM to transition from uncontrolled airspace to busy controlled airspace without overwhelming the Air Traffic Control (ATC) represents a key unresolved challenge (Nguyen et al., 2019). Likewise, the ability of the UAM pilot to communicate with both general aircraft and UAS is also unresolved. Conversely, the air traffic controllers will have a higher workload to manage communication, operational authorization, and guidance.

Previous research by Cohen et al. (2021) indicated that medium and high-density operations were associated with a high workload for the traffic controller. UAM scenarios with increasing levels of traffic density were simulated to be controlled by experienced traffic controllers. Although operational adjustments like route optimization and letter of agreement to reduce communication can reduce workload and increase efficiency, the reported workload remained high.

The UAM navigation in the urban environment also reflects on SA's concern. Urban spaces present obstacles such as tall buildings, towers, cables, and bridges that add challenges to collision avoidance. The same applies to urban dynamic weather conditions and dense populations, which can increase the risks of UAM navigation. Advanced sensor-based systems and augmented reality (AR) technologies to assist pilots in maintaining situational awareness in such challenging settings were recommended by Chen et al. (2022). Moreover, integrating AI and machine learning systems can significantly enhance SA by providing real-time data processing and predictive analytics. However, these systems also necessitate that operators are adept at managing and interpreting automated outputs without becoming overly reliant on them, which can erode critical SA skills.

Li et al. (2023) underscored the importance of realistic training scenarios. The study advocates using advanced simulation tools replicating urban flight conditions, enabling pilots and controllers to practice maintaining SA under various scenarios. Such training is shown to improve performance and resilience in actual operations.

2.4 Literature Review on Security

This section introduces the concepts and theoretical background of *Security*. The other topic investigated and presented below is *Resilience* due to the need to recover from security events. Then, relevant findings about security and reflections on the UAM operational context are

presented. The objective is to provide relevant information necessary to create the problem space and develop the solution presented in Chapter 5.

2.4.1 Security and Security Controls

Security is a broad field that mainly covers physical, personnel, information, and network security. Security risks are related to the loss of confidentiality, integrity, or availability and reflect the potential adverse impacts on organizational operations, assets, and stakeholders. Since security risks cannot be eliminated entirely due to limited resources, organizations aim to find the optimal balance between identifying, protecting, detecting, responding, and recovering (NIST, 2018).

Security Controls are mechanisms that could be physically or logically employed within a system or organization to protect the system's confidentiality, integrity, and availability from managing the security risk. As security controls impact system architecture, the selection, design, and implementation are essential to realize early in system development. NIST SP 800-53 r5 in NIST (2020) provides a catalog of security controls. Security capability is the system's ability to achieve a desired effect under specific conditions through a combination of security controls (NIST, 2021). Proactive security controls comprise a systemic approach that focuses on prevention. On the other hand, reactive security controls focus on detecting and responding to a security threat.

Previous work on security topics of UAM addressed vulnerabilities (Jordan et al., 2022; Cenk Erturk et al., 2020; Maxa et al., 2019; Tang, 2021) and discussed the security perimeter for UAM operation (Stelkens-Kobsch & Predescu, 2022). Others focused on authentication risk and mitigations (Kwon et al., 2022), security of autonomous operations (Torens et al., 2021), and communication enablers, including security concerns (Zaid et al., 2021). Most of the related work uses autonomous operation as an operational scenario and focuses the effort on communication and navigation security risks. The previous work's motivation is based on assessing vulnerabilities and dense UAM operations that foreseen unmanned vehicles. Although some use a cybersecurity framework like Jordan et al. (2022), no one uses an Enterprise Architecture to support the security analysis. Moreover, a comprehensive and up-to-date literature review revealed no studies evaluating the cyber, physical, and personnel security aspects of piloted UAM vehicle operations.

Security work using Enterprise Architecture, specifically Unified Architecture Framework, is recent. Hause (2020) and Hause & Kihlström (2021b) guided the use and integration of UAF

security views. In addition, UAF security views were explored with the Risk Assessment and Analysis Modeling Language (RAAML) and the Systems Modeling Language (SysML) in a Search and Rescue operation (Dandashi, 2022). No other work has been published uniting UAF security views and the UAM context.

2.4.2 Resilience

Resilience is a concept used in a wide range of definitions and applications. This work will focus on resilience engineering principles and explore resilience performance at an organizational level represented by the UAM ecosystem. Pillay (2017), an integrative review work on resilience engineering, demonstrated that despite not having a universally agreed definition for the term, the idea involves a collective aspect, is multifactorial, multilevel, and multidimensional, associated with four fundamental principles: anticipation, response, learning, and monitoring.

Resilience Engineering (RE) is a recent topic (2003) and was introduced in the safety domain associated with organizational behaviors by Woods (2008). The safety management topic explains the strong relation with organizational resilience, in which a proactive approach involving human factors and cultural behavior are protagonists (Hollnagel et al., 2008). Thus, the RE definition provided by Pillay (2017) and used in this article is "*a sophisticated approach for managing organizational safety through the development of cognitive, behavioral, and cultural abilities to enable organizational members at all levels to actively anticipate, respond, monitor, and learn to operate close to the boundary of safe operations (…)*".

The idea that resilience is not a static property but a performance in constant adaptation and improvement of organizations (or systems) has been defined by Mendonça (2008) and explored in different domains. Resilient performance is related to safety more broadly. For the work presented in the following sections, resilient performance refers to the ability of individuals, teams, and organizations to adapt and perform effectively in the face of security threats or malicious adverse events. Some researchers have addressed resilient performance in the security context, focusing on cybersecurity architectures or interfaces (Amin, 2012; Maksymyuk et al., 2018; Alsulami et al., 2021). Discussions on performance as cyber resilience metrics were also presented by Bodeau et al. (2018). Despite the insightful material Nemeth & Holbrook (2021) provided on how RE can enable the evolving airspace to adapt and perform resiliently, publications on resilient performance in UAM operations are restricted.

When it comes to exploring resilience engineering through modeling, the complexity of a systematic approach still represents an open gap. The literature review performed by Patriarca et al. (2018) shows an overview of the current effort to advance the RE research agenda into sparse work in different industries with a different focus. This reflects the nature of resilience and safety-critical operations. The inherent complexity of activities involving cognitive, behavioral, and cultural aspects of RE poses a challenge for modeling resilience in an organization.

2.4.3 Security Reflections on UAM Operational Context

In regards to security aspects of UAM operations for passenger transportation, previous works have started by analyzing the existing security incidents and vulnerabilities of commercial aircraft and Unmanned Aerial Vehicles (UAVs) (Jordan et al., 2022; Tang, 2021; Cohen et al., 2021). There are two main sets of operational considerations: (1) cybersecurity considerations relating to control and communication, navigation, and surveillance (CNS); (2) considerations relating to physical security. Most of the work mentioned previously has contributed to the first set of security considerations. The first set is commonly approached for the in-flight phase and is often related to autonomous operation. Tang (2021) provided a list of vulnerabilities that can compromise the integrity of the UAM system. The same article evaluates alternatives and potential solutions for protection from the attacks of such vulnerabilities. It is important to note that fully autonomous operation was suggested as one of the solutions for those vulnerabilities.

A similar approach focusing on identifying the cybersecurity and CNS operational risks was presented by Jordan et al. (2022). Using the NIST Cybersecurity Framework (NIST, 2018), the baseline of this analysis was the airspace pillar of the UAM Concept of Operations (FAA, 2020). Five research areas (communication, navigation, surveillance, C2 Link, and vehicle) were assessed regarding cybersecurity risks. The findings and research guidance showed the importance of performing systemic threat mitigation and adapting to a threat landscape that is constantly changing.

Maxa et al. (2019) analyzed three types of attacks (via system access, wireless, or sensor attack). It proposed a vehicle recovery system in case of intrusion. The intrusion detection system (IDS) was considered an important asset in supporting event detection and trigger recovery after an attack. The unmanned vehicle (and autonomous operations) is also the object of study in this work.

While physical security is not included in most publications, Cohen et al. (2021) considered it a critical public acceptance factor. Mitigations suggest personnel and passenger background checks. Concerns about sabotage, terrorism, and violence against passengers in vehicles without crew (autonomous scenario) were also raised. Lastly, the physical security of the vertiports, aircraft, charging/refueling, other physical infrastructure, and cargo must also be ensured.

2.5 Literature Review on Safety Culture

This section introduces the concepts and theoretical background of *Safety Culture*. *Just Culture* is also investigated since this viewpoint aims to create an environment of learning from events. Then, *Safety Management in Aviation* is also included in the literature review because we need to understand how safety culture is built within flight operations. Lastly, relevant findings about safety culture and reflections on the UAM operational context are presented. The objective is to provide relevant information necessary to create the problem space and develop the solution presented in Chapter 6.

2.5.1 Safety Culture and Just Culture

ICAO (2018) defines *Safety Culture* as "the enduring value, priority, and commitment placed on safety by every individual and every group at every level of the organization. Safety culture reflects the individual, group, and organizational attitudes, norms, and behaviors related to the safe provision of air navigation services". According to Reason (1997), safety culture comprises five elements: informed culture, flexible culture, reporting culture, just culture, and learning culture. These elements are interconnected and interdependent. For instance, the presence of an informed culture relies on a robust reporting culture, which, in turn, depends on implementing a just culture.

In the aviation industry, there has traditionally been a prevailing belief that a greater likelihood of assigning blame accompanies higher levels of professional responsibility. In many countries, pilots receive significantly higher wages for holding their licenses, so they are expected to shoulder the blame when necessary (Patankar & Sabin, 2010). Such a blame culture does not consider systemic issues or latent failures, discouraging open communication and honest disclosure, according to Dekker (2007). Recognizing this reality, numerous entities in commercial aviation, including

international organizations like ICAO and regulatory bodies like the FAA, are actively working towards fostering a just culture (ICAO, 2018; Key et al., 2023; CREU, 2010).

For Reason (1997), *just culture* is "…an atmosphere of trust, where people are encouraged, even rewarded, for providing essential safety-related information—but in which they are also clear about where the line must be drawn between acceptable and unacceptable behavior". In other terms, just culture means a culture in which front-line operators or others are not punished for actions, omissions, or decisions taken by them that are commensurate with their experience and training but where gross negligence, willful violations, and destructive acts are not tolerated (CANSO, 2023). Another perspective provided by Reason (2997) pointed out that just culture refers to "a way of safety thinking that promotes a questioning attitude, is resistant to complacency, is committed to excellence, and fosters both personal accountability and corporate self-regulation in safety matters."

Transitioning from a blame culture to a just culture requires establishing a robust and functional reporting system. Dekker (2007) argues that such a system enables individual employees to report their errors or identify systemic hazards without fear of retaliation. The level of trust between employees and management within an organization is the most crucial factor in determining and predicting the success of such a system. A safety culture that is characterized as *just* encompasses both individual and organizational aspects, extending to attitudes and structures. Personal attitudes and the culture within an organization can either enable or hinder the emergence of trade-offs and operational variabilities (GAIN, 2004).

Dekker (2006) provides a comprehensive guide to understanding human error and recognizes that a just culture does not imply unconditional forgiveness for the responsible party in the event of an error. It is founded on the understanding that professionals such as pilots, aircraft mechanics/engineers, and air traffic controllers must adhere to certain fundamental professional and ethical standards. If they operate within these standards and make errors, disciplinary or punitive measures may not be imposed. However, if their performance violates these standards, the error is deemed unacceptable and may result in disciplinary action. The EUROCONTROL, a civil-military organization dedicated to supporting European aviation, has a Just Culture Task Force composed of legal and safety experts from the Member States, the European Commission, ATM, and air transport associations. This group has developed a model for a policy regarding

criminal investigation and prosecution of aviation and railway incidents and accidents. The EUROCONTROL (2020) model contributes to achieving a balance between the administration of justice and safety requirements in accident investigations. It shows European aviation's interest in promoting a just culture and maintaining public confidence.

The balance between the administration of justice inside organizations and reporting culture includes a moral issue that Dekker and Breakley (2016) addressed by analyzing retributive justice and restorative justice. They argue that accountability considerations must be set alongside deeper concerns with safety and justice. Retributive justice focuses on establishing the appropriate course of action for individuals who have violated specific standards of behavior. Restorative just culture focuses on learning why it made sense to the operator to do what they did, looking ahead at promoting trust to repair the relationship between people whose safety depends on one another. This approach facilitates healing and drives more learning than a retributive approach.

Learning from events is the primary objective of just culture. However, promoting a reporting culture and assessing events effectively is a complex process and brings challenges. Kováčová et al. (2019) and Balk et al. (2011) provided different approaches to addressing the challenges of implementing a just culture. In terms of fostering a just culture, it was found that a hierarchical structure that values and promotes a retributive response adds complexity to cultivating a restorative culture. Senior management must effectively address these challenges to foster an environment that prioritizes restorative justice principles (Boskeljon-Horst et al., 2023).

Complimentary, Sharon Clarke's broader perspective on safety culture highlights the importance of considering systemic organizational issues and external factors when developing safety practices. Clarke argues that safety culture is not just an internal organizational matter but is also shaped by regulatory, social, and power dynamics, which can influence how safety is understood and implemented within an organization. This aligns with the complexities of promoting a just culture, as it requires not only internal adjustments but also an awareness of the broader context in which the organization operates (Clarke, 2006).

When it comes to modeling safety or just culture, Karanikas et al. (2017) suggest that several factors, including employees learning from behavioral outcomes, supportive conditions, and maintaining consistency over time, could influence the development of safety culture. Sharpanskykh (2012) presented a systematic evaluation of safety culture in socio-technical

organizations and highlighted the impact of the formal structure of organizations and the values and beliefs that drive individual behavior within organizations.

2.5.2 Safety Management in Aviation

The primary objective of a Safety Management System (SMS) is to establish a structured and comprehensive approach to managing risks and ensuring the effectiveness of safety controls (ICAO, 2016). In a highly regulated industry like aviation, SMS serves as a means for organizations to comply with safety requirements and assess their management capabilities. Besides compliance aspects, SMS enables the integration of safety principles into all aspects of an organization's operations. This integration includes organizational processes, strategic planning, resource allocation, leadership, performance monitoring, and staff recruitment, according to Easter et al. (2004).

In order to limit the scope of SMS for this article, we will focus on the components used by the modern aviation industry. In 2006, ICAO proposed a framework for SMS in aviation with four components: safety policy and objectives, safety risk management, safety assurance, and safety promotion (Carter & Mansouri, 2022). By implementing the principles and requirements outlined in Annex 19, ICAO aims to improve safety performance across the aviation industry. The goal is to enhance safety performance, reduce accidents and incidents, and foster a proactive and systematic approach to managing safety risks. Regulation authorities also rely on the four SMS components. The FAA, the EASA, and other regional authorities adopt ICAO standards and develop their regulatory frameworks and guidelines based on Annex 19. They ensure that aviation providers, including airlines, air taxi operators, corporate flight departments, and pilot schools, comply with SMS requirements and integrate safety management into their operations.

Hollnagel (2008) explored safety management by applying resilience principles, which state that effective safety management requires learning from the past and anticipating the future. Accident investigation (learning from the past) and risk assessment (projecting the future) depend critically on the organizations' models and methods. In his work, the variability of human actions is not a threat but a crucial resource. Therefore, four abilities characterize resilient organizations and apply to SMS: (1) the ability to respond to current challenges; (2) the ability to monitor incoming critical situations; (3) the ability to anticipate the occurrence of future events; and (4) the ability to learn from the past (Hollnagel, 2009). Further, Muecklich et al. (2023) provided a systematic review

evaluating resilience engineering among other theoretical perspectives in the aviation safety context. Although resilience engineering was the dominant approach, the analysis shows that past studies mainly looked at the primary operational aviation subsystems (air traffic control and flight operations). Secondary operational subsystems, such as ground operations and aircraft maintenance, were considerably less used, suggesting a gap in ecosystem perspectives.

Aviation providers have applied and learned from the SMS framework in recent decades. Technological advances in aviation have increased the complexity of operations, and the limitations of SMS have been identified and discussed. Malakis et al. (2023) presented a pragmatic approach that analyzed the SMS limitations based on the four components and provided a comprehensive perspective. Carter & Mansouri (2022) evaluated the complexities of safety management through a systems thinking lens. It suggests a systemic approach to managing the paradoxical states of the SMS and balancing dynamics within the organization.

2.5.3 Safety Culture Reflections on UAM Operational Context

The expansion of UAM into cities introduces a multitude of stakeholders, including multiple operators and service providers, and the establishment of numerous vertiports across the urban landscape. While this distributed operational network brings about various advantages, such as improved accessibility and flexibility, it also presents significant challenges in terms of managing safety (Bauranov & Rakas, 2019; Cokorilo, 2020; Wang et al., 2023). Ground transportation services are expected to be part of the UAM mobility scenario. Integrating air and ground transportation for passengers adds more providers and organizations to the UAM landscape. Each operator and service provider may have unique operating procedures, aircraft models, and safety protocols, leading to a diverse operating environment that requires careful coordination and harmonization (Ferrão et al., 2022).

Macro-level aspects such as urban settings and external factors like regulatory frameworks, public policies, societal attitudes, and economic factors all play crucial roles in shaping the environment in which UAM operates and the culture of safety that prevails. The industry's novelty, urban environment, distributed operational network, and integrated mobility services are macro-level aspects that affect safety performance and, consequently, the internal aspect and the micro-level behavior of organizations participating in a just culture. The successful integration of UAM into

urban environments necessitates a comprehensive understanding of the macro- and micro-level challenges.

By leveraging real data, learning from mistakes, and promoting a culture of safety and accountability, the UAM industry can pave the way for a sustainable operation. Furthermore, the concept of just culture plays a crucial role in generating the necessary information for learning within the UAM industry. It also encourages open communication, transparency, and accountability by creating an environment where individuals can report safety incidents and near-misses without fear of retribution. This enables the collection of valuable data that can be analyzed to identify system weaknesses, develop targeted interventions, and continuously enhance safety practices within the UAM ecosystem.

2.6 Literature Review on Sustainability

This section introduces the concepts and theoretical background of *Sustainability*. Eco-efficiency, environmental, and social impact are investigated to formulate the sustainability subject. Then, relevant findings about sustainability and reflections on the UAM operational context are presented. The objective is to provide relevant information necessary to analyze the problem and develop the solution presented in Chapter 7.

2.6.1 Sustainability and Eco-efficiency

Sustainability is a broad and multi-dimensional concept that involves balancing environmental, social, and economic considerations to meet current needs without compromising the ability of future generations to meet their own needs (Brundtland, 1987). This concept is widely acknowledged and applied across various sectors, including transportation, energy, and urban development. In 2012, the United Nations (n.d.) created the Sustainable Development Goals (SDGs) related to the environmental, political, and economic challenges we face as humanity.

This concept encompasses three main pillars: environmental sustainability, social sustainability, and economic sustainability. Environmental sustainability concerns conserving and managing natural resources to prevent environmental degradation. It involves practices that reduce pollution, conserve biodiversity, and manage resources sustainably to ensure the long-term health of

ecosystems (Gibson, 2006). Social sustainability emphasizes the importance of social equity, inclusion, and community well-being. It aims to improve the quality of life for all individuals by ensuring access to essential services, promoting social cohesion, and fostering resilient communities (Colantonio, 2009). Lastly, economic sustainability fosters economic growth and development while ensuring that such progress does not deplete natural resources or harm the environment (Barbier, 1987). It advocates for efficient resource use, innovation, and investments contributing to long-term economic stability and prosperity.

Eco-efficiency is a concept that emerged in the early 1990s and was popularized by the World Business Council for Sustainable Development (WBCSD, 2000). It describes the relationship between the use of ecological resources and the generation of economic value. The goal of eco-efficiency is to create more goods and services while using fewer resources and generating less waste and pollution (DeSimone & Popoff, 1997). The Organization for Economic Cooperation and Development (OECD, 2008) defines eco-efficiency as the efficiency with which ecological resources are used to meet human needs. It is measured by the ratio of an economic value (such as GDP) to an environmental pressure (such as CO2 emissions). Higher eco-efficiency indicates that more value is being created with less environmental impact.

Critical components of eco-efficiency include resource efficiency, which means optimizing the use of natural resources to reduce environmental impact as explored by Huppes, G., & Ishikawa (2005); emission reduction by implementing processes and technologies that reduce emissions of pollutants and greenhouse gases; and productivity and innovation which includes developing new products and services that meet consumer needs while minimizing environmental impact (WBCSD, 2000).

2.6.2 Sustainability Reflections on UAM Operational Context

The EASA (2020) conducted a survey in 2021 to gauge public perception of UAM, and despite being generally positive about UAM, the survey also found that the public (71%) is concerned about the environmental impact of UAM. Negative impact on animals, noise pollution, and environmental and climate impact were ranked among the first three concerns. In addition, 74% of the survey participants saw advantages in the idea of an eco-label for vehicles and operations. From the benefits perspective, UAM services expect to reduce pollution and congestion in urban

areas, offer more flexible delivery services, and facilitate access to hard-to-reach locations (Silva, 2023).

Regarding CO2 emissions, some works have demonstrated the environmental benefit of introducing electrified UAM services in urban areas (Schäfer et al., 2019; Afonso et al., 2021). However, the lack of accurate data forces researchers to use simulation scenarios and assumptions when calculating UAM polluting emissions, which may impact the study's outcomes. For instance, Mudumba et al. (2021) found different results after analyzing greenhouse gas (GHG) emissions for eVTOLs in comparison to ground-based cars. eVTOLs exhibit efficiency during the cruise phase but demand substantial energy for takeoff and climb, with their environmental impact significantly influenced by trip distance. In a 100 km point-to-point journey with a single pilot in an eVTOL, GHG emissions are 35% lower than those of a combustion engine vehicle but 28% higher than those of a battery-electric vehicle. On short trips (up to 35 km), which constitute the majority of travel instances for traditional cars, eVTOLs present higher consumption and GHG emissions, as demonstrated by Kasliwal et al. (2019). More comparative work was performed, including the access and egress routes to the vertiport using ground transportation. Based on the Tampa Bay city, Zhao et al. (2022) conducted a sensitivity analysis to understand how the environmental impact changes with the variation of different parameters. Results are similar: UAM releases higher amounts of greenhouse gases, and UAM is a better choice only when the ground distance is higher than the aerial route. Moreover, for eVTOLs to surpass the efficiency of conventional ground-based vehicles, operators must ensure that these aerial vehicles operate at near-full capacities.

An environmental life cycle costs (ELCC) study from Liberacki et al. (2023) evaluated the UAM total cost, energy effectiveness, and carbon footprint. Findings suggest that UAM is less cost-effective and energy-efficient than other ground transportation. In terms of carbon footprint, there is a consensus that the energy grid of each country plays a decisive role, in which a higher proportion of renewable energy in the grid results in a reduced carbon footprint (Schäfer et al., 2019; Mudumba et al. 2021; Liberacki et al. 2023). Still, Afonso et al. (2021) explain that for all-electric aircraft to achieve competitiveness in the energy aspect, enhancements are essential in the following aspects: (i) the proportion of renewable energy sources within the electric grid, (ii) the specific energy density of batteries, (iii) the number of recharge-discharge cycles, and (iv) the raw

materials employed in battery production. On another note, challenges arise in the production and widespread use of electric vehicles, particularly in dealing with the disposal of used batteries and ensuring the availability of vital resources like lithium for battery manufacturing (Romare & Dahllöf, 2017; Quinteros-Condoretty et al., 2023).

In the social sphere, there is also the understanding that pUAM will face challenges competing with conventional urban transportation modes. Inclusivity for impaired mobility groups is an aspect that might be a challenge for eVTOLs, introducing potential additional costs. Another concern is the urban space democracy once vertiports may not be accessible for all types of neighborhoods, as explored by Straubinger et al. (20121). Social exclusion of groups may also happen depending on the route planning and service affordability. Rather than bridging accessibility gaps in urban transportation systems, pUAM offers an additional and potentially more time-efficient mobility option. While establishing vertiports in less connected neighborhoods and remote suburbs could enhance transport accessibility, the low demand on those points can intimidate business motivation. Furthermore, residential and community acceptance becomes crucial, encompassing noise, visual pollution, security, privacy, and increased traffic (Cohen et al., 2021).

The willingness to embrace pUAM increases when users associate the service with reduced travel time, easy booking and payment process, comfortable vertiport access, appropriate waiting times, and high overall service quality. However, EASA (2021) survey demonstrated that concerns related to nearby vertiports and their surroundings include noise (48%), safety apprehensions (41%), visual pollution (32%), increased inbound and outbound traffic (29%), and the utilization of spaces better suited for living or recreation (28%). Participatory planning approaches involving residents are recommended to address social vertiport planning challenges (Biehle, 2022).

Sustainable urban mobility encompasses transportation methods that minimize environmental impact and provide an integrative approach to urban development with sustainability objectives in mind. Urban planners tasked with devising sustainable urban mobility plans must consider the resident population in urban areas while ensuring satisfactory transportation services (Kováčová et al., 2019; Raghuvanshi & Singh, 2020). Moreover, the study of Kasliwal et al. (2019) provided evidence that eVTOLs will have limitations in their contribution and role within a sustainable mobility system.

2.7 Summary of the Literature Gap

While SA has been extensively studied in various domains, including aviation, healthcare, and automotive industries, several gaps remain. The foundational models and theories, such as Endsley's three-level model, have laid the groundwork for understanding SA. However, most research has focused on traditional aviation environments and military operations. There is a noticeable lack of comprehensive studies addressing SA in emerging fields like UAM, where the operational dynamics and challenges differ significantly. For instance, the unique SA requirements for UAM pilots, who must navigate complex urban landscapes and interact with a higher density of airspace users and autonomous systems, need to be better understood. The current literature also tends to overlook the socio-technical aspects of SA, mainly how human operators interact with increasingly automated systems. This gap is critical as the reliance on automation grows, and the need for operators to maintain a high level of SA becomes more challenging.

Furthermore, despite significant advances in understanding SA within individual domains, the concept of SA as a SoS competence involving multiple levels of organizations, processes, and operators is still under-explored. Traditional research primarily focuses on SA within single systems, such as the cockpit or air traffic control, neglecting the broader interconnections and interactions in complex operational environments. This gap is particularly evident in fields like UAM, where diverse systems, including piloted vehicles, autonomous drones, air and ground control systems, and urban infrastructure, must work cohesively. The complexity of maintaining SA across these interconnected systems, each with its own processes and human factor limitations, presents unique challenges that current models need to address adequately. This gap is critical as the effectiveness of SA in a SoS context is essential for ensuring safety, efficiency, and resilience in dynamic and high-stakes environments.

The security review found that existing research predominantly focuses on the vulnerabilities of autonomous operations, such as cybersecurity risks in communication and navigation systems. However, there is a lack of comprehensive studies that evaluate the security aspects of piloted UAM vehicles, encompassing cyber, physical, and personnel security. Current literature often employs general cybersecurity frameworks without integrating these considerations into an SoS

architecture that could support a comprehensive security analysis. Moreover, while there have been efforts to apply the UAF to security views, these have yet to be extended to the specific context of UAM, leaving a gap in practical application and integration.

In terms of resilience, while the concept of Resilience Engineering (RE) has been explored in various domains, its application to the UAM operational context is limited. The multifaceted nature of resilience, involving anticipation, response, learning, and monitoring, has not been adequately addressed in UAM-specific scenarios. This gap is particularly evident in the need for more models for the cognitive, behavioral, and operational aspects of resilience within UAM operations. Additionally, the complexity of modeling resilient performance systematically remains an open challenge. This is critical as UAM operations require robust frameworks to ensure safety and resilience in dynamic and dense urban environments.

A significant body of work regarding safety culture within traditional aviation contexts exists. However, there is a substantial gap in research addressing the unique challenges UAM poses. Existing studies primarily focus on safety culture elements such as informed culture, flexible culture, reporting culture, just culture, and learning culture within conventional aviation settings. However, the rapid evolution and novel operational contexts of UAM, characterized by diverse stakeholders and complex urban environments, introduce new variables that traditional safety culture frameworks do not adequately address. Integrating multiple operators, service providers, and varying operational procedures in UAM requires a more nuanced approach to cultivating a safety culture that can handle these complexities.

Moreover, the concept of a just culture, which promotes open reporting and learning from incidents without fear of retribution, is critical but underexplored in the UAM context. The unique operational pressures and the need for seamless coordination among air and ground transportation services in urban settings pose additional challenges to implementing a robust just culture. Notably, no study has addressed organizational perspectives to foster a just culture in UAM. Likewise, current literature has not addressed how consensus among regulatory bodies and UAM operators will be achieved and how to prepare for a culture that will be granulated in different locations and small providers.

Regarding sustainability and eco-efficiency, existing studies predominantly focus on environmental sustainability, particularly the reduction of GHG emissions and resource efficiency

of eVTOL vehicles. However, these studies often rely on simulation scenarios due to the lack of actual operational data, leading to varying and sometimes conflicting results. For instance, while some studies suggest that eVTOLs could reduce emissions during the cruise phase compared to conventional vehicles, others highlight higher emissions during takeoff and landing phases, especially for short trips. A study has not been found that assesses and analyzes the sustainability relationships in UAM operations. Therefore, there is a gap in presenting the value and impact relationship in this context.

In addition, the social sustainability aspects of UAM, such as inclusivity, equity, and community acceptance, are not thoroughly examined. Concerns about noise pollution, visual impacts, and the accessibility of vertiports in diverse urban neighborhoods indicate that UAM might exacerbate social exclusion rather than bridge accessibility gaps. The integration of UAM with ground transportation services and its impact on urban mobility systems also requires a more comprehensive investigation to ensure that these services contribute positively to social sustainability.

Economic sustainability, while discussed in terms of eco-efficiency, lacks in-depth analysis regarding the long-term viability and economic impact of UAM operations. Studies often overlook the costs associated with the entire lifecycle of eVTOLs, including production, maintenance, and battery disposal. Additionally, the economic implications of ensuring efficient near-full capacity operations for eVTOLs have not been adequately addressed.

In summary, the literature offering SoS perspectives for the socio-technical concerns defined in this research is limited. More specifically, a comprehensive approach to address safety, security, and sustainability in future UAM operations presents a gap. Finally, EA modeling and UAF findings are also scarce in the civil domain.

Table 2.3 combines the existing literature and the gap for the research presented in this dissertation. The first half of the table summarizes the existing literature for each socio-technical concern according to basic principles, aviation-related and other domains knowledge, and UAM operations and infrastructure. The fifth row shows the approach used for other studies to address the UAM problem. The symbol ◯ in the table represents the gap encountered during the literature review phase. Note that UAM and safety culture have not been found in the literature. In addition, previous work has mainly used analysis and simulations for SA, and sustainability, which is expected for a

conceptual operation like UAM. For security, dedicated methods to assess UAM vulnerabilities were used.

The final two rows focus on the methods employed in this research: architecture-related definitions, EA, and UAF. Notably, no architecture definitions specifically addressing each concern within the UAM context exist. Furthermore, the gap in exploring the problem as socio-technical concerns within the UAM SoS is evident. This lack of prior evidence in both the problem and method areas underscores the significance and objective of this research.

Table 2.3: Summary of the literature per socio-technical concern

	Situation Awareness	Security	Safety Culture	Sustainability
Principles, concepts, and definitions	*Human perceptions* (Woods, 1988) *Three-level SA model* (Endsley 1995; 2004a; 2004b; 2015)	*Cybersecurity framework* (NIST, 2020; Jordan et al., 2022) *Security risks and controls* (NIST, 2021) *Resilience Engineering* (Pillay, (2017)	*Safety culture* (ICAO, 2018; Reason 1997; Dekker 2007) *Restorative and retributive justice* (Dekker & Breakley, 2016; Hollnagel, 2008; Clarke, 2006)	*Environmental, social, and economic sustainability* (Brundtland, 1987; WBCSD, 2000; Gibson, 2006; Colantonio, 2009; Barbier, 1987; DeSimone & Popoff, 1997; Huppes, G., & Ishikawa, 2005)
Study on aviation-related context	*SA criticality in aviation* (Nguyen et al., 2019; Helmreich & Foushee, 1993; Endsley, 1995; Jones & Endsley, 1996; FAA, 2004) *SA in Crew Resource Management (CRM)* (CAA, 2023; FAA, AC-120-51E; Woods, 1988)	*Organizational resilience and culture behavior* (Hollnagel et al., 2008; Woods, 2008)	*Just culture in aviation* (Patankar & Sabin, 2010; (ICAO, 2018; Key et al., 2023; CREU, 2010; CANSO, 2023; GAIN, 2004; Easter et al., 2004; Carter & Mansouri, 2022; Hollnagel, 2008; 2009; Malakis et al, 2023; EUROCONTROL, 2020)	*Not listed due to the literature found for sustainability in the UAM context*
Other domains/ industries	*Not listed due to the literature found for SA in Aviation*	*Measures of resilient performance* (Mendonça, 2008) *Cybersecurity architecture and interfaces* (Amin, 2012; Maksymyuk et al., 2018; Alsulami et al., 2021)	*Safety culture in High-Risk Industries* (Kováčová et al., 2019; Balk et al., 2011; Boskeljon-Horst et al., 2023; Sharpanskykh, 2012; Muecklich et al., 2023; Carter & Mansouri, 2022)	*Not listed due to the literature found for sustainability in the UAM context*
UAM operations and infrastruc-ture	*High Workload* (Nguyen et al. 2019) *SA in ATM* (Cohen et al. 2021) *SA in vehicle design* (Chen et al. 2022)	*Secure Communication and ATM security* (Jordan et al., 2022; Zaid et al., 2021; Tang, 2021) *Autonomous control vulnerabilities* (Maxa et al., 2019; Torens et al., 2021; Kwon et al., 2022)	*Safety Management* (Bauranov & Rakas, 2019; Cokorilo, 2020; Wang et al., 2023; Ferrão et al., 2022)	*Public perception* (EASA 2021). *Lifecycle Analysis* (Liberacki et al., 2023). *Social Impact* (Straubinger et al. 2021; Biehle, 2022; Kováčová et al., 2019; Raghuvanshi & Singh, 2020) *Eco-efficient Design* (Schäfer et al., 2019; Afonso et al., 2021; Mudumba et al., 2021; Zhao et al., 2022; Romare &

		Security Perimeter (Stelkens-Kobsch & Predescu, 2022)		Dahllöf, 2017; Quinteros-Condoretty et al., 2023)
Problem approach for UAM	*Analysis and Simulations* (Nguyen et al., 2019; Li et al., 2023; Cohen et al., 2021; Chen et al., 2022)	*Cybersecurity framework* (Jordan et al. (2022) *Security Risk Assessment Methodology* (SecRAM) (Stelkens-Kobsch & Predescu, 2022)	○	*Lifecycle Analysis & Simulations* (Liberacki et al., 2023; Kasliwal et al., 2019; Zhao et al., 2022)
Architecture Modelling, EA, and UAF	○	*Security viewpoint in UAF* (Hause (2020) and Hause & Kihlström (2021b) *UAF security views using RAAML* (Dandashi, 2022).	○	○
Socio-technical concerns of the UAM SoS	○	○	○	○

The gap identified in the text is significant for several reasons. Firstly, the lack of material using EA frameworks in the civil domain contributes to the gap. EA has traditionally been stronger in military applications, where much of the material remains classified, leaving the civil domain with limited resources and studies. Secondly, the EA as a formalized methodology in Systems Engineering is recent, the architecture process standard (ISO/IEC/IEEE, 2019b) is from 2019.

UAF is a powerful tool for modeling complex, interconnected systems, but its complexity can be a barrier to entry. The framework requires a high level of expertise in EA principles, systems engineering, and model-based systems engineering (MBSE) methodologies. In civil domains like UAM, where the EA discipline is still emerging, there is often a lack of skilled personnel or understanding of how to effectively implement UAF.

While there is growing interest in applying EA frameworks to civil domains, the adoption of UAF has been slow due to a lack of supporting resources, such as best practice guidelines, case studies, and academic papers tailored to civil sectors like UAM. This results in limited validation of UAF's applicability to emerging fields, creating a feedback loop where researchers are hesitant to use UAF due to its unproven nature in civil contexts.

In conclusion, the gap in EA literature, particularly regarding UAF viewpoints, stems from its origins in military applications, complexity, and the slow adoption in civil domains like UAM. While UAF offers significant potential for modeling the socio-technical concerns of UAM as a SoS, the lack of open access case studies, a steep learning curve, and underutilization of human-centric and organizational viewpoints have resulted in limited published work.

CHAPTER 3

Research Methods used for UAM as a System of Systems

This Chapter describes the methods employed to investigate the socio-technical concerns within the Urban Air Mobility (UAM) ecosystem. This section begins with an introduction to explain how the methodology was defined according to scientific rationale. The systemic approach to address UAM safety, security, and sustainability concerns is evaluated according to the research problem. Then, foundational systems principles and theoretical concepts that guide the research are presented. The enterprise architecture methodology is introduced, with more details of the modeling framework used in the research. The validation method and the modeling strategy are also described. Lastly, the section presents the limitations of the methodology.

3.1 Introduction

This section delineates the methods used to investigate UAM socio-technical concerns. The aim is to provide a detailed account of the methods and approaches that underpin the research, ensuring a thorough and systematic investigation of the identified problems. The primary objective is to develop a comprehensive understanding of the systemic issues affecting UAM operations and propose practical solutions that enhance safety and security, thereby making a tangible impact on urban air mobility.

A systemic approach is crucial for addressing the complex interdependencies within the UAM ecosystem. By leveraging enterprise architecture methodology, this research systematically analyzes the interactions and relationships among various components of the UAM SoS. This

approach ensures that all relevant factors are considered, leading to more robust and effective solutions.

This Chapter is structured as follows: It begins with evaluating the need for a systemic approach. This step aims to associate the problem and, consequently, the research's desired outcome with the approach adopted in this thesis. Then, socio-technical systems theory is introduced and associated with the modeling principles and theoretical foundations. Subsequently, the enterprise architecture methodology is presented, focusing on the UAF modeling framework. Next, the architecture validation method is described, detailing how the proposed models and frameworks are discussed and validated to ensure their effectiveness in addressing the identified safety, security, and sustainability concerns. The modeling strategy is explained to support the understanding of the research results. Lastly, the methodology's limitations, which must be considered in the results, are discussed and presented. This comprehensive methodology provides a robust foundation for understanding and mitigating risks concerning socio-technical concerns in the UAM environment.

3.2 Need for Systemic Approach

The systemic approach is crucial for addressing socio-technical concerns within the UAM ecosystem, as it necessitates a comprehensive and interdisciplinary study. Section 2 presents and reviews the variety of topics involved in the research. Different disciplines are involved in the research problem, which addresses UAM cross-cutting concerns. This section lays the groundwork by presenting the rationale for employing a systemic approach to explore complex issues such as situation awareness, security, safety culture, and sustainability. These interconnected concerns require an integrated perspective encompassing technological systems, operational processes, organizational structures, and human factors.

To build a solid foundation for this investigation, we first discuss the characteristics of each problem that reiterate the demand for the systemic approach. Understanding the need for a systemic approach provides a base for the research methodology and coherence with the theoretical foundations used and referred to in this thesis. In addition, making clear the systemic need is essential because it highlights the importance of considering the interdependencies and interactions between various components within the UAM framework. By doing so, we can better identify

potential risks, opportunities, and areas for improvement, ensuring that the development and implementation of UAM technologies are safe, secure, and sustainable.

The following topics will look into each of the four concerns— situation awareness, security, safety culture, and sustainability — and examine their specific attributes that motivate the systemic need for this research. How the problem in each concern is characterized in the systemic context is relevant to connect with the theory and methodology presented later in this Chapter.

3.2.1 Systemic Approach to Situation Awareness

A systemic approach is crucial for addressing situation awareness problems because it encompasses the full scope of interactions between human operators, technology, and the environment. Situation awareness involves understanding what is happening around a human operator to make informed decisions, particularly in complex, dynamic environments such as aviation, military operations, or emergency response (Endsley, 1988; Woods, 1988; FAA, 2004). Understanding the environment requires combining systems, data, processes, and human operators, as Endsley (2004a) addressed. By considering all components and their interactions, a systemic approach ensures that information is accurately perceived, comprehended, and projected into future states, reducing the likelihood of errors.

Human factors are central to situation awareness. Operators' ability to perceive and interpret information is influenced by their training, experience, and cognitive load. A systemic approach addresses these human aspects by integrating comprehensive training programs, ergonomic interface designs, and supportive team communication structures (Woods, 1988; Endsley, 2004a; FAA, 2004). This ensures that operators can effectively process information under stress and high workload conditions (Woods, 1988).

Technological systems also play a significant role. The design and functionality of these systems should facilitate real-time data collection, processing, and display in an intuitive manner. A systemic approach promotes the development of user-centered technologies that align with human cognitive processes, enhancing the ability of operators to maintain high levels of situation awareness (Endsley, 2004a). This integration minimizes information overload and helps prioritize critical data, leading to better decision-making (Jones & Endsley, 1996).

Finally, the environment in which these systems operate must be considered. Endsley (1988)

analyzed how external factors such as weather, regulatory changes, and socio-political influences can affect situation awareness. A systemic approach ensures that all environmental variables are accounted for, allowing organizations to anticipate and adapt to changing conditions. The FAA (2004) crew resource management approach believes that viewing situation awareness through a systemic lens is essential for organizations to create robust strategies that enhance overall performance and safety.

3.2.2 Systemic Approach to Security

Security challenges are inherently socio-technical, involving the interplay between people, technology, and organizational processes (NIST, 2020). A systemic approach to security ensures that all these elements are considered together to create a comprehensive and resilient security posture (Wing et al., 2020). This is particularly important in an era where cyber threats are sophisticated and continuously evolving, requiring a holistic understanding of vulnerabilities and defense mechanisms.

Human factors are a critical component of security. NIST (2021) considers that employees' behaviors, awareness, and adherence to security protocols significantly influence an organization's security. In NIST (2020), a systemic approach involves creating a security culture where employees are well-informed, vigilant, and proactive in identifying and mitigating threats. Training programs, regular awareness campaigns, and a clear understanding of roles and responsibilities are essential to foster such a culture.

On the technical side, security systems must be designed to detect, prevent, and respond to threats effectively (NIST, 2018). This includes robust cybersecurity measures like firewalls, encryption, and intrusion detection systems, as well as physical security controls. A systemic approach promotes integrating these technical solutions with organizational processes and human behaviors, ensuring that technology supports and enhances overall security efforts rather than functioning in isolation.

Moreover, the organizational and external environment must be considered, according to Carter & Mansouri (2022). Regulatory requirements, industry standards, and external threats from the geopolitical landscape can all impact security. A systemic approach proposed by NIST (2020) ensures that organizations remain compliant with regulations and adaptable to new threats. By

considering all these factors in a unified framework, organizations can develop a resilient security strategy that addresses security challenges' complex and dynamic nature.

3.2.3 Systemic Approach to Safety Culture

Safety Management Systems (SMS) are structured frameworks designed to ensure the safety of operations within organizations, particularly in high-risk industries such as aviation, healthcare, and manufacturing. Managing risks in critical safety operations relies heavily on the safety culture, which is an integral part of the SMS framework (Santos-Reyes & Beard, 2008).

SMS encompasses the entire organization comprehensively, considering elements from top to bottom, including communication channels, personnel, and more. It also accounts for the external environment, including all circumstances that impact the system and necessitate a response, such as political and economic influences (Santos-Reyes & Beard, 2008). A systemic approach is essential in this context, defined as the effort to perceive things holistically, viewing events, even failures, as outcomes of a system's operation. ICAO (2016) explicitly defines the need for a systemic safety management approach within the aviation industry's SMS framework.

A just culture depends on a healthy safety culture and a supportive safety management system. Both include human operators (with their behaviors, beliefs, subjectivity, and personal aspects), organizational structures, management styles and rules, policies, technical processes, and human-made systems. Patankar & Sabin (2010) argue that understanding the relationship between employee learning and organizational supportive conditions must be part of a positive safety culture. Moreover, a systemic approach is recommended by Carter & Mansouri (2022) for managing the paradoxical states and balancing organizational dynamics.

By linking safety culture, SMS, and the systemic approach, organizations can ensure safety is embedded in every aspect of their operations. The systemic approach helps to integrate human, technical, and organizational elements, creating a cohesive framework where safety culture and SMS work together to identify and mitigate risks effectively. This holistic perspective enhances safety outcomes and promotes continuous improvement and resilience within the organization (CANSO, 2023; ICAO, 2018; Carter & Mansouri, 2022).

3.2.4 Systemic Approach to Sustainability

Sustainability challenges are multi-faceted, involving economic, environmental, and social dimensions (Elkington, 1997). A systemic approach to sustainability ensures that all these dimensions are considered together, enabling organizations to develop strategies that are not only effective but also balanced and sustainable in the long term. This holistic view is essential for addressing complex interdependencies of sustainability issues (Meadows et al., 1972; Meadows, 2008).

Human behavior and social factors are central to sustainability. Encouraging sustainable practices among employees, consumers, and stakeholders requires a deep understanding of social dynamics and cultural norms (Hoffman, 2015). A systemic approach involves fostering a culture of sustainability within the organization and beyond through education, engagement, and incentives. It ensures that sustainable practices are adopted and ingrained in everyday behavior.

Technological innovations play a crucial role in advancing sustainability goals. From renewable energy systems to waste management technologies, the development and deployment of sustainable technologies are vital (Hawken, 1993). A systemic approach promotes the integration of these technologies into existing systems and processes, ensuring that they are used effectively and efficiently. Thus, it includes considering the lifecycle impacts of technologies and optimizing their use to minimize environmental footprints.

Sustainability also depends on external factors like environmental and economic aspects. Politics, energy sources, regulation, and social demographics can impact sustainability efforts. A systemic approach ensures that organizations are adaptive and responsive to these external influences, allowing for continuous improvement and long-term viability (Elkington, 1997; Hawken, 1993). By addressing sustainability through a systemic lens, organizations can create strategies that are robust, adaptable, and aligned with broader societal goals.

3.3 Socio-Technical Systems Theory

Socio-technical systems (STS) represent a holistic approach to understanding and designing complex organizational environments. Trist & Bamforth (1951) developed the STS framework,

emphasizing the interdependence between social and technical elements within any work system. Originating from research in the mid-20th century, STS focuses on achieving an optimal balance between human and machine contributions to enhance productivity and overall system success (Abbas & Michael, 2023). By integrating human factors such as behavior, ergonomics, and social interactions with technological aspects like tools, machines, and processes, STS aims to create more effective and resilient organizational structures.

The roots of socio-technical systems theory can be traced back to the 1950s when researchers Trist and Bamforth (1951) developed this theory based on their observations in the coal mining industry. They noticed that technical improvements alone were insufficient to solve productivity and safety issues without considering the social dynamics of the workplace. Thus, STS theory emerged as a paradigm shift from the traditional view of humans as mere extensions of machines to seeing them as critical resources that must be developed alongside technological advancements. Cherns (1976, 1978) explored sociotechnical design, proposing STS principles that underpin the theory, ensuring that both social and technical components are equally prioritized in the design and operation of the system.

Join optimization in STS theory involves balancing the needs and capabilities of both human and technological subsystems. It believes that systems achieve their highest performance when there is a harmonious integration between the social and technical elements, thereby reducing conflicts and enhancing overall system functionality. This integration is crucial for addressing the complexities and interdependencies inherent in modern work environments (Emery, 2016). Chai & Kim (2012), Ryan et al. (2002), and Sawyer et al. (2003) have applied STS methods and provided empirical findings in different domains.

The systemic approach within socio-technical systems theory further expands on these ideas by incorporating principles from general systems theory and open systems theory (Abbas & Michael, 2023). This perspective views organizations as open systems that continuously interact with their external environment, necessitating a dynamic and adaptable approach to system design. Environmental factors such as regulatory changes and technological advancements are integral to the system's operation and evolution. Thus, a systemic approach in STS focuses on internal harmony and responsiveness to external conditions.

Furthermore, socio-technical systems theory highlights the importance of considering broader

environmental subsystems in designing and analyzing work systems, as Cherns (1987) addressed. These environmental subsystems include the organizational culture, societal norms, and economic conditions that influence the functionality and performance of socio-technical systems. By acknowledging and addressing these broader influences, STS theory provides a more comprehensive and realistic framework for designing resilient, adaptable systems capable of continuous improvement (Imanghaliyeva, 2020).

Some aspects of STS are inherent to the problems explored in this research. Safety, Security, and Sustainability require a systematic approach due to the complex nature of their behavior across the UAM ecosystem (as described in previous sections). The combination of social and technical elements exists and is critical for all the concerns discussed earlier. Safety relies on both individuals adhering to protocols and the effectiveness of safety technologies. Security depends on human vigilance and properly implementing technical measures like encryption and surveillance systems. Both require an organizational culture that prioritizes these concerns and ensures policies are followed.

Similarly, sustainability requires an integrated approach, combining changes in human behavior and societal norms with technological innovations and regulatory frameworks. Achieving sustainability goals often involves developing new technologies, such as renewable energy systems, and promoting environmentally friendly practices. Organizations can create more effective and resilient safety, security, and sustainability strategies by holistically addressing these aspects and understanding the system's interdependencies.

Furthermore, key STS theory concepts and principles converge to the EA methodology. For instance, STS theory advocates for viewing organizations as complex systems where social (people, structures, cultures) and technical (tools, technologies, processes) elements are deeply interwoven. This perspective suggests that changes in one system component inevitably affect other components, necessitating a comprehensive approach to organizational design and problem-solving (Cherns, 1987). EA conceptualization process considers the problem space in social and technical dimensions, and the EA visualization process provides the organizational and holistic perspective suggested by STS theory. More details of EA are provided in 3.5.

3.4 Modeling Principles and Foundations

Modeling plays a crucial role in the relationship between systems and knowledge. The real world provides actual experiences translated into simple, complicated, or complex phenomena (Grabowski & Strzalka, 2008). Models can be used to represent the real world for analysis purposes and support the construction of wholes (synthesis world). The aspect of the knowledge world is the foundational knowledge that can model phenomena (science) and express abstractions (Natarajan et al., 2018).

Modeling is fundamentally related to General Systems Theory (GST) as it provides a practical means to represent and analyze the abstract concepts GST encompasses. Von Bertalanffy (1968) proposed the GST, claiming that systems can be understood by examining the interactions and relationships among their components rather than just their individual parts. Modeling serves as a tool to bring this theoretical framework to life by creating simulations or representations of these systems, capturing their structure, behavior, and dynamics (Weilkiens, 2007). Meadows (2008), in her systems thinking primer, believes that through models, researchers and practitioners can visualize complex interdependencies, test various scenarios, and predict outcomes, which aligns with GST's holistic approach. This helps identify emergent properties and understand the systemic nature of real-world problems, enabling applying GST principles to fields such as biology, engineering, sociology, and environmental science. It also implies that GST operates at a highly abstract level. Applying it to specific fields of knowledge makes it possible to develop numerous valuable tools and methods, especially within the Systems Engineering domain (Weilkiens, 2007).

In the information systems discipline, conceptual modeling is a foundational process for capturing, organizing, and representing the essential elements of a system or domain (Thalheim, 2011). At its core, modeling revolves around creating abstract and simplified representations, known as conceptual models, that encapsulate the key concepts, entities, attributes, and relationships relevant to the system under development. Therefore, modeling refers to constructing these conceptual models using various modeling languages, notations, and techniques. This modeling process involves translating real-world complexities into structured and understandable forms, enabling stakeholders to gain insights into the system's structure, behavior, and requirements (Thalheim, 2011).

Theoretical foundations for conceptual modeling include ontological, epistemological, linguistic, and pragmatic principles (Wand et al., 1995). These foundations allow for creating conceptual models capable of representing a domain and supporting the solution given a concern (Natarajan et al., 2018). The model's ability to capture knowledge about the relevant domain depends on ontology, semantics, language, and communicative acts (Wand et al., 1995). In summary, the conceptual aspects inherent to modeling consist of developing a clear understanding of the domain to be modeled, abstraction, knowledge, and visualization. Visual representations, such as diagrams to depict the conceptual model, ease the communication and understanding of the modeled system. Technical aspects focus on using modeling languages, tools, and techniques to represent, analyze, and simulate the conceptual model (Olivé, 2007).

Enterprise architecture modeling employs conceptual modeling techniques to capture and depict the fundamental elements and relationships within an organization's complex system, aiming to provide a holistic view supporting strategic planning, governance, and transformation initiatives. Enterprise architecture modeling is a systematic process of creating abstract representations of an organization's structure, processes, systems, and interactions to facilitate decision-making, alignment, and optimization of its enterprise-wide resources and capabilities (Polovina & Von Rosing, 2018). The holism and the synthesis construction of enterprise architectures serve the enterprise (business, systems, and organizations) domain and its inherent concerns. A framework, language, and methodology can define the abstraction level of a conceptual enterprise architecture (Alexa & Repa, 2017). More information about EA as a methodology is presented in the next section.

Lastly, modeling is linked to socio-technical principles as it provides a structured method to analyze and represent the complex interactions between social and technical components within a system. Through modeling, it is possible to create visualizations that incorporate both human factors and technical elements, enabling a comprehensive examination of how these components interact and influence one another (Whitworth & Ahmad, 2013). This approach helps identify potential issues, optimize performance, and enhance system resilience by considering social dynamics and technical functionalities (Sterman, 2000). By capturing the nuances of socio-technical interactions, modeling facilitates better understanding, decision-making, and innovation in developing and managing complex systems.

3.5 Enterprise Architecture (EA) Methodology

3.5.1 Motivation for applying EA Methodology

To explore a systemic view of the UAM ecosystem, the target of the research was system-of-systems-level modeling methodologies. As described in the previous section, the challenges of dealing with complex systems can be alleviated by employing modeling techniques, and tools can be utilized to analyze behaviors and relationships. In this context, EA emerges as a holistic discipline that addresses the complexities of an enterprise while ensuring its responses align with desired business objectives and outcomes (ISO/IEC/IEEE, 2109a). The objective of adopting enterprise architecture views is to understand its entities and their interactions thoroughly.

An *enterprise* is a system in which the components are the enterprise's resources. Thus, EA is anchored on system sciences, the discipline that provides the necessary foundations to model and design systems. Regarding the systemic philosophy and paradigm, the EA emphasizes viewing the enterprise as a cohesive system with interrelated and interdependent components (Wegmann, 2003). This methodology integrates various perspectives and domains, ensuring that strategic objectives are consistently reflected in the enterprise's initiatives and vice versa.

Regarding heuristics, enterprise-level models are related to SoS principles. These principles guide the development of architectures that integrate diverse and autonomous systems into a cohesive and functional whole. Enterprise-level models, when informed by SoS principles, emphasize modularity, interoperability, and scalability, ensuring that each subsystem can operate independently while contributing to the overall system's goals (Brook, 2015). This alignment allows flexibility, adaptability, and robustness in addressing dynamic business environments and complex organizational needs. By leveraging SoS principles, enterprise architecture can effectively coordinate multiple interconnected systems, enhancing the enterprise's capability to achieve strategic objectives.

Furthermore, the core elements of SoS engineering (SoSE) can be found in EA processes. According to the Systems Engineering Guide for Systems of Systems by the Department of Defense (DoD) (2008), core elements of SoS engineering include interoperability, modularity, and scalability. These elements are crucial for integrating multiple autonomous systems into a cohesive framework. As per ISO/IEC/IEEE 42020 (2019a), these SoS engineering elements are closely

linked to EA processes. Interoperability ensures seamless communication and functionality across different systems within the enterprise. Modularity allows for flexibility and adaptability by enabling independent subsystem development and integration. Scalability addresses the ability of the enterprise architecture to grow and evolve with changing requirements. Together, these principles ensure that EA processes can effectively manage and optimize complex, interconnected systems, aligning them with strategic business goals.

EA facilitates enterprise analysis, planning, governance, and evaluation as a well-defined practice. It employs holistic approaches for the successful development and implementation of strategies. Architects can leverage EA to apply architectural principles and practices, guiding organizations through changes in business, information, processes, and technology required to execute their strategies (ISO/IEC/IEEE, 2019a). These practices utilize various aspects of an enterprise to identify, motivate, and implement these changes.

In conclusion, EA resonates with the systemic need of the research problem, systems principle, and systems theory to address socio-technical concerns introduced earlier in this chapter. The following sections present more details about the EA methodology's scope, purpose, and processes. Likewise, the methodology's limitations are discussed at the end of the Chapter.

3.5.2 Enterprise Architecture Methodology Scope and Purpose

This research employs the enterprise architecture methodology described in the international standard ISO/IEC/IEEE 42020 “Software, systems, and enterprise—Architecture processes” (ISO/IEC/IEEE, 2019a). The ISO/IEC/IEEE 42020 scope includes guidance for architects and stakeholders involved in designing and implementing architectures within an enterprise context. It covers architecture frameworks, principles, and methodologies essential for creating and managing architectural descriptions. The standard applies to a wide range of domains, including software systems, information systems, and complex enterprise environments, making it versatile for various industries and organizations.

This methodology ensures that all architectural activities are systematically governed and managed, facilitating coherence and integration across these diverse domains. By providing clear guidelines and best practices for architecture processes, the EA methodology helps organizations achieve their business objectives, optimize resource utilization, and enhance adaptability to

changing business needs. Furthermore, it promotes stakeholder engagement, ensuring the architecture addresses all relevant concerns and supports informed decision-making, thereby driving organizational success and sustainability.

3.5.3 ISO/IEC/IEEE 42020 Overview and Architecture Processes

The standard defines six key architecture processes, each with a specific purpose to ensure comprehensive and effective architecture management:

1. Architecture Governance: Establish and maintain alignment of architectures (goals, policies, and strategies and with related architectures);
2. Architecture Management: Implement architecture governance directives;
3. Architecture Conceptualization: Characterize the problem space and determine suit-able solutions that address stakeholder concerns, achieve architecture objectives, and meet relevant requirements;
4. Architecture Evaluation: Determine the extent to which architectures meet their objectives, address stakeholder concerns, and meet relevant requirements;
5. Architecture Elaboration: Describe an architecture in a sufficiently complete and correct manner for the intended uses of the architecture;
6. Architecture Enablement: Develop, maintain, and improve the enabling capabilities, services, and resources needed to perform the other processes.

Figure 3.1 is part of the standard ISO/IEC/IEEE (2019a) and outlines the architecture processes and their interactions. As a scheme, the figure's simplification does not represent all the possible connections. Iterations and recursion are expected and detailed according to the processes to be covered.

Each process plays a role in adapting the architecture to a specific context. Conceptualization and elaboration directly facilitate the evolution and adaptation of the architecture. Evaluation provides evidence to inform decisions regarding architectural evolution and changes. While the architecture processes can influence architecture-related decisions, they are typically the responsibility of other processes where the decision is most pertinent. Governance and management offer directives and

instructions for architectural evolution and changes, while enablement provides the necessary capabilities, services, and resources to support the other processes adapting the architecture.

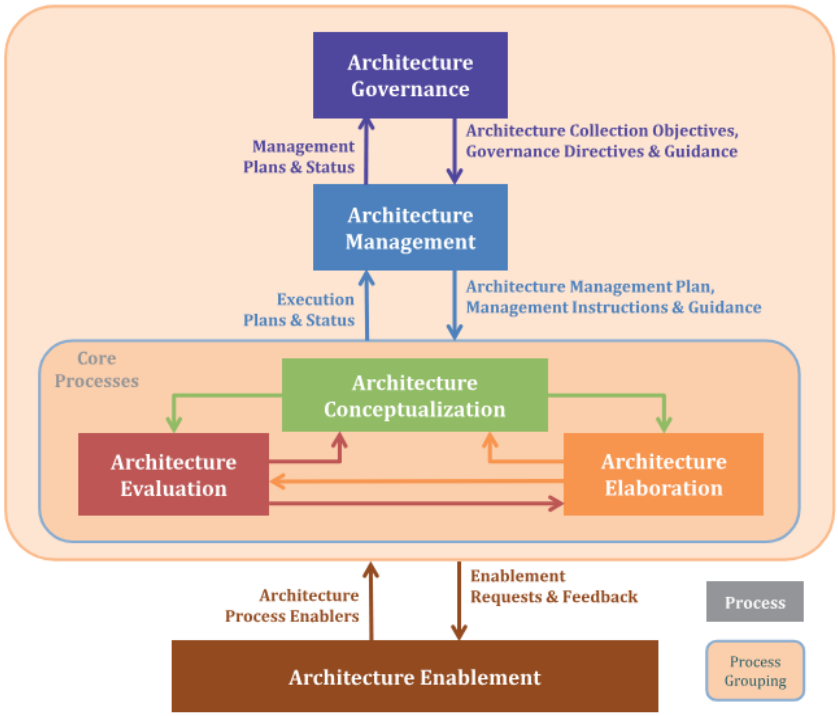

Figure 3.1: Overview of Architecture Processes and their Interactions from ISO/IEC/IEEE (2019a)

To answer the research questions and meet the intended use of the architecture effort, this research focuses on three processes: architecture conceptualization, architecture elaboration, and architecture evaluation. Figure 3.2 was extracted from the standard and depicts the processes tailored for the study. It also provides more information on how those processes interact.

In the first part of the results, the architecture conceptualization process is tailored to characterize the problem space and determine the solution space. This step is how the systemic view of each concern is debated and characterized. In addition, the strategy to elaborate on the architectural views is defined according to the intended purpose and the stakeholders involved in the problem and solution.

The second part applies the architecture elaboration process to create the architectural views. Visualizing the architecture through different perspectives and providing a clear understanding of

the solution needed are the purposes of this process. Since the research has various concerns, the outcome was tailored to communicate distinct ideas and reach different stakeholders.

The architecture evaluation process is not a one-time event but a continuous and iterative part of the research. It is mainly applied amid validation and iterations that occur during the research. The assessment, analysis, key findings, and recommendations are provided. These results are used to determine if the proposed architecture adequately addresses stakeholder concerns. Further iterations between conceptualization and evaluation are conducted if it does not, ensuring the research is constantly refined and improved.

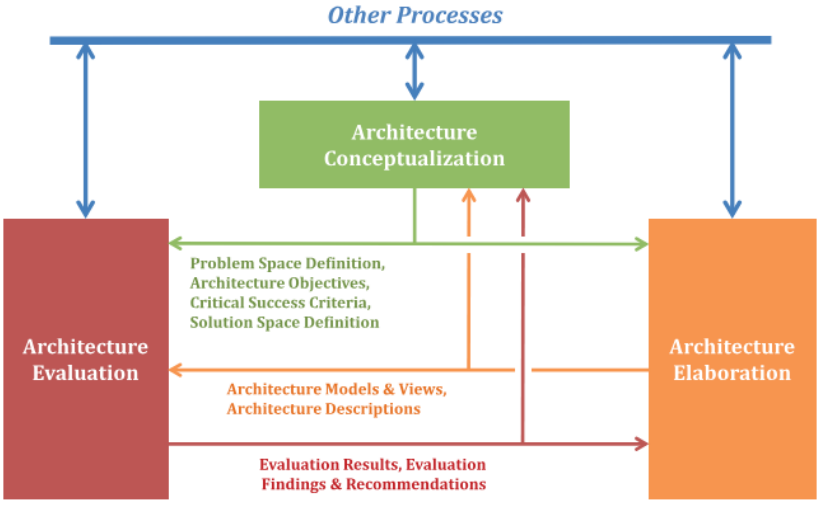

Figure 3.2: Architecture Processes Tailored in the Research from ISO/IEC/IEEE (2019a)

3.5.4 Architecture Conceptualization Process

The definition of the architecture conceptualization process is "to characterize the problem space and determine suitable solutions that address stakeholder concerns, achieve architecture objectives and meet relevant requirements. (…) Conceptualization is where there is a special focus on identifying solutions, but with also an emphasis on fully understanding the complete problem. This also entails defining and establishing architecture objectives, as well as negotiating with key stakeholders on prioritization of their concerns" in ISO/IEC/IEEE (2019a) p. 27.

The architecture conceptualization process is critical in developing an effective enterprise architecture. It provides the foundational understanding to guide subsequent architectural activities, ensuring that the architecture aligns with organizational goals and stakeholder needs.

The EA standard lists activities and tasks in the conceptualization process. Following is a summary of conceptualization process activities relevant to the research.

Characterize Problem Space (ISO/IEC/IEEE, 2019a item 8.4.3)

Characterizing the problem space is a fundamental step in the architecture conceptualization process. It involves identifying potential problem areas, including expectations for improvement, and using the term "problem" to indicate issues addressed by architectural solutions. The process starts by identifying the current and projected situations in the problem space, relating to end-user challenges and needs, and applying a systemic approach to ensure viable solutions are considered.

It includes identifying specific problems and opportunities within these situations, using a broad definition of "problem" that includes any event requiring investigation and corrective action. Relevant aspects of the problem, such as political, economic, social, technological, environmental, and legal factors (PESTEL), are then identified to ensure a comprehensive analysis. Understanding these aspects helps fully grasp the nature of the problems and opportunities.

Examining current and future business and mission needs about these problems and opportunities provides valuable insights and potential feedback for business or mission analysis processes. Stakeholders and their concerns must be identified and analyzed, considering both formal and informal requirements. This ensures that the architecture addresses all relevant stakeholder needs and expectations.

The process also involves determining the value stakeholders will receive when their concerns are addressed and prioritizing quality measures for development and evaluation. These quality measures, which can be linked to the problem or solution space, help assess the effectiveness of architectural solutions. Understanding how problems and opportunities impact different stakeholders and characterizing their complexities and cause-effect relationships is crucial for a thorough analysis.

Finally, formulating a clear statement of the problem, including risks, opportunities, and constraints, and producing a problem space definition report provides a structured foundation for developing architectural solutions. This comprehensive approach ensures

that all relevant issues are addressed and the architecture aligns with organizational goals and stakeholder needs.

Establish Architecture Objectives (ISO/IEC/IEEE, 2019a item 8.4.4)

Establishing architecture objectives involves several key steps. First, use identified problems, related risks, and constraints as the basis for gathering, analyzing, and negotiating requirements. Requirements should then be classified according to stakeholder needs to identify who is interested in each problem and opportunity. Boundary conditions, root causes, drivers, and relevant scenarios must be determined for each identified problem and opportunity. It is essential to identify gaps or shortfalls in current or planned solutions and to outline relevant assumptions, constraints, and challenges.

Next, define architecture objectives that address the identified problems and opportunities regarding stakeholder concerns, requirements, and quality attributes. Critical success criteria should be defined to assess the extent to which problems are resolved, focusing on achieving desired "ends." These criteria, also known as ends objectives, differ from means objectives, which are defined during solution space analysis. Finally, the critical success criteria are translated into evaluation criteria used during architecture evaluation and decision-making processes.

Characterize Solutions and the Tradespace (ISO/IEC/IEEE, 2019a item 8.4.6)

Characterizing solutions and the tradespace involves evaluating potential solutions from a technical perspective, focusing on aspects such as ease of realization, compatibility, and trends in technology. It complements architecture evaluation, which examines solutions in terms of stakeholder value and quality attributes. Characterization includes examining the context in which stakeholders perceive value, identifying strengths, weaknesses, opportunities, and threats for each solution, and considering important aspects such as risks, costs, schedules, reuse of architecture elements, assumptions, and additional problems caused by each solution.

Moreover, it involves harmonizing elements to ensure coherent realization and identifying tradeoffs between and within proposed solutions, the status quo, and other potential solutions. The collection of these tradeoffs and interactions is called the "tradespace." A

roadmap for implementing solutions is formulated, defining success criteria for assessing the extent to which solutions address specified problems. Finally, issues and areas for improvement are identified, and desired functional and non-functional characteristics are established, aligning with stakeholder concerns, requirements, constraints, and quality attributes from problem space analysis.

Formulate Candidate Architecture (ISO/IEC/IEEE, 2019a item 8.4.7)

In this activity, the first step is to identify the solutions to be architected and devise structural, behavioral, and organizational concepts and properties that support the desired characteristics, such as functional, non-functional, operational, business, and environmental impacts. These concepts can be expressed in various forms, including IT constructs (e.g., information flows, control flows, data structures) and other models (e.g., risk models, financial models, simulation models).

Next, identify and characterize the tradeoffs between candidate architectures for each solution and determine key characteristics based on stakeholder concerns, requirements, quality attributes, and architecture objectives. These characteristics help define the context and scope of each architecture. Principles, implications, guidelines, protocols, and standards for each candidate architecture should be formulated, and key characteristics should be decomposed and allocated to components, processes, and other elements.

Capture Architecture Concepts and Properties (ISO/IEC/IEEE, 2019a item 8.4.8)

Capturing architecture concepts and properties involves documenting the architecture to the appropriate level of detail for its intended users, often drawing on results from the Architecture Elaboration process. Initial conceptualization does not require significant elaboration; detailed views, models, and descriptions are typically developed later in the architecture's life cycle once the architecture has matured and undergone preliminary evaluations. This activity includes identifying the uses and users of architecture views and models, defining their purpose, scope, breadth, and depth, and addressing critical aspects relevant to stakeholders.

The process involves specifying suitable forms of expression for views and models, selecting or developing necessary enablers like architecture viewpoints, modeling methods,

and tools. Key architecture decisions, concepts, properties, guidelines, principles, protocols, standards, and components, along with their interactions and interdependencies, are captured in the specified form. The result is a comprehensive architecture description consisting of relevant viewpoints, views, models, and their correspondences, expressed in a detailed, correct, and complete manner suitable for their intended use.

Ultimately, the architectural conceptualization activities are interconnected, and their effectiveness depends on the alignment and iterations between them. The standard breaks down each activity into detailed tasks. During this study, it was necessary to tailor those activities for the purpose of the research. For example, the problem characterization activity was tailored to address the specific problems of the research. It focuses on combining context examination, element harmonization, negative and positive influences, and interactions between proposed solutions, as well as establishing desired functional and non-functional characteristics that correspond to the stakeholders' concerns. Section 3.5.7 presents more information on tailoring activities. Section 3.8 describes how the research defined a strategy to address the problems using EA-tailored processes.

3.5.5 Architecture Elaboration Process

The ISO/IEC/IEEE (2019a) definition of the architecture elaboration process is "to describe an architecture in a sufficiently complete and correct manner for the intended uses of the architecture" (p. 47). Elaboration involves detailed documentation and refinement of architectural components, ensuring the architecture is understandable and actionable. This process is critical for developing an enterprise architecture that can be effectively implemented and managed, providing a robust foundation for subsequent architectural activities.

The architecture elaboration process ensures that the architecture is thoroughly developed and detailed to align with organizational goals and stakeholder needs. The EA standard lists several activities and tasks in the elaboration process. Following is a summary of elaboration process activities relevant to the research.

Identify or Develop Architecture Viewpoint (ISO/IEC/IEEE, 2019a item 10.4.3)

Identifying or developing architecture viewpoints involves selecting, adapting, or creating viewpoints and model kinds based on stakeholder concerns. Relevant viewpoints may have been identified during the Architecture Conceptualization process and are examined to

determine if they can be used as-is or require modification. Viewpoints govern the views to be created, addressing specific stakeholder concerns, and should be developed by those familiar with the problem and concerns.

Identifying expected users of the architecture elaboration information, including descriptions, models, and data, is crucial. Establish or identify potential architecture frameworks for developing models and views, considering those established during conceptualization. Frameworks and viewpoints often include metamodels that may need modification for a specific purpose. These metamodels help ensure the completeness and consistency of the architecture description by identifying necessary architecture entities and relationships.

The rationale for selecting frameworks, viewpoints, templates, metamodels, and model kinds must be documented. Define the purpose and scope of each model and view to be developed. Additionally, select, modify, or develop supporting modeling methods and tools, as well as architecture frameworks, modeling templates, and metamodels. Finally, select, modify, or develop relevant metamodel specifications and templates to support generating the necessary models and views.

Develop models and views of the architecture (ISO/IEC/IEEE, 2019a item 10.4.4)

The development of architecture models and views should be tailored to address the specified concerns and questions and the defined purpose, scope, breadth, and depth in the architecture elaboration plan. These models and views must conform to the selected framework and viewpoints and meet stakeholder expectations.

The architectural context and boundaries regarding interfaces and interactions with external entities should be defined for each viewpoint. Identify the entities and their relationships that need to be modeled to address key stakeholder concerns and meet architecture objectives. These entities include organizations, facilities, activities, roles, systems, data elements, and more.

Modify metamodels and view templates associated with the selected frameworks to accommodate relevant modeling elements and relationships. Allocate concepts, properties, characteristics, behaviors, functions, features, or constraints to these entities and

relationships, ensuring they are detailed and relevant.

Identify principles and precepts guiding the evolution of the architecture entity. Select, adapt, or develop architecture models and compose views from these models to express how the architecture addresses stakeholder concerns, principles, precepts, and objectives while meeting requirements.

Identify and address risks and opportunities that emerge in the architectural views and harmonize the models and views with each other. Generate or modify the architecture description based on the relevant models and views, incorporating feedback from issue resolution during the development lifecycle. Finally, the architecture description should be placed in the architecture repository for future reference and use.

When the architecture requires further elaboration, the objectives, concepts, and properties are sufficiently and accurately defined. This provides a foundation for more comprehensive modeling, delineation, and decomposition of these elements. Detailed models and views, along with supporting materials, are used to deepen the understanding of the architecture and ensure consistency with the original concepts and alignment with the objectives.

Architecture processes contribute to creating an architecture description with varying scope, detail, and formality. However, the elaboration process ensures that the architecture description is sufficiently complete and accurate for its intended uses and users downstream from the initial architecture effort.

Notably, the elaboration of an architecture involves extensive effort and resources. The architectural views for this research were elaborated to answer the research questions. Furthermore, since communicating with stakeholders and providing different perspectives are part of the research objective, the elaboration process was driven by achieving specific perspectives. Thus, tailoring to the elaboration architecture process was also practiced, as described in 3.8.

3.5.6 Architecture Evaluation Process

The ISO/IEC/IEEE (2019a) definition of the architecture evaluation process is “to determine the extent to which architectures meet their objectives, address stakeholder concerns, and meet relevant requirements.” (p. 38). The evaluation focuses on verifying and validating that the

architectural solutions fulfill their intended purposes and conform to predefined criteria. This also entails assessing the architecture's performance, usability, and sustainability, as well as identifying potential areas for improvement and adaptation.

The architecture evaluation process is critical in ensuring that the developed enterprise architecture is effective and aligned with organizational goals. It provides a systematic approach to assess the architecture's quality and suitability, guiding necessary adjustments and refinements. The EA standard lists activities and tasks in the evaluation process. Relevant evaluation activities for the study are summarized below.

Determine evaluation objectives and criteria (ISO/IEC/IEEE, 2019a item 9.4.3)

Determining evaluation objectives and criteria involves setting both value assessment and architectural analysis criteria. Value assessment criteria determine how stakeholder concerns and architecture objectives are effectively met, while architectural analysis criteria focus on the concepts and properties contributing to the value assessment. The evaluation objectives may differ from the original conceptualization goals, primarily if the architecture is being evaluated for a different purpose.

First, identify relevant mandates, policies, standards, and stakeholders and their concerns, which may differ from those considered during the original conceptualization. Define value assessment objectives and criteria that align with critical success factors, indicators, and necessary decisions. These criteria should be evaluated for relevance and adapted as necessary for the current evaluation context.

Considering agreed-upon quality attributes, architectural analysis objectives and criteria should be defined to support the value assessment. Establish the structure and relationships between value assessment and architectural analysis criteria to determine how stakeholder concerns are adequately addressed. These relationships help correlate value assessments with analysis results.

Next, examine how the objectives and criteria relate to elements of value or utility, such as value functions or utility curves. Ensure that evaluation objectives and criteria align with requirements and validate them against stakeholder concerns and intended operational uses. Finally, inform stakeholders about the validation process, ensuring traceability to their

concerns, needs, or requirements.

Determine Evaluation Methods (ISO/IEC/IEEE, 2019a item 9.4.4)

Select or develop value assessment and architectural analysis methods that align with the defined objectives and criteria. These methods might already exist in the architecture repository from the Architecture Enablement process, or they can be developed specifically for the current evaluation and later shared for organizational reuse.

Identify and define factors for evaluation, assessment, and analysis according to the chosen methods. Review these methods and associated factors, scales, and weights with the sponsor and architect to ensure alignment. Additionally, identify sources of information to support the evaluation, which may include data from analysis, prior evaluations, operational experience, industry databases, system verification activities, and research efforts.

Establish Measurement Techniques, Methods, and Tools (ISO/IEC/IEEE, 2019a item 9.4.5)

Establishing effective measurement techniques, methods, and tools for architecture evaluation is essential to ensure that the evaluation process is tailored to meet the objectives and criteria without necessarily requiring complex multi-tiered structures or quantitative scales. Identify appropriate measures for relevant architecture concepts and properties and determine metrics to be derived from these measures. Define the relationships between measures, metrics, and evaluation objectives and criteria, and identify sources of information for obtaining values. This process ensures a structured and effective approach to architecture evaluation, facilitating the identification of trade-offs and presenting meaningful insights to stakeholders.

Collect and Review Evaluation-related Information (ISO/IEC/IEEE, 2019a item 9.4.6)

Start by identifying relevant information for the chosen methods and reusing existing data and results from previous evaluations if still valid. Collect all necessary information, including required architectural views and models. Examine and qualify the collected artifacts to ensure they are complete, correct, and consistent. Develop a comprehensive understanding of the architecture, its quality attributes, key decisions, and concerns related

to the architecture or associated entities.

The architecture evaluation process is inherently iterative. As new information emerges and stakeholder feedback is obtained, the evaluation criteria and processes may need to be refined and adjusted. This iterative refinement helps progressively improve the architecture, ensuring it remains aligned with changing needs and conditions. Continuous improvement activities, such as regular performance reviews and feedback loops, are essential to maintain the relevance and effectiveness of the architecture over time. More information on how the research applied evaluation activities is described in 3.7 and 3.8.

3.5.7 Architecture Tailoring

ISO/IEC/IEEE 42020 emphasizes the importance of tailoring architecture processes to meet an organization's unique needs, with a particular focus on iterative and recursive applications and life cycle stages. Process iteration involves repeatedly applying the same process or set of processes at the same level of an architectural structure. This iterative approach is crucial for progressively refining process outputs, such as building confidence in the architecture's suitability through successive evaluation efforts. Iteration is appropriate and expected, as it generates new information, often in the form of questions regarding architecture objectives, stakeholder needs, and analyzed risks or opportunities.

On the other hand, process recursion involves applying the same processes to the entire architecture and its various parts. This recursive method allows outcomes from one process application to serve as inputs for subsequent processes at the next level of recursion, facilitating the creation of a more detailed and mature architecture structure. This approach adds incremental value to successive iterations of the architecture.

The standard also highlights the importance of life cycle stages in managing architecture processes. The dynamic nature of influences on architecture—such as changes in the operational environment, new implementation opportunities, and modifications in organizational structures—requires continual review of process selection and timing. The life cycle approach is designed to dynamically respond to these external influences, incorporating changes into subsequent stages as necessary.

In summary, the discussion on the iterative and recursive use of architecture processes and the life

cycle approach does not imply any specific hierarchical or structural organization for the architecture. Instead, it underscores the flexibility and adaptability needed to manage and refine architectures effectively, ensuring they meet evolving requirements and stakeholder needs.

In the research, tailoring was performed continually. For instance, tailoring was used to frame different concerns, delimit the life-cycle stage, communicate with stakeholders, and improve the value of views and findings. More details about tailoring activities, purpose and outcomes, are provided in Chapters 4 to 7.

3.6 Modeling Framework

A *modeling framework* is a structured approach that provides the guidelines, methodologies, and tools necessary to create models representing various aspects of a system. In the context of EA, modeling frameworks offer a systematic way to capture, visualize, and analyze an enterprise's architecture. They help ensure consistency, accuracy, and comprehensiveness in documenting the enterprise's processes, information flows, organizational structures, and technological components.

A modeling framework typically includes the following:

a. a language metamodel, which defines the syntax and semantics of the modeling language used;

b. processes, which outline the steps and methodologies for developing models and

c. tools, which facilitate the creation, manipulation, and analysis of models.

These components enable architects to effectively design, assess, and manage the enterprise architecture, aligning it with strategic business goals and ensuring its adaptability to changing requirements.

The EA modeling framework utilized in this research is the Unified Architecture Framework (UAF). Thus, the views generated during the architecture elaboration process were modeled according to the UAF standard (ISO/IEC, 2022). The following sections will introduce the UAF standard as a metamodel and language, explain its scope, and present the UAG grid. Next, an

explanation of how UAF adheres to EA processes and the modeling tools used to elaborate the architecture.

3.6.1 The Unified Architecture Framework

The UAF is a standardized framework designed to support enterprise architectures' development, maintenance, and management, particularly in complex and mission-critical environments. As both a metamodel and a language, UAF provides a structured approach to model and analyze various aspects of architecture, ensuring consistency and interoperability across different domains and stakeholders.

The UAF formal specification was released by the Object Management Group (OMG). The document that provides all information regarding the UAF Domain Metamodel is also a standard named ISO/IEC 19540-1 Information Technology — Object Management Group Unified Architecture Framework (OMG UAF) — Part 1: Domain Metamodel (DMM) (ISO/IEC, 2022).

Origins and Influences

The UAF is a relatively recent development in enterprise architecture. It evolved from a need for a comprehensive and standardized approach to modeling complex systems. The first official version, UAF 1.0, was released in 2017. The most up-to-date version is UAF 1.2, which was released in December 2021. UAF's origins can be traced back to various architectural frameworks that preceded it, particularly those developed to support defense and governmental organizations.

Recognizing the need for a unified approach that could integrate the best practices and methodologies from DoDAF (U.S. Department of Defense Architecture Framework), MODAF (U.K. Ministry of Defense Architecture Framework), and NAF (NATO Architecture Framework), OMG initiated the development of UAF. The goal was to create a comprehensive framework for defense and other civil domains, such as healthcare, finance, and transportation.

UAF Scope and Intended Usage

The UAF facilitates modeling strategic capabilities, operational scenarios, services, resources, personnel, security, projects, standards, measures, and requirements. This supports best practices through the separation of concerns and abstractions. Additionally, UAF enables the modeling of related architectural concepts such as the system of Systems (SoS); Information exchanges

consistent with the National Information Exchange Model (NIEM); The Department of Defense's (DoD) doctrine, organization, training material, leadership & education, personnel, and facilities (DOTMLPF); The UK Ministry of Defence Lines of Development (DLOD) elements; and Human-Computer Interfaces (HCI).

Moreover, UAF adheres to the terms defined in the ISO/IEC/IEEE 42020 standard for architecture description. It includes terms like architecture, architecture description (AD), architecture framework, architecture view, architecture viewpoint, concern, environment, model kind, and stakeholder. These terms form correspondence rules specified as constraints on UAF, ensuring consistency and standardization in architectural modeling.

UAF Grid

The UAF grid is designed to manage the complexity of multiple viewpoints with overlapping concerns and metamodels. It organizes these viewpoints into a more manageable format, refining the standard viewpoints from the donor frameworks. This refined approach allows for better handling and visualization of the architectural data.

The primary purpose of the UAF grid is to capture and organize information from the contributing frameworks into a coherent structure. It helps users navigate the complexity of the architecture by providing a structured way to understand how different parts of the architecture relate to each other. Architects can use the grid as a map to understand views and find perspectives, which can be helpful for the modeler's intention.

Figure 3.3 shows the UAF grid presented in ISO (2022) (p. 13). The UAF grid is composed of view specifications, viewpoints (formerly known as domains), and aspects (formerly known as model kinds):

a. View Specifications (Cells): Each cell in the grid represents a view specification detailing a specific aspect of the architecture.

b. Viewpoints (Horizontal Rows): The rows correspond to different viewpoints, capturing various domains within the architecture.

c. Aspects (Vertical Columns): The columns represent aspects that describe the view specifications, offering different perspectives on the architectural data.

The acronym for each view is defined according to viewpoint and aspect.

Table 3.1 was extracted from the UAF specification and provides descriptions of all viewpoints. Similarly, Table 3.2 provides definitions of the aspects of the grid. The UAF grid offers a structured and organized way to handle the complexity of enterprise architectures. Breaking down the architecture into manageable view specifications, viewpoints, and aspects helps to ensure that all relevant information is captured and accessible.

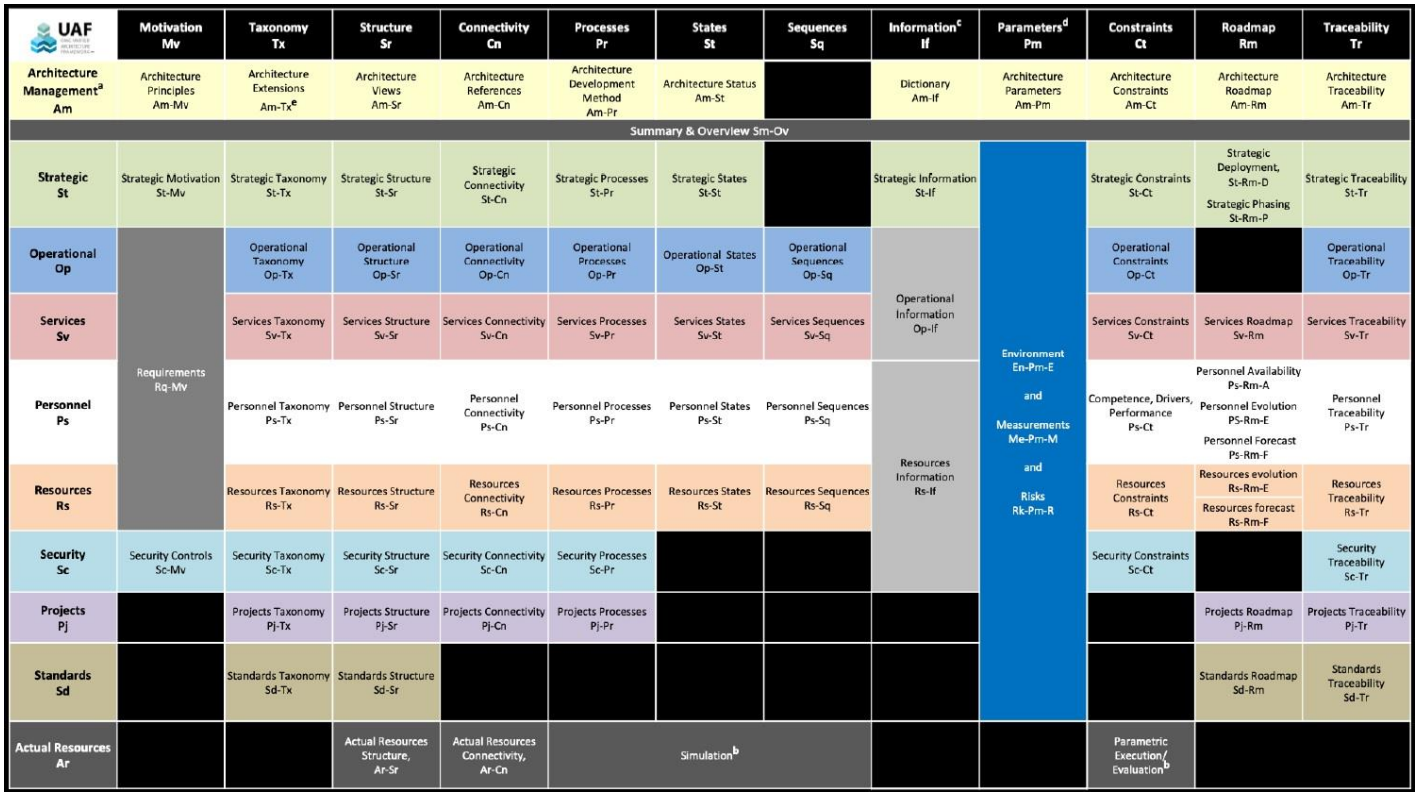

Figure 3.3: UAF Grid (ISO/IEC, 2022) (p.13)

Table 3.1: Descriptions for the Viewpoints in ISO/IEC (2022) p. 14

Viewpoint	**Acronym**	**Description**
Architecture Management	Am	Identifies the metadata and views required to develop a suitable architecture that is fit for its purpose.
Strategic	St	Capability management process. Describes the capability taxonomy, composition, dependencies, and evolution.
Operational	Op	Illustrates the Logical Architecture of the enterprise. Describes the requirements, operational behavior, structure, and exchanges required to support (exhibit) capabilities. Defines all operational elements in an independent implementation/solution manner.
Services	Sv	The Service-Orientated View (SOV) describes services needed to directly support the operational domain as described in the Operational View.
Personnel	Ps	Defines and explores organizational resource types. It shows the taxonomy of types of organizational resources as well as connections, interaction, and growth over time.
Resources	Rs	Captures a solution architecture consisting of resources, e.g., organizational, software, artifacts, capability configurations, and natural resources that implement the operational requirements. Further design of a resource is typically detailed in SysML or UML.
Security	Sc	Security assets and security enclaves. Defines the hierarchy of security assets and asset owners, security constraints (policy, laws, and guidance), and details where they are located (security enclaves).
Projects	Pj	Describes projects and project milestones, how those projects deliver capabilities, the organizations contributing to the projects, and dependencies between projects.
Standards	Sd	MODAF: Technical Standards Views are extended from the core DoDAF views to include non-technical standards such as operational doctrine, industry process standards, etc. DoDAF: The Standards Views within the Standards Viewpoint are the set of rules governing the arrangement, interaction, and interdependence of solution parts or elements.
Actual Resources	Ar	The analysis and evaluation of different alternatives, what-ifs, trade-offs, and V&V on the actual resource configurations. Illustrates the expected or achieved actual resource configurations.

Table 3.2: Definitions of the Aspects in ISO/IEC (2022) p. 15

Aspect	**Acronym**	**Description**
Motivation	Mv	Captures motivational elements, e.g., challenges, opportunities, concerns about enterprise transformation efforts, and different types of requirements, e.g., operational, services, personnel, resources, or security controls.
Taxonomy	Tx	Presents all the elements as a standalone structure. It presents all the elements as a specialization hierarchy, provides a text definition for each, and references the element's source.
Structure	Sr	Describes the breakdown of structural elements, e.g., logical performers, systems, projects, etc., into their smaller parts.
Connectivity	Cn	Describes the connections, relationships, and interactions between the different elements.
Processes	Pr	Captures activity-based behavior and flows. It describes activities, their Inputs/Outputs, activity actions, and flows between them.
States	St	Captures state-based behavior of an element. It is a graphical representation of the states of a structural element and how it responds to various events and actions.
Sequences	Sq	Provides a time-ordered examination of the exchanges between participating elements resulting from a particular scenario.
Information	If	Address the information perspective on operational, service, and resource architectures. Allows analysis of an architecture's information and data definition aspect without consideration of implementation-specific issues.
Constraints	Ct	Details the measurements that set performance requirements constraining capabilities. It also defines the rules governing behavior and structure.
Roadmap	Rm	Addresses how elements in the architecture change over time.
Traceability	Tr	Describes the mapping between elements in the architecture. This can be between different viewpoints within domains as well as between domains. It can also be between structure and behaviors.

UAF Viewpoints

Although the grid is the primary tool for expressing the relationships between *Viewpoints*, *Aspects*, and *View Specifications*, its two-dimensional format is insufficient for explaining the abstract interrelationships between the viewpoints. Figure 3.4 illustrates how the viewpoints are interrelated. When a Viewpoint is depicted vertically, it indicates that the viewpoint is a cross-cutting concern that spans various levels of abstraction within the architecture. Conversely, when a viewpoint is depicted horizontally, it signifies that it occupies a layer of abstraction between the viewpoints above and below it and that there are interrelationships with the viewpoints on either side.

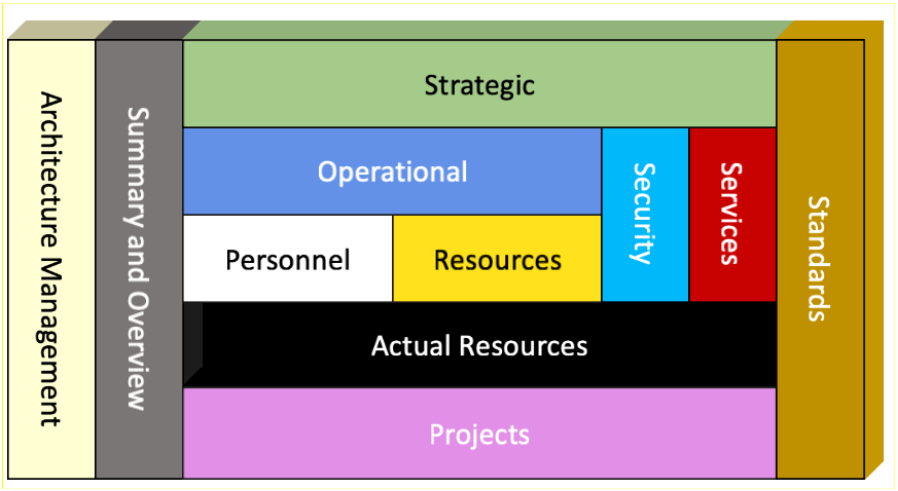

Figure 3.4: UAF Viewpoints (ISO/IEC, 2022) p.16

UAF Modeling Language

While the UAF Domain Metamodel (DMM) (ISO/IEC, 2022) establishes foundational constructs for modeling an enterprise and its major entities, the UAF Modeling Language (UAFML) provides the modeling language specification for implementing the UAF DMM using Unified Modeling Language (UML) profile and OMG Systems Modeling Language (SysML). OMG also released the UAFML specification, and information about version 1.2 was provided in OMG UAF (2022a).

The UAFML was built on top of SysML. In other words, the UAFML profile fully imports the SysML profile to ensure seamless integration with system modeling using SysML and to fully utilize SysML's capabilities within UAFML. This integration allows for incorporating Requirements (from the SysML environment) into UAFML, utilizing Parametric Diagrams

(SysML), and integrating elements based on instance specifications.

The specification OMG UAF (2022a) details the language architecture by describing the reused parts of UML 2.5.1 and SysML 1.7, along with the specific UML 2.5.1 extensions. It also guides on implementing UAFML.

Stereotypes in the UAFML are predefined extensions of the UML and SysML profiles. These stereotypes provide specific constructs representing the unique elements and concepts defined in the UAF DMM. Pre-determined stereotypes in UAFML include those directly inherited from SysML, ensuring a consistent and standardized approach to modeling. These stereotypes are designed to address the requirements outlined in the UAF, such as architectural components, relationships, and viewpoints.

UAFML also allows the customization of stereotypes or viewpoints to meet specific modeling needs. Customization can be achieved by extending existing stereotypes, creating new stereotypes, or using UML profiles. It typically involves defining additional properties, constraints, or behaviors specific to the user's domain or project requirements. The same applies to viewpoints. As described in the previous section, UAF has predefined viewpoints but also allows customization. Customization in UAFML enhances the framework's flexibility, enabling it to be tailored to a wide range of industries and use cases. This adaptability is crucial for addressing the diverse needs of stakeholders and ensuring that the architecture accurately reflects the complexities of the enterprise. The research has created viewpoints (explained in 3.8) to address specific concerns using predefined stereotypes and aspects.

EA processes in UAF

OMG has provided the UAF specifications (normative documents) a guide to implementing EA processes. The informative document is named EA Guide for UAF (OMG UAF, 2022b) and is designed to be used alongside the UAF Sample Problem (OMG UAF, 2021), which defines architecture views for a Search and Rescue Mission. The EA Guide for UAF outlines a workflow for generating EA views using the UAFML.

The workflow consists of nine steps that align with UAF stakeholder viewpoints, ensuring the creation of the necessary architecture views for each viewpoint. This method for describing architecture is an implementation of the Architecture Elaboration (presented in 3.5.5 according to

ISO/IEC/IEEE (2019a)), and it can be integrated with the processes for Conceptualization and Evaluation of an architecture (3.5.4 and 3.5.6). Additionally, it serves as a foundation for an EA modeling methodology, architecture development planning, and organizing and planning modeling projects. The Guide addresses both the enterprise architecture and the high-level architecture of major entities within the enterprise.

The workflow for implementing the elaboration architecting activities is depicted in Figure 3.5. Each step in this workflow helps iteratively define both the problem and solution spaces (i.e., implementation and instantiation). During this process, tradeoffs are identified, and the outcomes of architectural decisions are documented in the architecture views as they are developed.

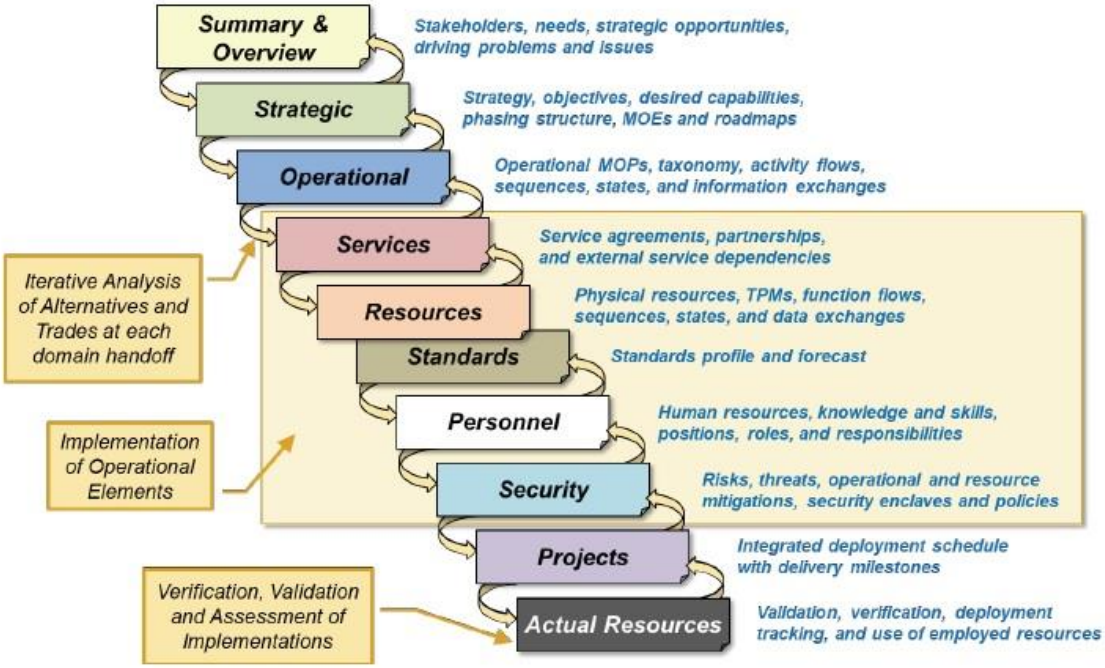

Figure 3.5: General Nature of the Workflow (ISO/IEC, 2022) (p.16)

The process involves back-and-forth repetition between steps to ensure a complete and coherent depiction of the architecture. It is not strictly necessary to implement this in a top-down manner, as this can sometimes be counterproductive. The downward arrows in the figure represent the progression from higher levels of abstraction to more concrete elements, not a sequential order of tasks. The upward arrows indicate the iteration back to higher levels of abstraction for necessary adjustments and modifications.

These steps are often executed simultaneously with significant iteration within and between the

viewpoint levels. Collaboration between stakeholders at different viewpoint levels is also common. In any architecting effort, only some of these steps are typically completed. For instance, the problem framing step, related to 3.5.4 and described in OMG UAF (2022b) item 2.4, helps identify the most relevant and valuable architecture views to collect or create. This step focuses on the users and uses of each view and the questions each view intends to answer. This approach was followed during the architecture elaboration in this research, as explained in 3.8.

3.6.2 Modeling Tool

The digital tool used to model architecture views during the research is:

CATIA Magic Systems of Systems Architect (versions 2022x), Dassault Systems;

Student Seat License; Registered to Keio University Graduate School; Windows 10 Operating System.

3.7 Validation Methods

The EA methodology offers guidance for validating architecture as described in ISO/IEC/IEEE (2019a and 2019c). The standard ISO/IEC/IEEE 21840:2019(E) (2019c) defines on page 53 the purpose of the validation process as "to provide objective evidence that the system, when in use, fulfills its business or mission objectives and stakeholder requirements, achieving its intended use in its intended operational environment." Validating the architecture involves modeling verification and validation and the architecture evaluation process defined in EA standard ISO/IEC/IEEE (2019a).

For this research, the validation process was conducted both internally and externally. Internally, the methodology's validation processes and modeling verification were utilized. Externally, the proposed solution was evaluated against the operational context and principles of safety, security, and sustainability. External validation involved safety, flight operations, security, sustainability, and systems engineering professionals. Each concern generated a viewpoint presented and discussed with experts on the problem's domain. These validation efforts (internal and external) occurred iteratively, recursively, and sometimes concurrently.

3.7.1 Evaluation Objectives and Criteria

Defining evaluation objectives and criteria involved setting both value assessment and architectural analysis criteria. Value assessment criteria ensure that stakeholder concerns and architecture objectives are effectively met. For this step, the research strategically created separated viewpoints, using the same UAM SoS architecture, to address stakeholders' concerns (see 3.8). First, stakeholders that share the same concern or are affected by the solution space were identified. During the research, discussions with other researchers and practitioners provided insights and refined the list of relevant stakeholders. Eventually, more practitioners and experts on stakeholder perspectives were invited to discuss and contribute to the results. Then, for each concern, a dedicated multidisciplinary team has assessed the value of architecture views.

Invited contributors with different backgrounds analyzed the architecture regarding the clarity of the solution, the effectiveness of the diagram visualizations, the accuracy of elements and their interactions according to projected operations, and the architecture's coverage (breadth and depth). Next, the objectives and criteria were examined with elements of value or utility, such as value functions or utility curves. Architectural analysis objectives and criteria were defined to support the value assessment, considering the research purpose and objective. In other words, the results considered the boundaries of the study, as well as its effectiveness in answering the research questions.

3.7.2 Evaluation Methods

The stakeholder's validation (external) was fundamental in evaluating the effectiveness of the proposed architecture. It validates that the architecture aligns with stakeholder requirements and expectations. Validators can verify that the architecture adequately addresses business needs, technical specifications, regulatory compliance, and other key requirements, enhancing overall alignment and stakeholder satisfaction (ISO/IEC/IEEE, 2023). Experienced systems engineers, safety practitioners, and pilots were invited to understand the research and the different architectural views. The discussion carried out by the multiple perspective groups has the purpose of challenging the architecture elaboration, the ideas represented by diagrams according to theoretical foundations, and practicality in the UAM's future operations.

Most of the external assessments were conducted through virtual meetings, with individuals, or

during group seminars, and feedback was provided during those sessions. For each concern, there is a published article with different co-authors. Analyzing the diagrams and rationale was similarly performed during the preparation, review, and peer-review process. Different feedback was received, which included improving the diagram presentation, correcting resource exchange naming and flows, including new elements, and modifying responsibilities. The discussions with multidisciplinary teams help the conceptual modeling process and, most importantly, the qualitative assessment of the proposed solutions according to ISO/IEC/IEEE (2019a).

With respect to the modeling effort, the author performed a (internal) consistency check and semantic analysis considering the elaboration process and modeling framework (ISO/IEC, 2022; OMG UAF, 2022a). Although not all views, model aspects, and elements were elaborated for each viewpoint, the enterprise motivation and strategy were defined for all concerns due to time and resource limitations. From the defined goals (mission and values), the strategic capabilities were then defined and associated with goals. The strategic capabilities are the base for defining the functional architecture, resource architecture, and personnel structure. More explanations of the elements and the development of the architecture are described in the following Chapters. Thus, verification and validation were conducted through analysis activities, including element associations, tracing, and coverage after multiple iterations and corrections. Language verification was also performed to check the semantics.

3.8 Modeling Strategy and Organization

In the UAF standard ISO/IEC (2022), a *view* is a representation of a whole system or a subsystem from the perspective of a related set of concerns. Views are used to describe the system's architecture, focusing on specific aspects that are important to stakeholders. Each view contains one or more models that address a set of concerns, providing a comprehensive depiction of the system’s architecture. A *viewpoint* specifies the conventions for constructing and using a view. It defines the stakeholders whose concerns are being addressed by the view, the elements that appear in the view, and the methods and techniques used to create and analyze the view. Essentially, a viewpoint provides the framework for creating views, ensuring consistency and relevance to the stakeholders’ concerns.

The relationship between views and viewpoints in UAF is critical for organizing and managing architectural information. Viewpoints define the perspectives and rules for creating views, ensuring that each view is constructed to address specific stakeholder concerns effectively. By adhering to defined viewpoints, views are created consistently and systematically, allowing for comprehensive analysis and communication of the architecture.

This study has used the model element <<concern>> to express the socio-technical concerns of the research scope. This means that for each concern, there is a group of stakeholders interested in and a view to address the problem in the UAM context. Figure 3.6 depicts the modeling strategy to organize the viewpoints according to concerns.

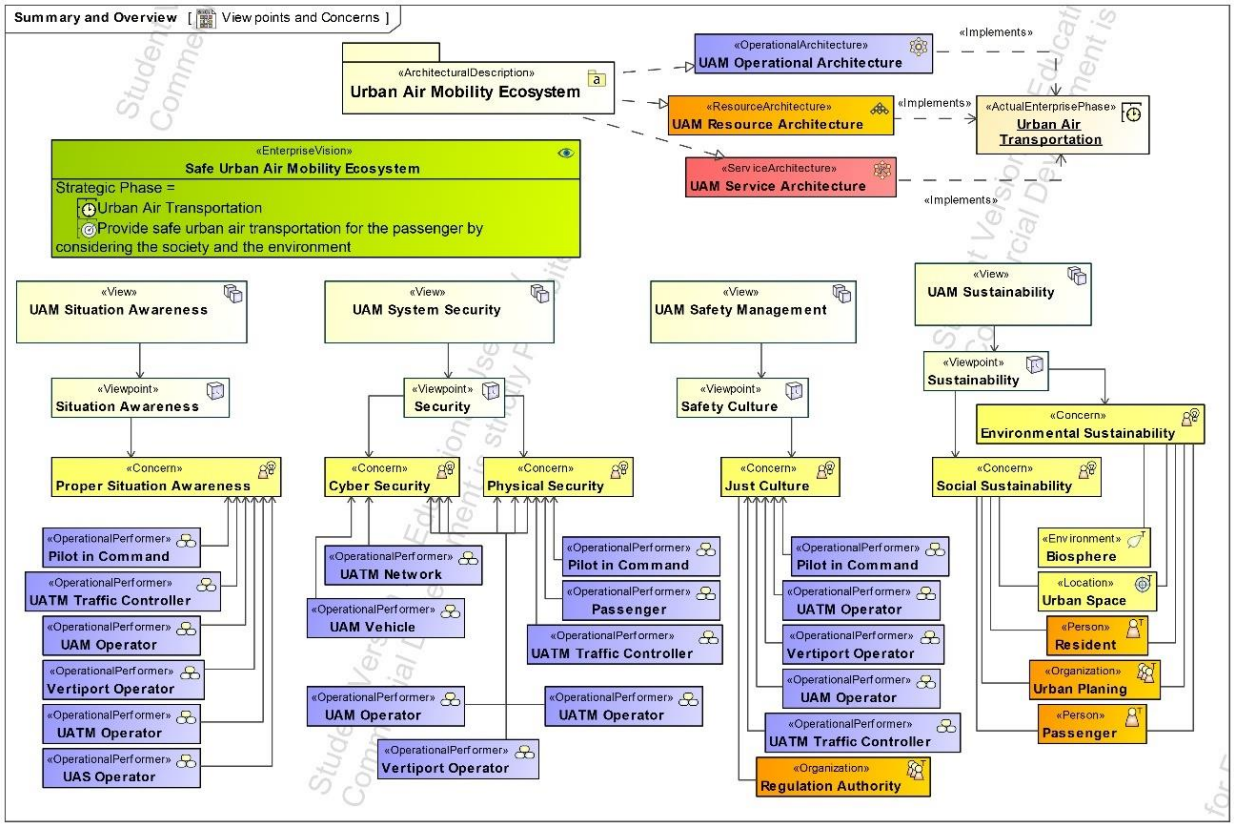

Figure 3.6: Modeling Strategy and Organization: Viewpoints and Concerns

The *Summary and Overview (St-Sr)* diagram in the UAF provides a high-level summary of the architecture, offering a comprehensive overview that captures the essential elements and their relationships within the system. This diagram intends to communicate the overall architecture to stakeholders. It also helps define the scope of the architecture, outlining the boundaries and main

elements. This is useful for identifying what is included in the architecture and what is not, providing clarity on the extent of the architectural effort.

The diagram aims to inform that one single enterprise represents the UAM SoS as <<ArchitectureDescription>> *Urban Air Mobility Ecosystem*. There are three types of architectures realizing the UAM enterprise: «OperationalArchitecture» which describes the UAM operational aspects, «ResourceArchitecture» representing the resources required for the UAM operations, and «ServiceArchitecture» which outlines the services provided within the UAM enterprise. Those are predefined viewpoints of the UAF and are valuable for exploring operational processes, resource planning, and service structures, to mention a few examples. Still, on the top of the diagram, the element <<ActualEnterprisePhase>> *Urban Air Transportation* aims to show that all architecture types implement the UAM during the utilization stage, specifically urban air transportation. This is an important boundary and assumption for the conceptualization and elaboration of the architecture.

The <<EnterpriseVision>> (green box) is another significant value that will drive the enterprise goals. The vision of the *Safe Urban Air Mobility Ecosystem* is the vision of the enterprise and is further detailed in the statement: *Provide safe urban air transportation for the passenger by considering society and the environment*. This vision shall encompass all concerns; consequently, all viewpoints must be aligned with the enterprise's higher priority. It serves as a pointer to coherently combine viewpoints into a unity, an ultimate common goal.

At the bottom of the diagram are four views: UAM Situation Awareness, UAM System Security, UAM Safety Management, and UAM Sustainability. Each <<View>> has its own <<Viewpoint>> that can address one or more <<Concern>>. Below each concern, there is a set of stakeholders associated with it. For instance, all the <<OperationalPerformers>> on the bottom left are concerned about achieving and maintaining a *Proper Situation Awareness* (<<Concern>> addressed in <<Viewpoint>> *Situation Awareness*) during UAM operations.

The same applies to the security viewpoint, with the difference that it addresses two concerns: *Cyber Security* and *Physical Security*. Some stakeholders can be concerned only with cyber threats, while others are with the physical world. Alternatively, it can still have both concerns, like the <<OperationalPerformers>> UAM Operator (or Vertiport Operator, or UATM Operator), which is involved with digital and physical systems.

In the safety management view, the <<Viewpoint>> *Safety Culture* addresses the <<concern>> *Just Culture.* Stated differently, the UAM safety management takes care of the safety culture and is concerned about establishing a Just Culture. The operational elements that are interested parts in this concern are listed and associated with it. Particularly, in this view, there is an external stakeholder, the <<Organization>> *Regulation Authority*. In Chapter 6, this essential relationship will be explained and reasoned.

Lastly, the <<Viewpoint>> *Sustainability* addresses two concerns: *Social Sustainability* and *Environmental Sustainability*. The stakeholders in this case are represented by other kind of entities, such as <<Environment>> *Biosphere*, <<Location>> *Urban Space*, <<Person>> *Resident*, <<Organization>> *Urban Planning*, and <<Person>> *Passenger*. The diagram does not intend to include all stakeholders who have any relation to the problem or the solution. Instead, it informs the primary stakeholders affected by the concern. The view in Figure 3.6 aims to depict the most critical players interested in addressing the concern, not all who could benefit from the solution. More explanations on each concern will be presented in the following Chapters.

In conclusion, the modeling strategy was designed to organize the views and explore the concerns in an exclusive environment with particular goals and objectives. Boundaries and constraints depend on the problem. Likewise, external influences and how they can impact each desired effect rely upon individual views. With this strategy, it was possible to explore the viewpoint holistically, dedicating the model effort to customized views with distinct purposes. This view is also a guide for the evaluation and validation when it comes to assessing the value of the architecture regarding the stakeholder's needs. Moreover, it provides a scheme to understand how the problems were discussed and analyzed. Chapter 4 will show the Safety Awareness viewpoint, Chapter 5 the Security viewpoint, Chapter 6 the Safety Culture viewpoint, and Chapter 7 the Sustainability viewpoint.

3.9 Limitations of the Research Methods

This subsection discusses the limitations inherent in the methodology applied in this doctoral research. It addresses potential constraints, biases, and challenges encountered during the study and how these limitations may impact the findings and interpretations.

Models are inherently simplifications of complex systems and may not capture all the nuances of real systems. They rely on assumptions and approximations that can introduce uncertainties and potential biases. Consequently, the results derived from these models should be viewed as indicative rather than definitive. Acknowledging that these models cannot account for every variable and dynamic interaction in real-world scenarios is essential. Therefore, while they provide valuable insights and help guide decision-making, they should not be considered absolute representations of reality. Researchers and practitioners must interpret these findings cautiously, understanding that they offer a framework for understanding trends and potential outcomes rather than exact predictions. This recognition of the limitations of modeling underscores the need for continuous validation and refinement of models with real-world data as UAM technology and operations evolve.

The EA standard ISO/IEEE 42020 (2019a) does not establish formal traceability with the System Life Cycle standard ISO/IEC/IEEE 15288 (2023) or any other specification. As a result, satisfying all the requirements in EA 42020 does not guarantee that the architecture process requirements outlined in other Systems Engineering specifications are also fulfilled.

Regarding the modeling framework, the UAF has a metamodel (ISO/IEC, 2022) with a defined ontology and semantics. Although the architect has some freedom to create elements, views, and relationships, most of the modeling effort follows the established rules in the language specification and guides (OMG UAF, 2022a; ISO/IEC/IEEE 2019c). The architect is a limitation as a resource that conceptualizes the architecture. Even skilled architects may lack specific knowledge or present bias that brings limitations to the architecture as a product of human cognitive work.

Moreover, conceptualizing and elaborating architecture is deeply influenced by the architect's subjectivity, a unique and valuable perspective in collaborative efforts. Different individuals or groups of architects can propose different solutions for the same problem, each bringing their own distinct viewpoint. This process involves multidisciplinary teams, discussions, validations, iterations, and recursions, all of which are different parts of the methodology that aim to converge to an elegant solution. Notably, the outcome of the architectural elaboration is typically not rigid and final. Modifications, improvements, and situational tailoring are expected and can occur in a manner that supports the enterprise's goal.

Complexity is another aspect that brings limitations. UAM is a complex and evolving System-of-System. Despite efforts to explore it holistically, the dynamic nature of UAM may result in some aspects being beyond the scope of this thesis. On top of a complex ecosystem, UAM is a conceptual operation. Data availability relies on conceptual studies and proposals for an imagined future. There are no actual data, only extrapolations and reasonable assumptions. The quality and availability of data related to UAM are also limitations.

The lack of actual regulatory information for UAM operations is pertinent to mention. In aviation, regulatory standards are typically a hardship constraint. Not having operational definitions during the UAM utilization stage poses a significant limitation for any study proposing solutions for its future operations. Developing comprehensive and feasible solutions that ensure safety, security, and compliance becomes challenging without established regulations. This regulatory uncertainty leads to difficulties in predicting the requirements and constraints that future UAM operations must adhere to, thereby limiting the ability to design robust and scalable operational frameworks. Additionally, the absence of clear guidelines hinders the ability to align proposed solutions with potential regulatory developments, increasing the risk of misalignment with future legal and operational standards.

Lastly, there are interdisciplinary challenges. Integrating multiple disciplines, methods, and subjects, as this work does, is challenging. The interdisciplinary approach introduces complexities that require trade-offs in depth and breadth. Since the ecosystem perspective proposes a whole visualization, there are more perspectives than those developed by this research. Likewise, experts invited to discuss and validate the views do not represent all possible contributors. Consequently, the validation and discussion are limited to the expert's experience and knowledge.

The structured methodology of identifying relevant stakeholders, engaging them through discussions, and iteratively refining the architecture based on their feedback is a replicable process. Future researchers can follow a similar approach by engaging stakeholders relevant to their specific context, using virtual or in-person meetings for discussions, and incorporating feedback to ensure that the architecture aligns with stakeholder needs. The use of established standards and frameworks (e.g., ISO/IEC/IEEE) for consistency checks and semantic analysis further supports the replicability of the approach.

However, reproducing the process and getting the same results is not trivial. Like any modeling

framework, the results are subject to the assumptions and simplifications inherent in the chosen resources. Additionally, proposing solutions for socio-technical concerns involves a broad and diverse range of possibilities. The intention of the modeling effort and the desired level of detail can be different and produce different views. The challenge of reproducing the same results by following the same steps relies on each human resource involved in the process: researchers, architects, and stakeholders. Recognizing these limitations is crucial for interpreting the findings and for future research to build upon and refine the proposed solutions.

CHAPTER 4

Situation Awareness Concern in the UAM System of Systems

4.1 Introduction

Situation Awareness (SA) is a critical socio-technical concern in UAM operations, as achieving success at SA levels requires the systemic integration of technology, people, organizational structures, and operational procedures. In the densely populated and dynamic urban environments where UAM operates, high levels of SA are essential for safe and efficient air traffic management. This necessitates advanced technological systems for real-time data acquisition and processing, skilled personnel capable of interpreting and acting on this information, well-defined organizational structures to support communication and decision-making, and robust operational procedures to ensure consistent and effective actions. Failures in these components can compromise SA, leading to significant safety risks, operational inefficiencies, and potential accidents. Therefore, addressing SA as a socio-technical concern is essential for mitigating risks and ensuring the successful integration of UAM into urban infrastructure.

SA refers to the perception, comprehension, and projection of elements in an environment over time. In the context of UAM, SA encompasses the ability of operators, pilots, and autonomous systems to perceive their surroundings accurately, understand the implications of their current state, and anticipate future conditions. Given the complex nature of urban airspaces, achieving high levels of SA is required to prevent accidents, manage traffic, and respond to emergencies effectively.

This Chapter investigates the various facets of SA within the UAM ecosystem. It begins with exploring the SA problem space and identifying key challenges and obstacles that hinder the attainment of optimal SA. Following, it transitions into the SA solution space, where we discuss

potential technological and procedural measures designed to enhance SA in UAM operations. Subsequent sections provide detailed architectural views and discussions on SA. Different enterprise perspectives are presented, including enterprise strategic vision, capability taxonomy, constraint taxonomy, operational concept, process flow, and service taxonomy. Results include diagrams and insights, and lastly, SA is discussed as an enterprise competence. Finally, it concludes with validating the proposed SA views, supported by multidisciplinary discussions and expert feedback.

Furthermore, this Chapter aims to answer Research Question 2: "How does Situation Awareness behave as a collective cognitive process distributed at different UAM ecosystem levels, and how does it compromise UAM safe operation?". Addressing this question involves examining how SA operates across various levels of the UAM ecosystem, from individual operators to interconnected systems, and understanding the potential risks and safety concerns arising from compromised SA.

The theoretical foundations of SA and existing literature evidence introduced in Chapter 2's literature review will be instrumental in discussing the problem space and the proposed solutions in this Chapter. The diagrams presented in this Chapter were created per EA methodology, utilizing the Unified Architecture Framework (UAF) version 1.2, as explained in Chapter 3. Additionally, it is noteworthy that most of the content of this Chapter has been published in the IEEE Open Journal of Systems Engineering in March 2023 in the article called "Urban Air Mobility Situation Awareness from Enterprise Architecture Perspectives" (Hoffmann et al., 2023a).

Through a comprehensive examination of SA in UAM, this Chapter aims to contribute to the broader discourse on UAM, providing an SoS-level understanding of achieving and maintaining high levels of SA in this ecosystem.

4.2 UAM Situation Awareness Problem Space

Increased airspace traffic, the augmented need for communication with other vehicles and traffic controllers, reduced crew sizes, and the proximity of urban terrain, which adds obstacles, are just a few factors contributing to the complexity of UAM operations. Additionally, introducing new technologies, which can reduce operator trust due to unfamiliarity and perceived unreliability, and

implementing novel procedures and protocols all contribute to a significantly higher workload during UAM operations. In this context, SA is not just important but strategic and vital for ensuring the safe operation of UAM systems.

To address the SA problem space, the architecture conceptualization process from EA methodology provides some steps to characterize the problem as described in ISO/IEC/IEEE (2019a) item 8.4.3. It starts by identifying the potential problem areas that need to be addressed. These include increased airspace traffic, the augmented need for communication, reduced crew sizes, urban terrain obstacles, and the challenges posed by new technologies and procedures (Vascik et al., 2018; Thipphavong et al., 2018; Straubinger et al., 2020).

Next, we identify the current and projected situations in the problem space. Currently, operators are overwhelmed by high traffic and communication demands, are unfamiliar with new technologies, and must deal with urban obstacles. Future scenarios projected by Edwards et al. (2019) indicated that further increases in air traffic and technological advancements will continue to raise workload and complexity.

We then identify the problems and opportunities in these current and projected situations. The main problems are high operator workload, reduced situational awareness, and potential safety risks. However, there are also opportunities to enhance SA through better technology integration, support from autonomous systems, improved training, and optimized communication protocols (FAA, 2022; Edwards et al., 2019). Identifying relevant aspects of these situations involves considering human factors such as cognitive load, trust in technology, and training needs. Technological factors include real-time data analytics, AI-driven decision support, and communication systems. Organizational factors encompass resource and workload management, coordination mechanisms and processes, preparedness for response protocols, and supportive processes to enable the operator's capabilities.

Examining current and future business and mission needs concerning these problems and opportunities reveals that current needs focus on effective air traffic management, reliable communication systems, and operator training. Future needs will require scalable systems to handle increased traffic, the integration of advanced technologies, and adaptive training programs.

Identifying stakeholders and their concerns related to these problems and opportunities is crucial. Key stakeholders include individual operators like pilots and ground operators; air traffic controllers; technology developers (vehicle systems and network systems developers), also known as Original Equipment Manufacturers (OEMs); regulators like aviation agencies and urban planners; and service providers like UAM Operator and Vertiport Operator.

It is crucial to understand how the problems and opportunities affect different stakeholders and their priorities. Individual operators prioritize manageable workloads, reliable systems, and accurate decision-making. Air traffic controllers focus on effective communication and traffic management. Technology developers aim for user-friendly, trustworthy systems and appropriate operational tasks. Urban planners seek safe integration with urban infrastructure. UAM and Vertiport Operators must provide safe services within the UAM business for continued user acceptance and business sustainability.

Finally, formulating a clear statement of the problems involves identifying risks, opportunities, and constraints. The main problem is that integrating UAM into urban environments poses significant challenges in maintaining Situation Awareness due to increased airspace traffic, communication demands, reduced crew sizes, urban obstacles, and the introduction of new technologies and procedures. These factors contribute to higher operator workloads and potential safety risks. The primary risks include overwhelmed operators, reduced SA, and an increased likelihood of accidents. Opportunities exist to leverage advanced technologies, improve operator training, and optimize communication protocols. Constraints include planning for human systems integration capabilities, preparing the whole organization to establish SA as a competence, integrating with existing infrastructure, and complying with regulations.

4.3 UAM Situation Awareness Solution Space

To develop the SA solution space, the EA conceptualization process, as described in ISO/IEC/IEEE (2019a) item 3.4.6, was tailored to the research objectives. This section will describe the concept of the solution space, which will be detailed in the architectural views. It starts by examining the context in which stakeholders perceive value and formulating value propositions for the potential solution. By understanding the specific needs and expectations of different

stakeholders defined in the problem space, we can create value propositions that address their concerns and enhance SA.

Next, we identify the potential solution's strengths, weaknesses, opportunities, and threats. Strengths include the organizational ability to prepare for SA, identifying strategic capabilities for the whole enterprise, and how its parts contribute to it. Leveraging enterprise processes, knowing the operators involved in those processes, and harmonizing them with advanced technologies can enhance situational awareness. Weaknesses involve the high costs and complexity of implementing these technologies and the potential resistance to change from operators accustomed to traditional systems. Enterprise solutions combining a large number of collaborators and processes can also be challenging to manage and assess for improvement. Opportunities exist to improve operator training programs and individual assessment, optimize communication protocols, and integrate new technologies to automate routine tasks, reducing operator workload. Threats include regulatory constraints, potential external threats like cyber-security risks, technological immaturity or failures, and the challenges of ensuring collaboration between operators from different organizations.

Harmonizing the elements of the potential solution is crucial to ensure they can be realized coherently and cohesively. This step involves integrating various components, such as human factors, technological systems, and organizational processes, to create a unified approach to enhancing SA. Harmonization can be achieved by ensuring that technological systems are user-friendly and support operators' tasks, training programs are designed to address specific needs and challenges, and organizational processes facilitate effective communication and decision-making.

At this point, it is vital to have a high-level definition of functional and non-functional characteristics for the potential solution. Functional definitions are expected to reflect on systems' performance or intended outcomes in operational processes. The desired functional characteristics for SA in UAM include enhanced communication systems for operators and traffic controllers, user-friendly interfaces for operators, automated monitoring and alert systems, and real-time data acquisition and processing. The operational process and the human aspect involved in this functional definition are critical aspects of the research's contribution. Therefore, a particular focus should be given to human capabilities and constraints when elaborating the solution architecture.

Desired non-functional characteristics include high reliability and availability of technological systems, user acceptance and ease of use to ensure operator trust and efficiency, interoperability between different systems and devices, and scalability to accommodate future growth and increased traffic.

Placing SA as a core value of the entire UAM ecosystem is crucial for identifying the first level of requirements necessary to promote and secure SA during operations. SA capabilities, ecosystem entities, and behaviors that consume and affect SA must be coherent and consistent throughout the entire enterprise. By identifying and exploring human factors issues such as task demand, associated workload, and performance at an early stage of concept definition, we can pinpoint capabilities, potential risks, and mitigation strategies for human operator roles.

In conclusion, the envisioned solution must provide a systemic approach, addressing the SA problem from the conceptual stage as an enterprise socio-technical concern (system integrated with operators). The solution must aim to understand the process of achieving SA from the perspectives of UAM ecosystem entities and provide means to support proper SA during the concept, design, and operation stages. The boundaries of solution space must include technical, operational, organizational, and human factors to address SA effectively.

4.4 UAM Situation Awareness Enterprise Views

The beginning of the architecture elaboration process (according to ISO/IEC/IEEE (2019a) item 10.4.1) involves planning the model effort to architect and represent the solution. The intended users are the stakeholders identified in the previous section. The architecture objective is to understand the process of achieving SA from the perspectives of UAM ecosystem entities and provide means to support proper SA during the concept, design, and operation stages. The objective is also aligned with the research question intended to be answered by this Chapter.

This section presents the results of the SA viewpoint to address the SA socio-technical concern. It is organized as follows: after defining SA as an enterprise goal in 4.4.1, the higher-level requirements structure is established in 4.4.2. Thenceforth, sections 4.4.3 to 4.4.6 develop the model's elements usage and definition, starting with SA capabilities and constraints and UAM operational concept, then exploring SA behavior and services required to provide SA.

4.4.1 Situation Awareness as a UAM Ecosystem Enterprise Goal

Architecture governance is a process that establishes and maintains alignment with enterprise goals, policies, and strategies. It starts with examining and evaluating the current and future enterprise vision. Once passenger transportation is defined as the UAM ecosystem mission, the enterprise vision is defined by safe urban air mobility transportation. In the strategic structure (St-Sr) (Figure 4.1), it is possible to define the vision statement, vision goals, and utilization phase. In addition to safety purposes, UAM operation also envisions an efficient aviation transportation system in which business success aspects are also important. With the purpose of exploring SA, this viewpoint will focus only on the safety vision. Thereby, enterprise goals can be extracted from the enterprise vision.

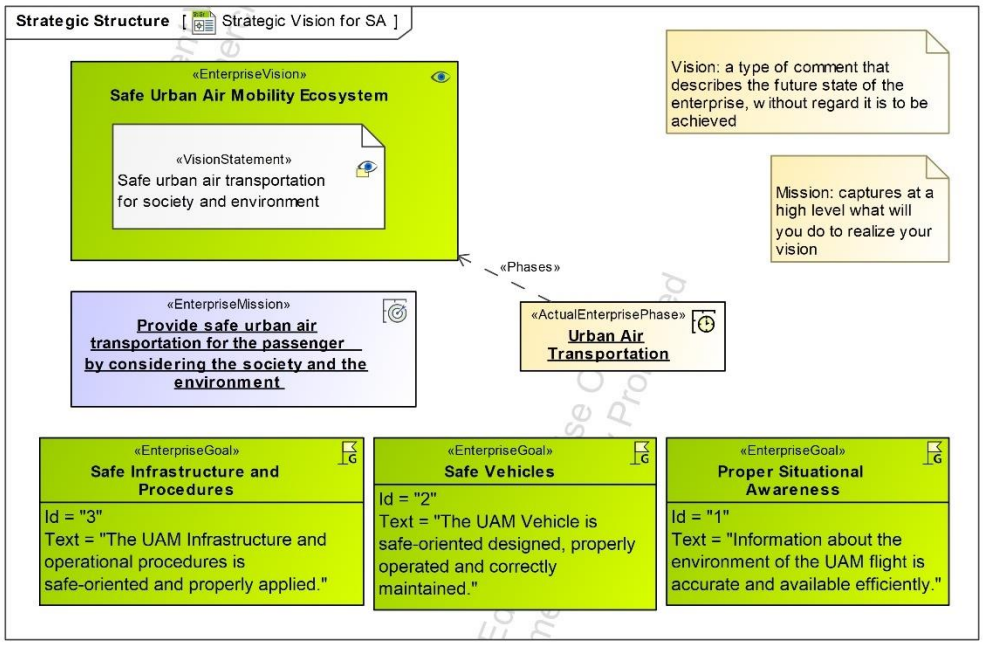

Figure 4.1: Strategic Safety Vision Diagram (St-Sr)

What makes UAM a safe transportation? The enterprise goals can be defined by answering this question from a high-level perspective. Inspired by commercial aviation regulation, it is opportune to start with two main ideas: vehicle design and operational aspects. The vehicle shall be designed according to safety standards and shall be able to operate safely (<<EnterpriseGoal>> Id 2). The ecosystem shall provide the appropriate infrastructure to accommodate the operational procedures for safe operation (<<EnterpriseGoal>> Id 3). The first goal (<<Enterprise Goal>> Id 1) proposed in this view is *Proper Situation Awareness: Information about the environment of the UAM flight*

shall be accurate and available efficiently for all operators. This definition is strategic for exploring SA in the UAM ecosystem, as proposed by this study. This comprehensive description of the SA goal concerns the emissary and the recipient of the information. The *accurate* meaning is related to the integrity, validity, and accuracy of *what* data is available. The *efficiently* relates to *how* the data is available. The recipient is the agent for what (or who) the information is efficient. Who receives the information judges the efficiency of the information received based on all the context that impacts the recipient's perception: workload, operational procedures, human factors, and human systems integration (HSI). Understanding how this can be achieved through operators' capabilities, services, personnel structure, roles, and responsibilities is possible through the UAF views.

The enterprise goals represent complex ideas that have integrated or overlap concepts. Although there is a goal specifying SA, the vehicle and the infrastructure/operational procedures are profoundly connected with SA accomplishment. The complexity of systems and the environments in which they operate means the process of achieving a safe operation is not linear. Instead, it is driven by a complex web of relationships and behaviors between humans, technology, and their environment (Underwood & Waterson, 2014). From a systems perspective, emergent interactions and behaviors are essential to understanding and defining safety operations. Placing SA as an enterprise goal permits scrutinizing the UAM ecosystem from a situational awareness perspective, provided that the next steps for the architecting processes are reasoned on the SA goal.

The lifecycle stage intended to be covered by this vision and goals is represented by the element <<Actual Enterprise Phase>>. In this view, the enterprise phase is exclusive to the utilization stage, which is the flight operation phase, and all the enabling processes directly related to this phase.

4.4.2 Situation Awareness as an Enterprise Requirement

Understanding and planning the architecture requires analyzing stakeholders' needs and defining requirements at a high level. A requirement is a definition of a property that a system or process must be able to perform. As proposed in previous sections, Situational Awareness is a requirement, considering that the enterprise's vision is to provide safe UAM transportation. Moreover, the requirements are coherent with the enterprise goals, including SA, vehicle, infrastructure, and procedures in the high-level structure. The problem statement that binds the requirement definition to the business rationale is 'Without accurate situational awareness, the pilot in command and the

traffic management controllers cannot operate a safe UAM transportation."

Defining SA as the top-level requirement aligns with the idea of the UAM ecosystem providing SA as competence (Figure 4.2). From that level, it is possible to decompose into three lower requirements. The information available, infrastructure and operational procedures are the three pillars of achieving a proper level of SA. The significance of SA Level 1 is represented by a dedicated requirement (Id 1.1) to assure that the critical information affecting SA shall be presented correctly and efficiently and be promptly available to the pilot and involved entities. Jones & Endsley (1996) reported that failure to monitor or observe available information is the most prominent reason for the loss of SA among 262 errors that occurred in 143 incidents. The *Information Available* <<requirement>> "*The critical information affecting SA shall be presented correctly and efficiently, and be promptly available to the pilot and involved entities*" is then derived into four requirements (Ids 2 to 5). By specifying behaviors required for the source requirement (Id 1.1) compliance, it is possible to organize the requirement structure to be coherent with the high-level operational concept. Although all requirements exhibited on the diagram represent a high-level definition of the ecosystem, detailed requirements can be organized into a hierarchy using relationships such as derive, trace, refine, and containment. Satisfying each detailed requirement results in meeting the higher-level and, ultimately, the top-level requirements.

The UAF requirement structure and relationship help manage the complexity of large systems. *Vehicle Internal Information* (Id 2), *Vehicle Communication* (Id 3), *Traffic Controller* (Id 4), and *Operators* (Id 5) are requirements that have comprehensive coverage of topics related to SA and safety operations. From the high-level requirements depicted on the diagram, it is possible to reach a massive number of requirements, from functional to very detailed low-level components. The requirement definition process is expected to encompass definitions for vehicle design, traffic management, infrastructure, training, safety culture, operators/personnel, and operational standards.

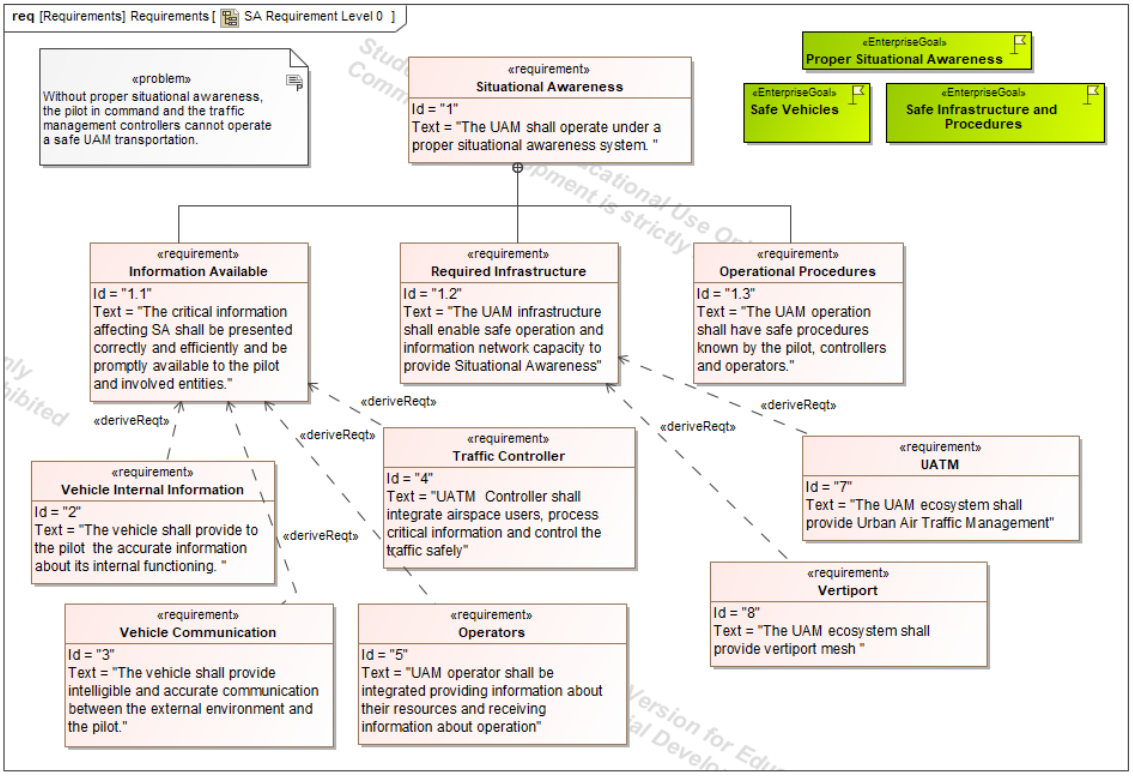

Figure 4.2: Requirements Diagram (req)

Requirements (Id 7 and Id 8) derived from *Required Infrastructure* (Id 1.2) are a sample to illustrate how the UAM infrastructure shall be designed to enable SA. The same applies to *Operational Procedures* (Id 1.3). All three elements (Ids 1.1 to 1.3) are interrelated and constitute a complex web of needs and enabling components. Defining requirements as they are independent and isolated is not possible with SA. The dependency relationship is a constant presence and becomes even more complicated when SA is a product that affects the system that generates it. As explored in the following sections, UAF domains and views can help understand how the elements are integrated towards SA achievement.

4.4.3 Situation Awareness Capabilities and Constraints

Capability is a high-level specification of the enterprise's ability to execute a specified course of action (ISO/IEC/IEEE, 2019a). DoDAF defines *capability* as the ability to achieve the desired effect under specified (performance) standards and conditions through combinations of ways and means (activities and resources) to perform a set of activities. The definition of capabilities is crucial for the architectural conceptualization process because most operational, resource, personnel, and service definitions strongly relate to capabilities. Furthermore, defining the

architecture capabilities allows understanding of the system's purpose and the model's purpose.

UAF has a set of views for defining capabilities. Traceability and association relationships can be used among different views, including the operational architecture, which defines the system's abstract, logical, and solution-independent expression intended to be used in operations. As a result, the system views can define how these capabilities and operational architecture will be realized (Hause & Kihlström, 2021b). The Strategic Taxonomy (St-Tx) view specifies all the capabilities referenced throughout one or more architectures. In addition, it can be used as a source document to develop high-level use cases and user requirements.

The UAM ecosystem is composed of physical entities and human operators. When analyzing what types of abilities those components are required to provide a proper SA level, it is expected to consider systems capabilities from a technology perspective and human operation. Starting from SA Level 1, the perception stage requests monitoring the environment as a capability. There are different ways of achieving it, as represented by the generalization relationship for *Listen*, *See*, and *Feel* (Figure 4.3). A generalization describes a relationship between a general kind and a more specific kind of thing. It is possible to monitor the environment by listening, seeing, feeling, or simultaneously with two or three senses. Much of Level 1 SA comes from the individual directly perceiving the environment (Endsley, 2004a). In the UAM context, the pilot uses all its sensory systems to capture information in highly dynamic behavior. Not only are flight deck displays or sound alerts present at this stage, but the pilot will eventually look out the window or feel acceleration motions on his body. Traffic controllers also need to use vision and hearing to monitor instruments and perceive the environment, although it represents a different information set. Verbal and nonverbal communication with others form an additional informa-tion source drawn upon and contributes to Level 1 SA (Endsley, 2004a). In this diagram, four types of *communication* were specified for differentiating the capability according to the resource's operational activity. This semantic of the model is strategic and valuable once the activities and services are being defined for the enterprise entities.

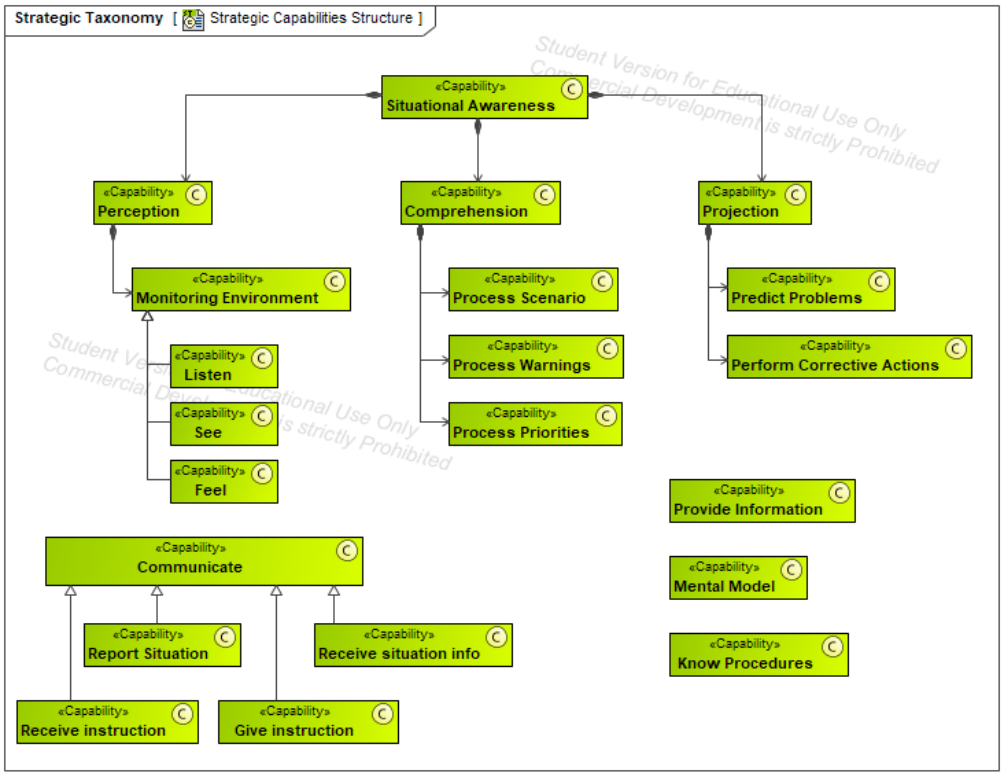

Figure 4.3: Capabilities (St-Tx) diagram

Level 2 SA requires a mental process to comprehend the scenario. *Comprehension* is based on a synthesis of level 1 elements and comparing that information to the mission objective. It involves integrating many pieces of data to form information and prioritizing that combined information's importance and meaning (Endsley, 2004a). *Process scenarios*, *process warnings*, and *process priorities* are parts of this stage and are defined in the capability's taxonomy. The significance of the information perceived in the previous stage depends on the meaning of a specific operational goal. For instance, a pilot may comprehend a scenario differently when performing different tasks. During take-off, some goals and tasks are associated with the vehicle's airspeed, attitude indicator (artificial horizon), and propulsion. In contrast, propulsion system indication data comes to attention in the cruise phase if there is an off-nominal occurrence.

Level 3 SA is associated with the ability to project the future of the elements in the environment. The third and highest level of SA is achieved through knowledge of the status and dynamics of the elements and comprehension of the situation, both Level SA 1 and Level 2 SA (Endsley, 2004b). Anticipating the projected future situation gives the pilot (and air traffic controller) time to resolve conflicts and plan a course of action to meet their goals. Therefore, time is a critical piece in this

stage. *Predict Problems* and *Perform Corrective Actions* are capabilities necessary to project the near-term future of UAM operation. For example, UAM traffic controllers will need to manage considerable airspace traffic, and avoiding collisions is one of their goals. They will need to put together information on various traffic patterns and flight plans to determine which UAM route will be accessible and where collisions are potentially possible.

Provide Information was added to the capability taxonomy as a counterpart of the perception level. In the UAM ecosystem, human users perceive the environment because there are physical or human entities providing information. Most problems with SA in the aviation domain occur at Level 1. In some cases (roughly two-fifths), this occurred because the needed information was not provided to the person who needed it or was not provided clearly due to system limitations or shortcomings (Jones & Endsley, 1996). The proposal to look at SA as an enterprise product must include the system's capability to provide the correct information in the best way and in a timely manner to achieve the intended safe performance.

Mental Model is a systematic understanding of how something works. Also known as schema or long-term memory structures, mental models were defined by Rouse & Morris (1986) as "mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future states." Mental models are based on both semantic knowledge and system knowledge and are complex structures people use to model the behavior of specific systems and operations. Moreover, this capability is a cognitive structure that allows humans to interact effectively with their environment by organizing knowledge into meaningful patterns. A mental model allows a pilot to take control of his attention and anticipate the consequences of those actions. Training, practicing different scenarios, and hours of practice can strengthen a mental model. Apart from the cognitive aspect that involves the mental model, operational procedures play an important role in aviation operations. Operational checklists, authorization procedures, health checks, and turnaround procedures are also ways of organizing knowledge into corrective actions. A mental model without knowing the procedures is not effective.

Similarly, knowing procedures with a poor mental model does not help predict problems. In this sense, *Know Procedures* is defined as a capability and is crucial for safe operation. Considering that the model is defined for the utilization phase, operational standards and procedures are

expected to be already defined. Those topics are typically explored and defined by federal and local authorities, together with industry, OEMs, and stakeholders. The capability described in this taxonomy is intended to cover the dissemination and application of such procedures during operation.

Evidently, the capabilities of users and systems are deeply connected and constitute a complex dependency relationship. It is not possible to look into one capability without considering the others. UAF's strategic domain also includes connectivity, states, parameters, and traceability views to explore capabilities and capability management processes.

Figure 4.4 shows the constraints, which are performance requirements that constrain capabilities. The diagram defines a set of constraints related to human factors and the UAM ecosystem. *Workload Level* (composed of *Boredom* and *Fatigue Handling*), *Emotion Handling*, *Trustability*, *Physical Discomfort Handling*, *Out of the Loop Syndrome*, *Attention Tunneling*, and *Complexity Creep* are known hurdles for acquiring and maintaining SA from the user perspective (Endsley, 2004a). All the constraints can reduce or cause loss of users' SA. This taxonomy is essential to define system states and behaviors since proper SA is a performance the ecosystem intends to achieve. The strategic constraints are all related to the recipient's context and what can affect the capability of processing and achieving SA. It allows us to focus on the pilot (or controller) when they receive information. The efficiency of the information provided must be considered based on the recipients' capability of dealing with constraints.

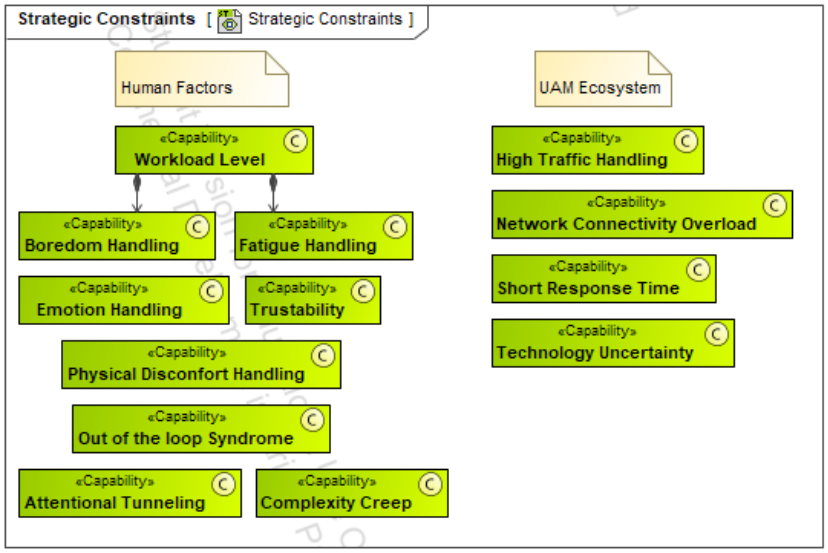

Figure 4.4: Constraints (St-Ct) diagram

When defining organizations and roles' responsibilities, knowing the constraints enables the enterprise to be prepared to prevent them. Correspondingly, UAM ecosystem constraints like *High Traffic Handling*, *Network Connectivity Overload*, *Short Response Time*, and *Technology Uncertainty* can affect the capability of physical components. *High Traffic Handling* increases the workload for both pilots and controllers. *Network Connectivity Overload* can affect the information flow accurately and at the right time. *Short Response Time* is related to the operational concept of the UAM flight profile, in which the pilot and controllers will have less time to react against an off-nominal situation. Lastly, *Technology Uncertainty* is a barrier to the UAM operation because new technologies in the vehicle (propulsion, energy, navigation, and traffic avoidance systems) and network (traffic management) can add failures and faults, increasing the operators' workload.

There are undoubtedly other constraints for UAM operation like the weather, regulation, public acceptance, business model, security, and noise levels, to mention a few. However, as stated before, this model develops the architectural views and defines elements, placing SA as a centerpiece.

4.4.4 UAM High-Level Operational Concept from a Situation Awareness Perspective

Urban Air Mobility operation is the topic most discussed by the industry and lawmakers. Initiatives to discuss operational aspects involve many stakeholders and have raised different approaches. Operational considerations depend on vehicle type, airspace classification, business model, regulation, and specificity of locations, such as topology, local laws, public acceptance, demand, and infrastructure capacity. Traffic density projections and the infrastructure required to provide transportation and automation levels make it necessary to define implementation in stages. Both FAA (2020) and EmbraerX (Air Service Australia & Embraer, 2020) published ConOps, which envisioned evolutionary states demonstrating how UAM operation can achieve a mature status. In this study, the UAM operational context includes medium-density operation, eVTOL vehicle type, Pilot in Command (PIC) on-board, Human-within-the-Loop (HWTL), and dedicated traffic management (UATM). Although autonomous flight is out of the scope of this architecture, Human-on-the-Loop (HOTL), in which humans have supervisory control of the automation systems and can take full control when required or desired, can benefit from the findings of this work.

The UAF High-Level Operation Concept diagram describes the resources and interactions required

to meet an operational scenario from an integrated systems point of view. It is used to communicate overall quantitative and qualitative system characteristics to stakeholders. With SA in mind, the diagram in Figure 4.5 depicts how the pilot, operators, and controllers receive and provide information during a UAM Flight.

Urban Air Traffic Management (UATM) is the collection of systems and services that support the integrated operation of UAM vehicles in low-level airspace. Traffic management for UAM, Unnamed Aerial Systems (UAS), and traditional aircraft must be integrated, and vehicle interactions will occur. In the UAM operational context, the pilot in command receives information from the UAM Traffic controller, which in turn receives integrated information about external elements like weather information provider, UAS, and general aviation traffic (through ATC). UATM, represented as a symbol in the diagram, is the network system that integrates the external providers, and the UATM Traffic Controller is the human operator communicating with the PIC using data from the UATM network.

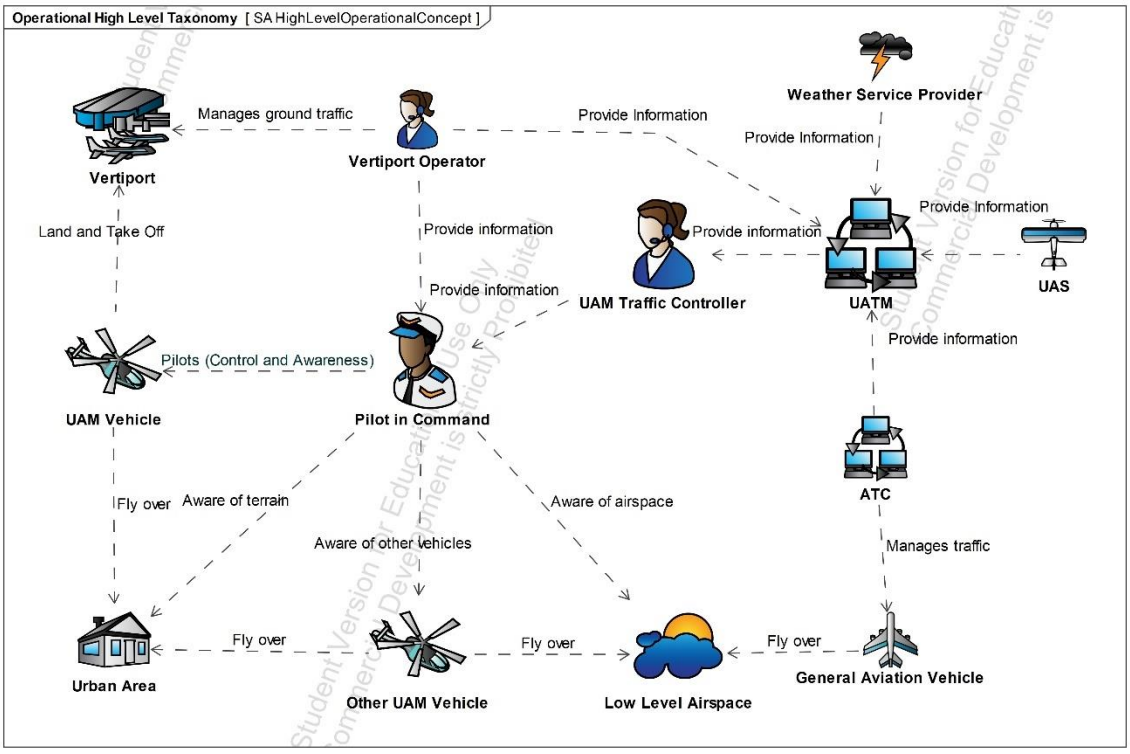

Figure 4.5: Operational High-Level Concept diagram

Vertiport is an area where UAM vehicles (eVTOL) are used to take off and land. A vertiport can have single or multiple UAM Final and Take-Off Areas (FATOs). Vertiports can be dedicated to

passenger transit, maintenance services, and a place for charging the battery and parking vehicles. Navigation aids and visual cues with corresponding instruments are expected to be used in vertiport operation. For emergencies, vertiport could be required to have contingency FATO and stands. Vertiport resources management is done by the vertiport operator, which also provides pertinent information to UATM. Moreover, ground traffic management is controlled by a vertiport operator, who provides guidance and information to the PIC while the UAM vehicle is on the ground.

UAM Operator is composed of pilots and vehicles. The organization runs the operation and has direct contact with the passengers. During the flight, the pilot must be aware of the vehicle (internal environment), terrain, airspace, and other vehicles (external environment).

This view represents a simplified idea of how the information is integrated into the UAM ecosystem and how it flows. As an ecosystem, or according to the SoS definition, UAM is not an extensive monolithic system. There is operational and managerial independence of their components, and it has an evolutionary nature, emergent behavior, and a geographic extent that limits the interaction of their components to information exchange. The UAF high-level concept diagram is essential to understanding which entities are integrated and how information is shared. This step is crucial to defining organizations, operational processes, and activities. According to the operation described above, the UAF Personnel domain defines organization roles and responsibilities. Even though personnel details are not depicted in the diagram, a sample of how personnel elements are valuable for the architecture definition process is discussed in 4.5.

4.4.5 SA behavior during UAM Flight from the Sensorial Systems Perspective

The UAF Operational (Op) domain illustrates the enterprise's logical architecture. There are ten different views capable of describing operational behavior, requirements, structure, and exchanges required to support (exhibit) capabilities. UAF Operational Processes (Op-Pr) view concerns capturing activity-based behavior and flows. Having the operational performers defined by UAM Vehicle, Pilot in Command, UATM Traffic Controller, UATM Network, Vertiport Operation Manager, and Vertiport, it is possible to describe the activities typically conducted in the course of a UAM Flight. SysML activity diagrams are used to explain a system's behavior by telling a story and conveying a narrative. In this diagram, it is possible to know *who* (performers allocated on swimlanes) perform the *behavior* (action), what is needed as *input*, and what the *output* of each

action (token flows and pins) is. The intended usage of the Operational Processes (Op-Pr) view includes a description of activities and workflows, requirements capture, definition of roles and responsibilities, support task analysis to determine training needs, operational planning, and Information flow analysis.

The traditional approach for defining operational flow in aviation is based on flight phases. A timeline is followed to describe the steps from flight plan approval, pre-flight check, take off, cruise, approaching, landing, and post-flight check. Analyzing the operational steps according to the flight phase and understanding the pilot, controllers, and other operators' tasks are fundamental to planning a safe flight. However, it does not clearly represent SA behavior. The proposed approach in this work intends to answer the following questions: “If it was possible to see the situation awareness behavior from the human operators' sensorial systems through a diagram, what would it look like?” Figure 4.6 demonstrates how the UAM ecosystem uses the SA capabilities and represents the operator's sensory systems consuming capabilities while performing SA actions during UAM Flight.

Aircraft's flight deck systems mostly combine visual and auditory displays and panels, making the pilot process multisensory information. In everyday life, a person can see, hear, smell, taste, feel different environments, and process information without much effort. Our brain can integrate and combine multiple senses' input even when there is incongruency among the information being received. In the cockpit, the sensory system of the pilot is the leading performer in acquiring situational awareness. In the operational flow (Figure 4.6), the pilot acknowledges the vehicle status using his primary capabilities: see, listen, communicate, and feel. Vehicle displays can show visual information about all its subsystems in different colors, layouts, sizes, and dynamics (blanking or fixed). Pilots need to acknowledge vehicle status to understand the vehicle's health state and to aviate and navigate. Data about systems status, faults, and failures (health data) will provide SA about the internal environment: the vehicle. The same applies to sound alerts in which vehicle warnings and cautions are emitted to inform the pilot of a situation requiring attention. Different tones and messages are played in the cockpit to alert the crew when certain conditions exist internally or externally (for example, terrain warnings). Communication represents the capability of hearing and speaking as operators' dual and combined activity. The vehicle provides communication systems, allowing the pilot to receive information about the internal and external

environment from other vehicles and ground controllers. Still, from the vehicle as an operational performer, the pilot can feel the flight motion and inform about the vehicle's state, like acceleration force or vibration during abnormal conditions.

The actions allocated to the operational performer *Pilot in Command* include acknowledging the internal environment (vehicle) and external environment (airspace and ground) using its primary capabilities from its sensory systems. After receiving inputs from different sources, the pilot is able to perceive the environment and build the first SA Capability, *Perception* (in pink). When the pilot is capable of processing what the information perceived means in terms of the mission goals, it can achieve level 2 SA Capability: *Comprehend* (in orange). If he can project the scenario, predict problems, and take corrective actions, he can reach *Projection* (in purple), level 3 SA. The SA operational flow aims to fly the vehicle safely. Therefore, the action *Fly Vehicle* in the diagram represents the operational outcome of this behavior.

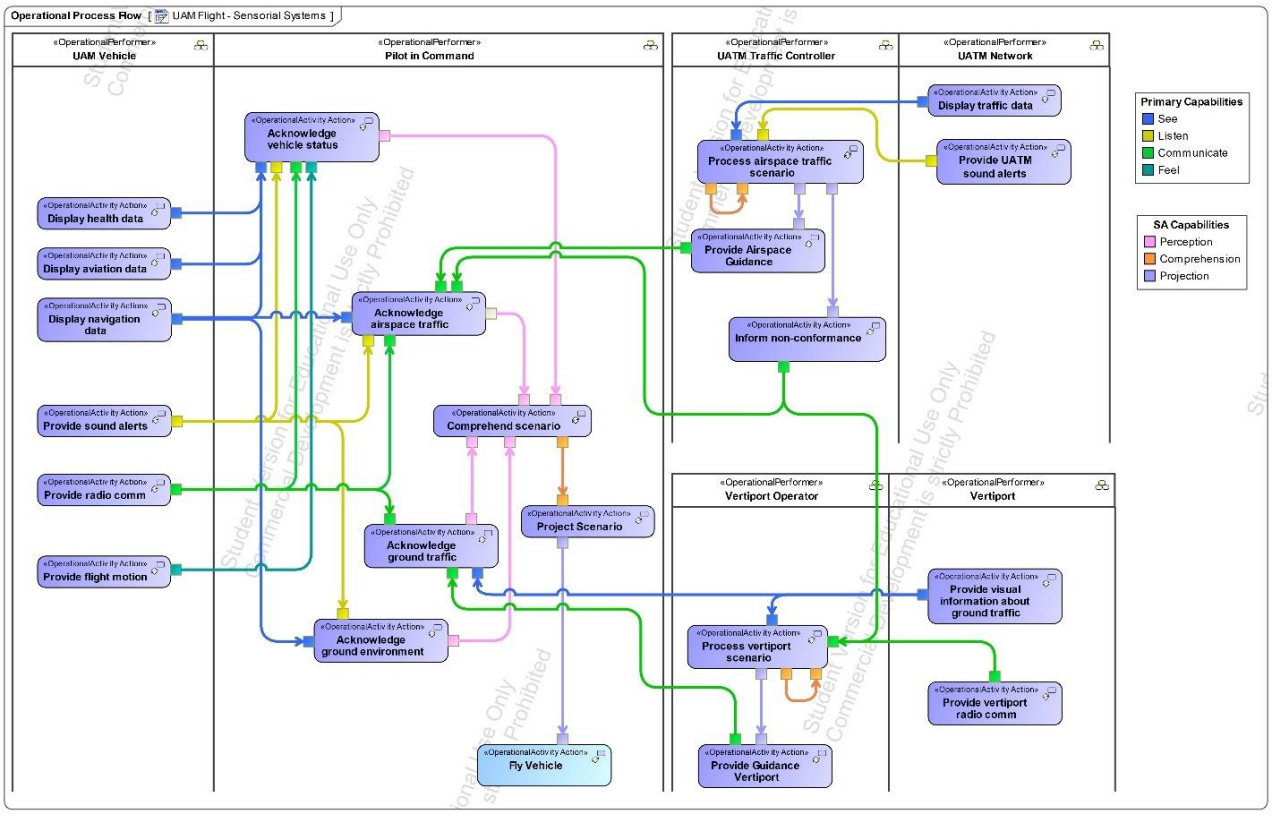

Figure 4.6: Operational Process Flow (Op-Pr)

Traffic controllers and vertiport operators are also part of the UAM SA behavior when it comes to informing about the pilot's external environment. Controllers and operators collect and process

visual and auditory data, providing information, guidance, and warnings to the pilot through communication capability. Likewise, controllers and operators also perceive the environment, comprehend the information in the mission goal's context, and project scenarios to provide the correct guidance for safe traffic management. In the diagram, the controller's input (primary capability) came only from the UATM, an operational performer integrated with other organizations sharing the airspace. However, the communication output after projecting scenarios is expected to happen with different vehicles simultaneously. The same is true for the vertiport operator who may need to control more than one vehicle while on the ground, guiding before take-off, after landing, during taxing, parking, and battery or maintenance support. The Vertiport operator also communicates with UATM, who may inform about any emergency condition requiring vertiport usage and needs a vertiport status report.

SA is not linear, and the human cognitive process is very complex to be captured in only one behavior diagram. The inputs to the pilot's sensory system are part of a dynamic process, increasing the challenge of reproducing in the model. The dynamic aspect of an actual flight is an important temporal aspect of SA. Since the situation constantly changes, the pilot's and controllers' SA must also constantly change or become outdated and thus inaccurate (Endsley, 1995).

The lack of "initial" and "final" nodes in the diagram is a symptom of behavior with little linearity and order. Nonetheless, understanding how human operators use their sensory systems in the UAM ecosystem is essential to knowing the extent of the workload and cognitive process to maintain a good level of SA. The limit of how many elements one person can pay attention to at one time affects how much information one can process, forming a central bottleneck for SA (Endsley, 2004a). Simultaneous information can be more easily processed (e.g., visual and audio information) or can place a person in cognitive overload. If information requests the same resources (central processing) from the operator, like visual, auditory, tactile, or smell, it is more difficult to attend to simultaneously (Wickens, 1992).

Considering the workload and the amount of information received during a flight, which are major concerns in this process flow, the sources of information shall share the same goal: to keep efficiency for the recipient. Mapping the source of information and how the human operators use their SA capabilities brings light to the analysis of acquiring and maintaining SA in the UAM ecosystem.

4.4.6 Services to achieve Situation Awareness during UAM Flight

UAF Operational Processes (Op-Pr) view also describes the activities conducted while achieving business goals that support a capability. In the UAM context, the *Pilot in Command* is an <<OperationalPerformer>> capable of performing UAM Flight. As a high-level activity, it can then be decomposed by *Monitor Vehicle*, *Aviate Vehicle*, *Navigate Vehicle*, and *Communicate*. Each activity is linked with one (or more) enterprise capability with a specific relationship called *Map to Capability*. For instance, *Monitor Vehicle* is mapped to *Provide Monitoring Environment* (and its subtypes see, *listen,* and *feel*), *Aviate* and *Navigate* to *Process Warnings*, *Process Scenario*, *Process Priorities*, *Predict Problems* and *Perform Corrective Action*, and *Communicate* evidently is mapped to the subtypes of capability *Communicate*.

UAF Services (Sv) domain shows the specifications of services and service levels of these specifications required to exhibit a <<Capability>> or to support an <<OperationalActivity>>. Services in UAF are intended to allow the operational layer to be developed without impacting the resource layer, provided that the operational layer consumes the functionality defined for the service interfaces. Likewise, the resource layer can develop independently without impacting the operational layer, provided the service interfaces are untouched (Hause & Kihlström, 2021a).

Figure 4.7 shows the Services Taxonomy (Sv-Tx) diagram specifying the services consumed by the <<OperationalActivities>> performed by the *Pilot in Command*. Each service specification exhibits the capability requested by the operational activity. *Monitor Vehicle Service* is a critical service on which other services depend. For the pilot to aviate, navigate, and communicate, he or she must constantly monitor the vehicle. The service methods are defined and represent the behavioral aspect of the performer (pilot) consuming the service. Thus, pilots see displays, listen to audio alerts, feel the environment (with their body through tactics, smelling or feeling acceleration and vibrations), and see components (like switches, buttons, and lights) in the vehicle. Access to the behavioral methods is the pilot's sensory system, which is defined by the *Service Port* propriety. In order to consume this service, the UAM vehicle, already defined as an <<OperationalPerformer>>, also has an <<OperationalActivity>> called *Provide Vehicle Data* and consumes the service *Vehicle Data Delivery Service*. This service exhibits the <<capability>> *Provide Information* and is specified following the service required by the pilot.

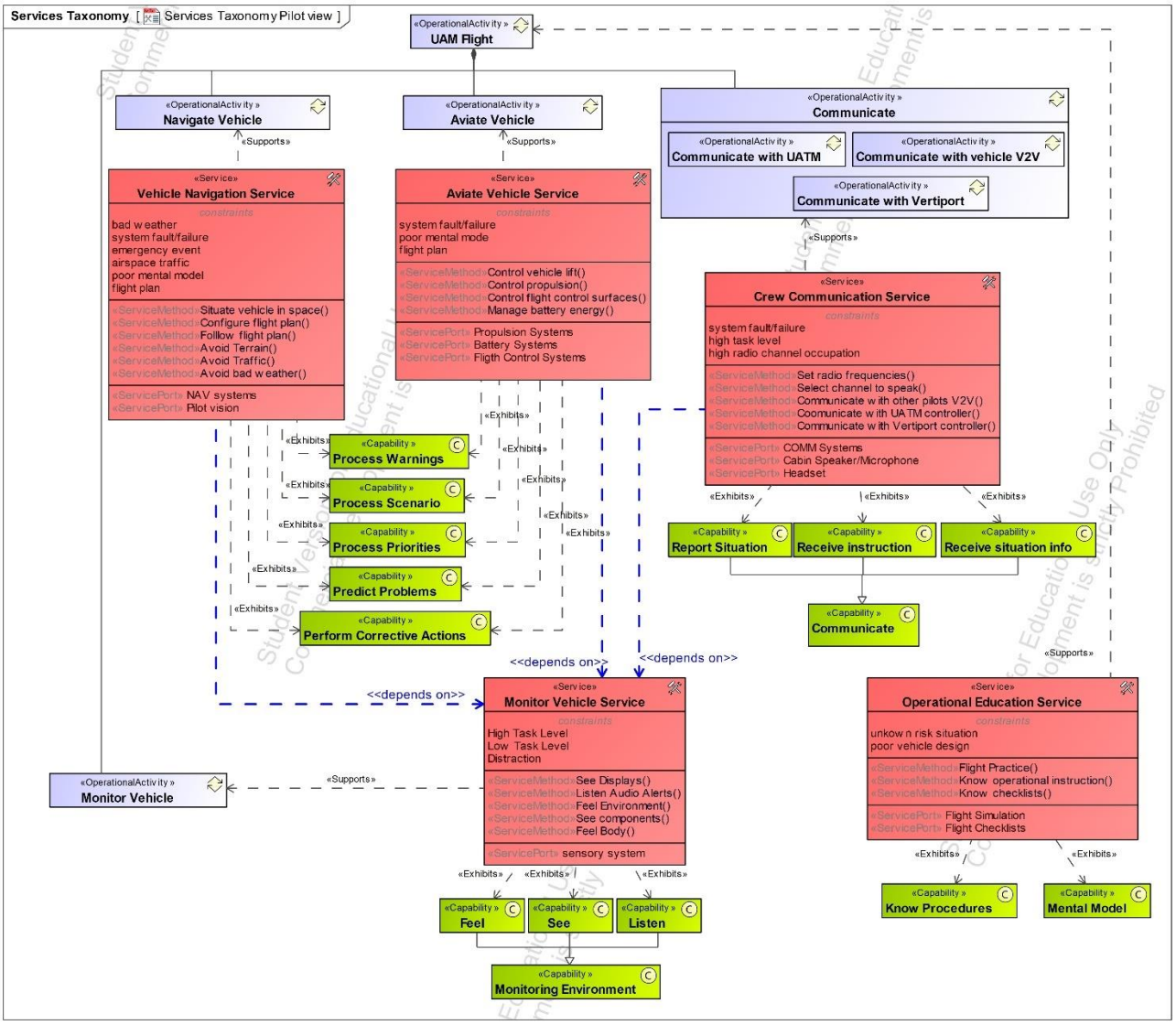

Figure 4.7: Services Taxonomy (Sv-Tx)

According to the strategic view, the workload is specified in this service as a constraint that can affect the capability exhibited by the pilot as a recipient of the vehicle's information. However, using the service view is strategic in covering the service requested and coherently provided by the enterprise. It also defines all operational elements in an independent implementation/solution manner.

Similarly, *Vehicle Navigation Service*, *Aviate Vehicle Service*, and *Communicate* were specified to accomplish the correspondent capability exhibition. The operational tasks like aviate, navigate and communicate are complemented by the operator's needs to achieve and maintain SA and other

important human factors. Constraints to the service are related to the vehicle or other physical entity, and most importantly, in this approach, they are related to the pilot's ability to process SA. Poor mental mode, workload level, distraction, emergency events, and unknown procedures are constraints that compromise the pilot's SA. In the vehicle data delivery service, for example, graphical and sound alerts have human factors as constraints. Therefore, providing data needs to consider the human response to best deliver the information to the operator.

The service specification is a valuable tool in the enterprise architecture when designing for SA is the primary goal. Services are not limited to internal system functions and can include Human System Interface (HSI) and Graphical User Interface (GUI) functions (Hause & Kihlström, 2021a). The external service data providers and consumers can represent the humans interacting with the service. Constraints to the services can be explored to identify mechanisms to mitigate SA loss in every service instance. As Endsley (2004a) observed, ensuring that the system obtains the necessary information and is presented in a way that makes it easily processed by the system users is crucial. The reason is that system users often have many competing pieces of information contending for their attention.

Operational knowledge and training needs are essential components of SA. Pilots can only comprehend and project the flight scenario if the operational procedures are safe and properly known (as defined in requirement ID 1.3 in Figure 4.2). The *Operational Education Service* is consumed by the UAM Flight and is necessary for all its owned operational activities. The service that provides the pilot education must consequently match the specification and should be planned by the UAM Operator accordingly. With other UAF views in the Service (Sv) domain, it is possible to define service connectivity, interaction scenarios, parameters, processes, roadmaps, and traceability. In addition, a service interface can be defined to invoke a service regardless of the technology. This is helpful because specifying the interface for the service provides a way of determining compatibility between service consumers and providers. In architecture, where SA is a goal, it is precious to verify whether human aspects are being provided as requested by human performers.

4.5 Discussion about UAM SA Viewpoint

Competence in UAF is a specific set of abilities defined by knowledge, skills, and aptitude. Competence in the framework metamodel can be required or provided by an organizational resource. A function can also be associated with a set of competencies to show what is needed to conduct the function. In addition, there is the *Competence for Role*, a tuple used to associate an organizational role with a specific set of required competencies. Having the element <<*Competence*>> and its relations provided by the model, this work proposes exploring SA as a competence in the UAM Ecosystem.

The cognitive process serves as a function of the human operator's mental equipment. SA is the product of these processes, which also affects the process in a circular fashion (Endsley, 2015). Acquiring SA is a long and complex process that encounters obstacles from different sources and nature. Using enterprise architecture views, it is possible to group elements of the physical and technological environment (vehicle, network, devices), organizations with roles and responsibilities, operational flows, and human aspects imbued with constraints, services, relationships, capabilities, and competencies. By developing a good understanding of how people develop SA in the UAM operation and the challenges and limitations to the process, strategies for designing to enhance SA will be more apparent (Endsley, 2004a).

The Architecture Enablement process aims to develop, maintain, and improve the enabling capabilities, services, and resources needed to achieve the architecture goals. For instance, enabling services include, among other things, infrastructure, technologies, skilled personnel, and automation agents. Enabling resources include, among other things, an architecture repository, a library, and human and technical resources. As a result of the successful implementation of the Architecture Enablement process: a) Enabling capabilities, services, and resources are available when and where they are needed and are accessible by those who need them; b) Enabling services are suitable for and accessible to the architecture process activities; c) Enabling resources are suitable for and accessible to the architecture process activities and d) Personnel have the requisite knowledge and skills for proper use of the enabling capabilities, services and resources (ISO/IEC, 2022). The Personnel (Pr) domain describes the human-related elements of the architecture. It aims to clarify the role of Human Factors (HF) when creating architectures in order to facilitate both

Human Factors Integration (HFI) and systems engineering (SE).

Personnel Taxonomy (Pr-TX) shows the taxonomy of types of organizational resources. It shows the possible relationships between organizational resources and composition relationships (one organizational resource being part of a parent organization). In addition, roles and responsibilities can be defined, as well as the interactions between those roles, where "roles" represent the functional aspects of organizational resources. Figure 4.8 is a sample of the types of relationships that can be explored. Other taxonomy diagrams defined posts on the three prominent organizations identified from the high-level operational concept: UAM Operator, UATM Operator, and Vertiport Operator. Each of the posts can then have all responsibilities defined and associated. In the diagram below, a few posts are linked to the owner organization and some of the responsibilities allocated to them. It shows only one post for each organization and a set of responsibilities to illustrate how the relationship with the operator, activity, organization, and competence can be defined. It is clear that pilots require SA to perform a flight. However, his organization also *requires* SA competence since other posts plan flights and control the vehicle operation schedule.

At the other end of the question, organization, posts, and process also *provide* the competence SA. Alternatively, entities that provide SA directly impact the UAM SA's competence. For example, the *UAM Operator* needs a post to manage the pilot, who is responsible for defining the pilot's work scale and availability. Also, pilot credentials and skills guidelines must be managed according to the training agenda defined and offered by another post, the training manager. Health condition guidelines and managing pilot health (physical and mental) are other departments' responsibilities and contribute immensely to the pilot's SA competence. The same reasoning applies to other posts in other organizations, like *UATM* and *Vertiport Operators*. There are modeling tools to understand and visualize the extent to which SA can be affected and how it is achieved. Relation maps and tables in the UAF are especially useful in complex architecture. SA, as a competence in the UAM model, can be viewed as a product that affects the process of achieving it. Moreover, it is possible to show how a post that performs administrative work can affect the other end when a pilot performs a landing task, for example.

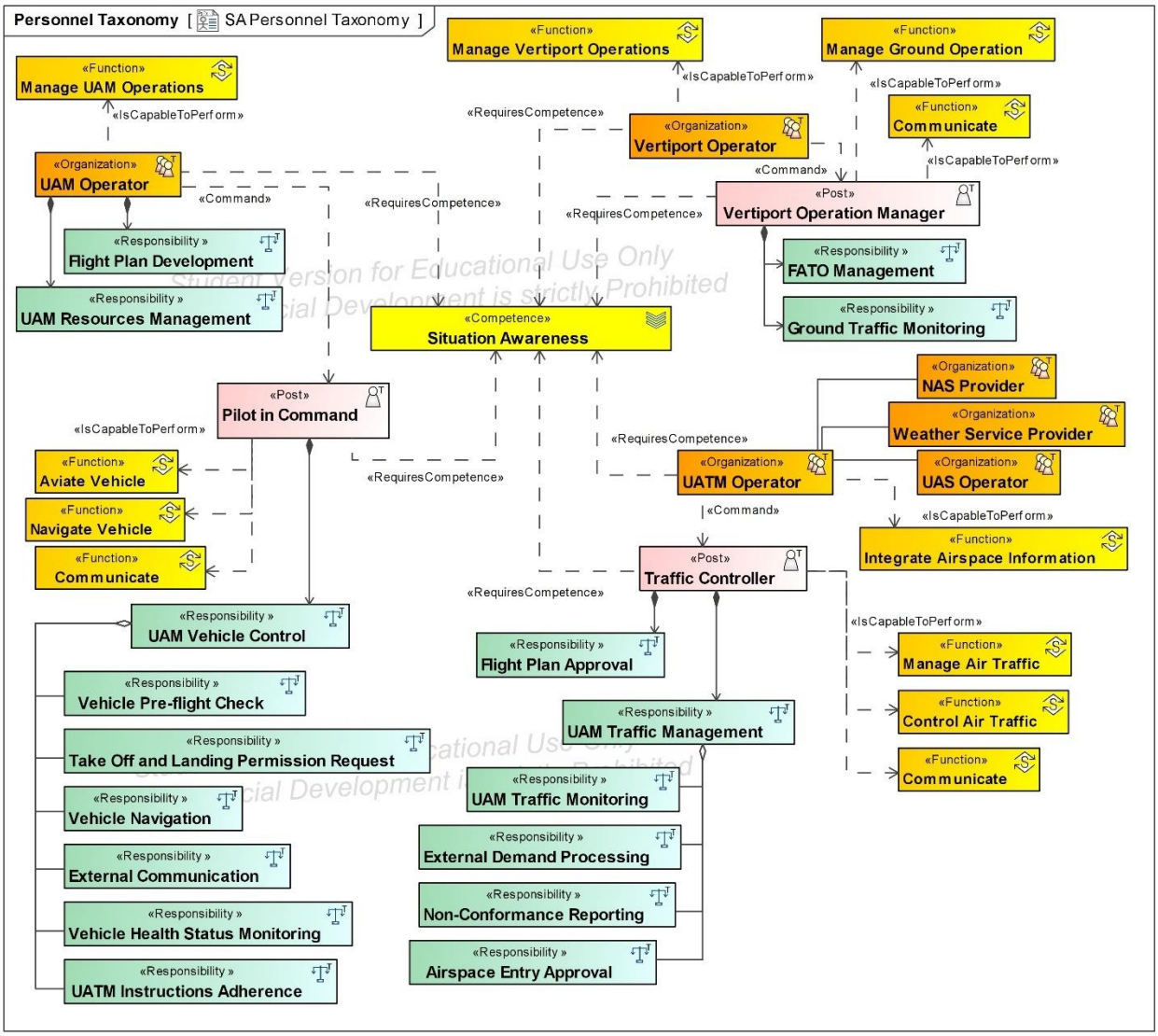

Figure 4.8: Personnel Taxonomy (Pr-Tx)

4.6 Validation of UAM SA Views

Traditionally, SA is part of the Crew Resource and Management framework, applied during the utilization stage, where operators provide transportation services and comply with safety standards. The architecture views presented in this Chapter proposed a new approach to handling the SA concern before UAM operation. In other words, SA as an enterprise strategy could enable the UAM ecosystem to plan for a proper level of SA at all its enterprise levels. Therefore, the architecture objective for the SA viewpoint is to understand the process of achieving SA from all

the ecosystem entities' perspectives and provide means to support a proper SA during the concept, design, and operation stages. The original approach includes other organizational levels and their engagement (functions and responsibilities) in the SA as an enterprise competence. Therefore, evaluating this architecture purpose was also in the validation scope.

The success of the modeling effort was measured by achieving different views with coverage, coherence, and consistency and receiving validation from experts in the research field. The UAF has fulfilled the purpose of modeling consistent architecture for the UAM system-of-systems (SoS) and supporting the analysis, specification, and design of UAM SA. Moreover, the model provided insightful outputs to understand SA behavior and structure. In the UAF Personnel domain, organizations and roles are parts of the architecture and have responsibilities directly associated with the SA effort. Therefore, personnel views allowed for analyzing human aspects quantitatively and qualitatively when operational activities, responsibilities, and service specifications were defined through the SA lenses.

Experts in the following fields validated all diagrams: UAM Operation (UAM Navigation Systems engineer), Flight Experience (commercial pilot), Situation Awareness (Human Factors engineer), and Architecture Modeling (senior Model-Based System Engineer).

The first version of the model was scrutinized by experts and modified to better represent SA in the UAM ecosystem. Several interactions occurred to refine the idea conveyed in each diagram and answer questions that could result from ambiguity or inconsistency. In addition, uncertainties were discussed to better address the SA with the available information from the UAM ConOps and assumptions.

Group presentations and discussions also occurred during the modeling elaboration. Students and researchers on System Design and Management (SDM) at Graduate School (Keio University) participated in a seminar in which the content of this Chapter was presented, explained, and discussed. Seminar discussions often bring valuable insights and questions. During the SA related discussion, one member highlighted the proximity with resilience and Safety II concepts, inspiring the other viewpoint, Safety Culture.

When the material was submitted to the IEEE Open Journal of Systems Engineering, the peer review process also provided comments and suggestions that added value to the findings. In

another opportunity, the same material was presented to researchers and modelers during a Conceptual Modeling International Conference in Lisbon (ER, 2023). Feedback and comments confirmed the successful goal of the viewpoint.

CHAPTER 5

Security Concern in the UAM System of Systems

5.1 Introduction

Avoiding, withstanding, and recovering from security risks is critical for UAM's safe operations. Achieving high levels of security requires the systemic integration of technology, people, organizational structures, and operational procedures. Thus, security is a critical socio-technical concern in future UAM operations. In the urban environments where UAM operates, robust security measures are essential for protecting digital systems, physical systems, and people (crew, passengers, and the public) from threats. Advanced technological systems for threat detection and response, skilled personnel capable of applying security protocols, well-defined organizational structures to support communication and coordination, and robust operational procedures are required to ensure consistent and effective actions. Failures in these components can compromise security, leading to significant safety risks, operational inefficiencies, and potential breaches. Therefore, addressing security as a socio-technical concern is essential for mitigating risks and ensuring the successful integration of UAM into urban infrastructure.

This Chapter investigates the security viewpoint within the UAM ecosystem. The security viewpoint in this thesis comprises cyber security (related to digital systems) and physical security (related to people, properties, and physical assets). It begins with understating the security problem space and identifying key challenges and obstacles related to security risks. Following this, the security solution space to address those risks is explored. The following sections provide architectural views and discussions about security concerns. Different enterprise perspectives are presented according to the goals defined in the solution, including security risk taxonomy, security structure, capability structure, and security states. Resilience operation is discussed, and security

processes are defined for the UAM ground operation. Finally, we explain how the security views were validated.

Furthermore, this Chapter aims to answer Research Question 3: "Which security controls and processes are necessary for the UAM ecosystem to manage cyber, physical, and personnel security risks?". Addressing this question involves examining how the UAM SoS can provide the necessary processes and structure to protect, withstand, and recover from security risks.

The theoretical foundations and past findings on security and resilience operations presented in Chapter 2's literature review were used to understand the problem space and the proposed solutions in this Chapter. The diagrams presented in this Chapter were created per EA methodology, utilizing the UAF version 1.2, as explained in Chapter 3. Additionally, it is noteworthy that most of the content of this Chapter was published in the IEEE Open Journal of Systems Engineering in October 2023 in the article "Security Viewpoint and Resilient Performance in the Urban Air Mobility Operation" (Hoffmann et al., 2023b).

This Chapter presents the results of the security viewpoint to address the security socio-technical concern. It is organized into three main parts: The security problem space is discussed in 5.2, and the security solution space in 5.3. Secondly, we define the risk taxonomy to identify what threats we must address in 5.4.1. Then, in 4.4.2, the security structure is presented to show which assets are threatened by previously defined risks. Next, the capability structure in 4.4.3 shows the enterprise-level taxonomy of capabilities to address security risks. Closing this section, 5.4.4 elaborates a security state view to analyze the behavior of what happens when an attack occurs. In the second part, resilience drives discussions and architecture elaborations. In 5.5.1, security processes are defined according to the UAM ground operations, followed by more definitions of the processes flow in 5.5.2. Finally, the resilient performance of ground operations is analyzed using a security traceability matrix in 5.5.3. Validations are presented in 5.6, completing the security viewpoint.

5.2 UAM Security Problem Space

To understand the security problem space, the architecture conceptualization process from EA methodology provides some steps to characterize the problem as described in ISO/IEC/IEEE

(2019a) item 8.4.3. It starts by identifying the potential problem areas that need to be addressed. In the security context, security threats and risks are drivers for analyzing the problem. Once the security vulnerabilities of the operation are known, we can define which areas need to be addressed. In this case, increased airspace traffic, augmented need for communication (with other vehicles and traffic controllers), vertiports in congested urban areas, public proximity to information systems and networks, and reduced and easily accessible crew can contribute to UAM vulnerabilities.

The problem space in UAM security is an extensive set of elements and processes. Vulnerabilities of the urban space (easy access and how data will be exchanged near the public areas), vulnerabilities of the personnel involved in UAM operations, risks related to data and information systems, risks to passengers and the pilot, and risks related to controlling and CNS during flight. Threats and attacks can be diversified. Physical assets might be the ultimate target of a malicious event. However, people can be used to achieve an intrusion or even perform sabotage. There are different ways of affecting the confidentiality, integrity, or availability of UAM operations. The problem space encompasses all elements that are associated with those risks.

Moreover, manned (and unmanned) aerial vehicles will heavily depend on computers, software, and automation. Organizations will use databases to store sensitive data and share data through networks as providers or operators, making them vulnerable to cybersecurity threats. Ground staff, controllers, and pilots are also susceptible to security risks. Intentional damage to a vehicle or network can target UAM personnel to start an attack.

Identifying stakeholders and their concerns related to these problems and opportunities is crucial. Key stakeholders include individual operators with access to the vehicle, such as pilots and ground personnel, who need to ensure personal and passenger safety; security personnel responsible for monitoring and responding to threats; technology developers (vehicle systems and network systems developers), also known as OEMs, who must create secure and reliable systems; and service providers like UATM Operators, UAM operators, and Vertiport operators, who need to maintain secure operations for business sustainability and user trust.

5.3 UAM Security Solution Space

EA conceptualization process in ISO/IEC/IEEE (2019a) item 3.4.6 was tailored to elaborate the security solution space towards the research objectives. In this section, the concept of the solution space will be defined to drive the security architectural views in the next section. It starts by examining the context in which stakeholders perceive value and formulating value propositions for the potential solution. By understanding the specific needs and expectations of different stakeholders defined in the problem space, we can create value propositions that address their concerns and enhance UAM security.

Understanding the vulnerabilities more broadly supports a comprehensive approach in the solution space. Security viewpoints, including physical and cyber aspects, must consider different threats and behaviors that lead to a more protective and resilient ecosystem. For a complex operation like UAM, different perspectives are necessary to understand how systems and personnel can act together, not only protecting but adapting and learning from events. A comprehensive exploration to unveil unintended consequences can mitigate unknown vulnerabilities in UAM security. UAM operational concepts need to explore the critical functions of avoiding, withstanding, and recovering from threats. This strategy may be compromised if the solution lacks an ecosystem-level perspective.

Protective technologies are necessary but not enough to avoid attacks. Operational procedures must be aligned with the daily operations and human operators' performance. Assets are integrated with people and might be vulnerable through this relationship. Figure 5.1 depicts the high-level operational taxonomy where the main assets are represented. Identifying and exploring security capabilities by understanding how assets are organized within the ecosystem is the base for a strategic solution.

Considering the high-level operational concept for the security scenario, it is vital to understand the functional and non-functional characteristics of the potential security solution. Functional definitions are expected to reflect on systems' performance or intended outcomes in operational processes. The desired functional characteristics for security in UAM include advanced threat detection and response systems, comprehensive surveillance and access control systems, robust encryption and authentication mechanisms, and real-time monitoring and alert systems. These

functions are critical to ensure that potential threats are promptly identified and effectively neutralized, thereby protecting digital and physical assets within the UAM ecosystem.

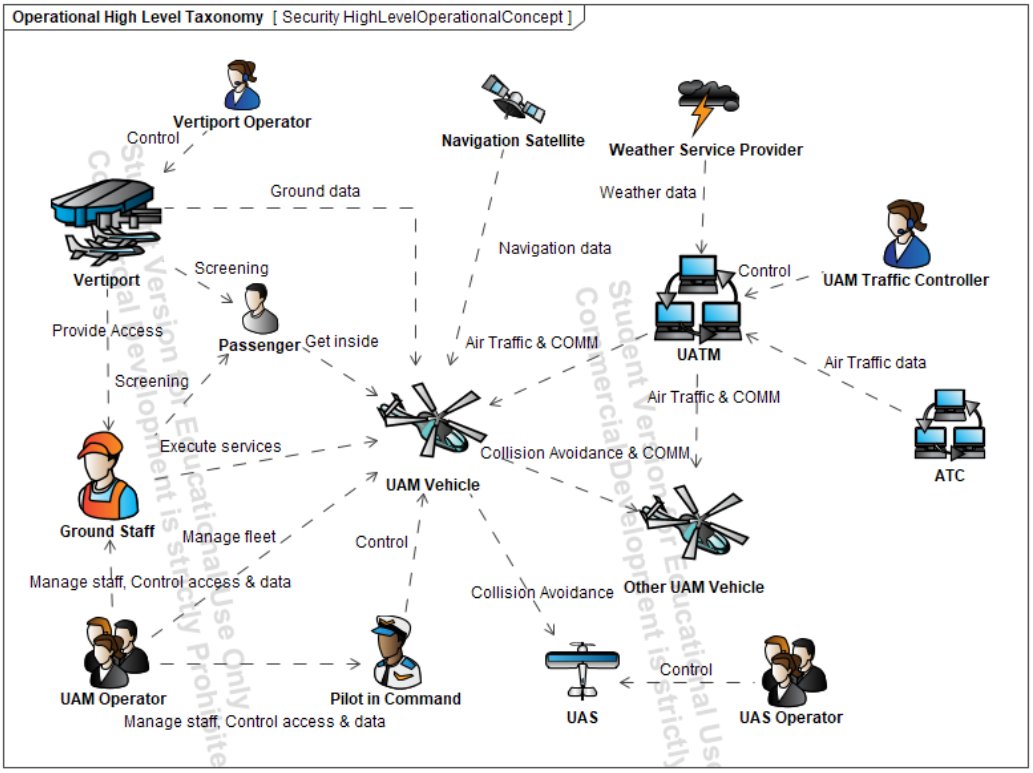

Figure 5.1: Operational High-Level Taxonomy (St-Sr)

In terms of operational processes, the integration of these security systems must be consistent, ensuring that all security protocols are adhered to without causing disruptions to regular operations. Additionally, the human aspect involved in these functional definitions is critical to the research's contribution. Therefore, a particular focus should be given to the preparedness of security personnel and designing processes coherent with the operator's functions.

Desired non-functional characteristics include high reliability and availability of security systems, ensuring they are continually operational and can handle high volumes of data and activity without failure. Interoperability between different systems and devices is essential to create a cohesive security network that can operate effectively across various platforms and technologies. Scalability is another essential non-functional characteristic, ensuring the security systems can grow and adapt to increasing threats and expanding UAM operations.

Furthermore, resilience is a key non-functional characteristic, encompassing the ability of the security systems to recover from attacks or failures quickly and maintain continuous protection. This includes having robust recovery plans, redundant systems, and adaptive protocols that ensure the UAM operations can withstand and bounce back from security incidents with minimal disruption. In conclusion, the boundaries of the solution space in this research comprise the security viewpoints with security risks, controls and processes, and SoS perspective to achieve resilient performance in UAM operations.

5.4 UAM Security Enterprise Views

The UAF was created as a combination of the architecture frameworks from the U.S. Department of Defense Architecture Framework (DoDAF) and the British Ministry of Defence Architecture Framework (MODAF). Although DoDAF and MODAF do not provide security views, it was added to the UAF profile (OMG UAF, 2022b). UAF's security viewpoint is based on Canada's Department of National Defense Architecture Framework (DNDAF) (DND, n.d.) and the North Atlantic Treaty Organization (NATO) Architecture Framework (NAF) version 4 (NATO, 2020).

The UAF security views are intended to depict the security assets, enclaves, constraints, controls, families, and measures required to address specific security concerns. They aim to define the security constraints and information assurance attributes on exchanges between systems, operational elements, and the elements themselves. The stakeholders who benefit from these views include security architects, security engineers, systems engineers, and operational architects (ISO/IEC, 2022).

The beginning of the architecture elaboration process (according to ISO/IEC/IEEE (2019a) item 10.4.1) involves planning the model effort to architect and represent the solution. The intended users are the stakeholders identified in the previous section and represented in Figure 5.1. The architecture objective is to develop a comprehensive security strategy that addresses various scenarios and vulnerabilities within the UAM ecosystem, encompassing personnel, infrastructure, and daily operational processes while integrating digital and physical security measures. The objective is also aligned with the research question intended to be answered by this Chapter.

5.4.1 Risk Taxonomy

The first step in the security architecture elaboration process is defining the security taxonomy (OMG UAF, 2022b). This step includes identifying risks, affected assets, security controls, security enclaves, and security constraints. *Risk* in UAF is a type that represents a situation involving exposure to danger of affectable elements like assets, processes, or enterprise goals. The effects of such exposure can be characterized in terms of the likelihood of occurrence of a given threat and the potential adverse consequences of that threat's occurrence. *Security Risk* is a specific type of risk related to the impact on enterprise operations, assets, or individuals resulting from the potential impact of a threat given an information system. This element was defined in UAF according to the NIST (2018) cybersecurity framework.

Figure 5.2 presents the *Risk Taxonomy* diagram. There are four main categories of risks: *Loss of Confidentiality*, *Loss of Integrity*, and *Loss of Availability*. *Loss of Availability* concerns the disruption of access to, or the availability of, information or an information system. *Loss of Authenticity* is the lack of being genuine and being able to be verified and trusted; confidence in the validity of a transmission, a message, or a message originator. *Loss of Integrity* is the unauthorized modification or destruction of the information. *Loss of Confidentiality* is related to unauthorized disclosure of information.

The diagram of Figure 5.2 defines generalization relationships between <<Risk>> and <<Security Risk>> in the context of the UAM by the solid line with the white triangle arrow pointing to the generalized risk. *Loss of Availability* was divided into two categories better to accommodate the security views in the following sections. Either *Loss of Navigation* or *Loss of Communication* can happen when there is *Signal Jamming* or *Denial of Service*. Signal jamming is an attack that blocks or interferes with radio or wireless signals. Denial of service (DoS) is when traffic is used to flood a network or server, overwhelming its capacity and causing it to crash or become unavailable to legitimate users. *Spoofing* is a specialized risk of *Loss of Authenticity*. It happens when an attacker impersonates another entity or user to gain access to sensitive information, perform unauthorized actions, or deliver malware.

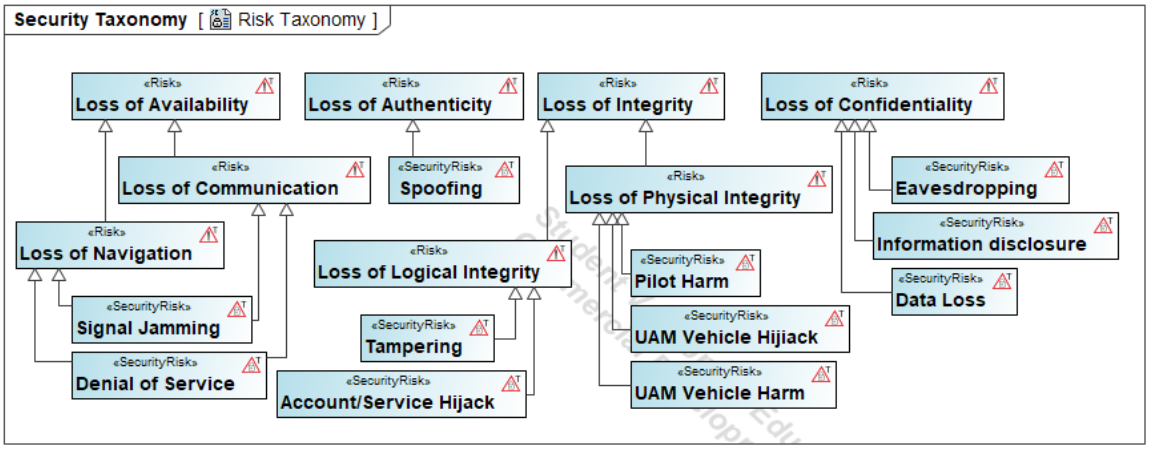

Figure 5.2: Security Taxonomy (Sc-Tx)

The *Loss of Integrity* can be logical or physical. Logical comprises *Tampering* and *Account/Service Hijack*, while physical comprises *Pilot Harm*, *UAM Vehicle Hijack*, and *UAM Vehicle Harm*. Tampering is intentionally modifying or manipulating data, systems, or other assets for malicious purposes. An account or Service Hijack is when an attacker is able to access and control a user account or service without authorization. In terms of physical integrity, it is possible to harm the vehicle through a malicious attack using physical parts (like sabotage during replacements) or through external connectors during unauthorized maintenance activities. *Vehicle Hijack* refers to the act of taking control of a vehicle for malicious purposes. *Pilot Harm* is when the target is the pilot, which can happen when hijacking the vehicle or affecting the service.

Lastly, there are three ways to lose confidentiality. *Eavesdropping* refers to the interception and monitoring communication between two parties by an unauthorized third party. *Information disclosure* involves unintentional or intentional exposure of sensitive information to unauthorized individuals or systems. *Data Loss* is when there is unintentional or intentional destruction, deletion, or corruption of digital data.

The main reason for starting with the risk taxonomy is that it prompts the need for security controls and other security aspects. Unlike in systems engineering, where requirements drive system development, in security engineering, the driving force is risks (Hause & Kihlström, 2021b). The security taxonomy can be defined after identifying all types and subtypes of risks. It includes the hierarchy of security assets and asset owners available to implement security, security constraints (policy, guidance, laws, and regulations), and details of where they are located (security enclaves).

With the security taxonomy complete, it is possible to understand which and how the assets can be affected, how to mitigate them, and, consequently, build the enterprise security strategy. The complete security taxonomy is not depicted due to limited space and resources. Moreover, risk analysis should be done constantly so that the architecture can evolve with new risks or once unknown vulnerabilities are perceived. Still, in the security structure diagram below, some elements defined in the taxonomy are represented along the relationships between them.

5.4.2 Security Structure

Creating the security structure is the second step. The objective is to capture the allocation of assets (operational and resource, information and data) across the security enclaves and show applicable security controls necessary to protect organizations, systems, and information during processing, storage, and transmission. This view also defines the hierarchy of security assets and asset owners that are available to implement security, security constraints, and details about security enclaves.

Figure 5.3 shows the diagram *Security Risks Owners and Affected Assets,* which presents an overview of the security risks and the enterprise assets at risk. <<SecurityRisk>> blocks were already defined in the risk taxonomy diagram of Figure 5.2. There is *Loss of Communication* and *Loss of Navigation*, general classifiers of *Signal Jamming*, and *Denial of Service*. Furthermore, there are more specialized risks like *Spoofing*, *Signal Jamming*, *Eavesdropping*, *Information Disclosure,* and so forth. From the asset representation perspective, there are elements from the operational domain like the <<OperationalPerformer>> blocks and from the personnel domain like <<Organization>> and <<Post>> blocks.

The resource layer in this diagram aims to point to risk owners and assets affected by threats related to the risks. In the UAM ecosystem, three main operators share space and work with interdependent processes. The <<Organization>> *Vertiport Operator* is responsible for managing and controlling the vertiport facility, which includes takeoff and landing pods, embarking/disembarking area, maintenance area, and battery recharging area. It also provides ground communication and surveillance. <<Organization>> *UAM Operator* is the organization responsible for the travel service, owns the vehicle, provides the flight plan and passenger and crew list, and is responsible for vehicle maintenance and operations. <<Organization>> *UATM Operator* is the service provider responsible for integrated airspace traffic management, including providing authorizations and airspace awareness.

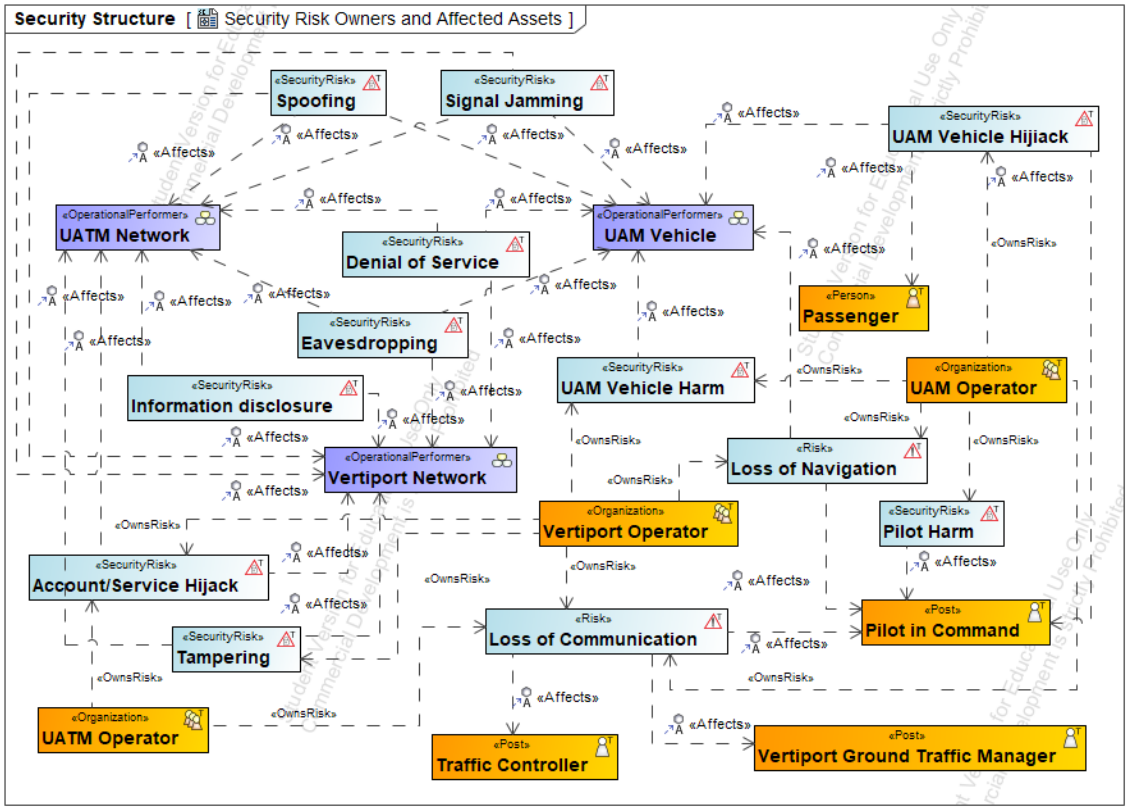

Figure 5.3: Security Structure (Sc-Sr)

Regarding risk ownership in complex operations like UAM, having a single entity is not always simple and straightforward. For instance, the <<Security Risk>> *UAM Vehicle Harm* is a risk owned by the asset owner and shared responsibility with the *Vertiport Operator* since the vehicle will most of the time occupy the vertiport facilities. The same applies to *Loss of Communication* or any other risks affecting networks. Losing or using a compromised communication link is a risk that affects all three operators. Despite not showing the relationship <<OwnRisk>> to all of the risks (to keep the figure's clarity), it is expected that operators share the ownership and responsibility.

There are also two levels in the personnel elements. The <<Organization>> *UAM operator* owns integrity risks that affect people and vehicles. However, the <<Post>> *Pilot in Command* is part of the *UAM Operator* organization. The vulnerability of the pilot is represented by the different risks affecting the post in different operational phases. Single pilot operation is expected in the early phases of the UAM services. Planning for the pilot's security is crucial. The organization-level effort should be considered when protecting and preparing for responding to events. The

ground operation explored in 5.5 further explains the security controls and mitigations related to the pilot's vulnerabilities.

5.4.3 Capability Structure

Capability is a high-level specification of the enterprise's ability to execute a specified course of action (ISO/IEC, 2022). In DoDAF, a capability is further described as the ability to meet performance standards and conditions by combining activities and resources to achieve the desired effect. Defining capabilities is crucial to the architecture conceptualization because it is closely related to operational, resources, personnel, and services definitions. The system's purpose and the model's objective can be understood by defining architecture capabilities.

UAF offers a set of views for defining capabilities. Traceability and association relationships can be established across different views, including the operational architecture. The operational architecture provides a solution-independent expression of the system intended to be used during operations. Thus, the system views can determine how the capabilities and operational architecture will be realized (Hause & Kihlström, 2021b). The Strategic Taxonomy (St-Tx) view is used to identify all the capabilities referenced across one or more architectures. It can create high-level use cases and user requirements as a source document. The Strategic Structure (St-Sr) can show the relationship between the capabilities, and the Strategic Connectivity (St-Cn) describes the dependencies between planned capabilities.

The next step is defining capabilities to achieve a secure and resilient operation after identifying the risks and security structure. Figure 5.4 shows the structure organized from the top-level capability of *System Security* using composition and generalization relationships. The composition notation is the solid line with the tail attached to the part and the black diamond arrowhead attached to the whole. Composition relationships demonstrate that it is necessary to fulfill all four capabilities to achieve System Security: *Threat Prevention, Threat Detection, Threat Response*, and *Threat Recovery*. These parts were defined considering the NIST (2018) Cybersecurity Framework functions and then tailored to explore security views and resilient operations in the UAF model. These functions are Identify, Protect, Detect, Respond, and Recover. The functions assist an organization in articulating its approach to managing cybersecurity risk by structuring information, facilitating risk management decisions, mitigating threats, and enhancing its practices through learning from prior experiences.

Threat Detection (second block from left to right in the second line) is about the ability to identify and diagnose threats. It has two parts represented by the capabilities *Threat Identification* and *Threat Diagnosis* (the two blocks below the *Threat Detection*). *Threat Identification* refers to the mechanism of detecting an event. A good performance of this capability is not only to detect known or expected threats but to bring awareness when something does not seem right, even about unknown threats. *Threat Diagnosis* is about knowing the threat profile, where, and how the event threatens the system's health, which is essential to address a more effective response.

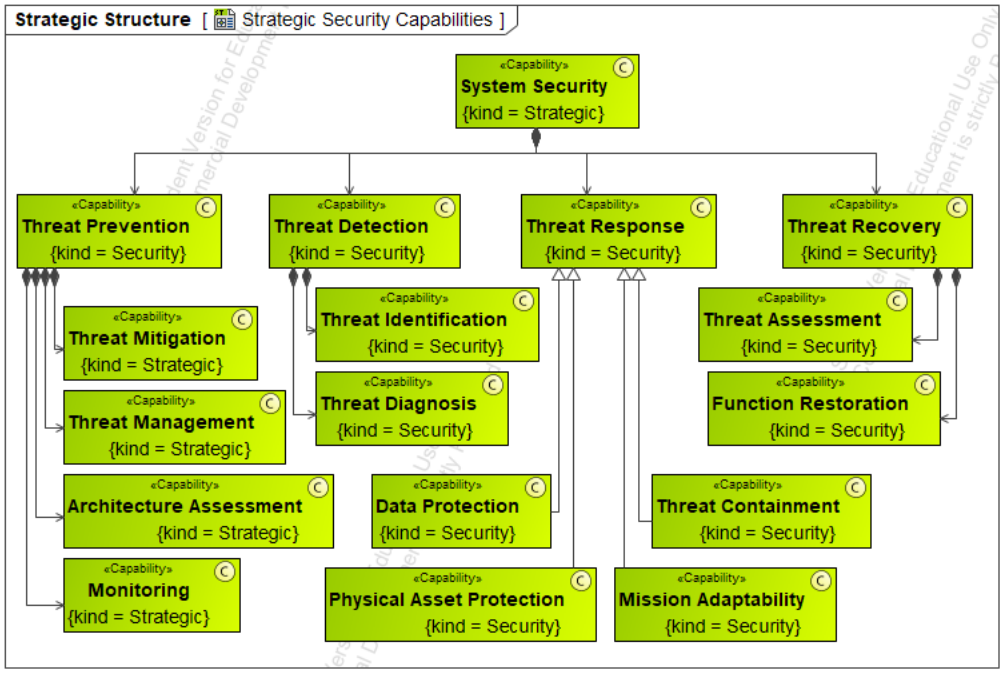

Figure 5.4: Capability Structure (St-Sr)

Threat Response (third block from left to right in the second line) can address protection or contingency measures to respond to a threat. The generalization arrow links four types of responsive capabilities. Protecting the system provides a means to avoid attacks getting adverse outcomes in the system. Two possible types of assets in the security domain require two protection types: *Data Protection* and *Physical Asset Protection* (blocks below the *Threat Response* on the left side). *Data Protection* refers to the protection of logical data exchanged by the UAM system. *Physical Asset Protection* is related to physical and environmental security, such as operational procedures. Contingency is about the ability to control attacks to the most negligible effect possible. There are two ways of doing it (blocks below the *Threat Response* on the right side).

Threat Containment refers to isolating the attack or controlling its boundaries to minimize its functioning or eventually make it harmless. The other way of contingency is *Mission Adaptability*. Inactivating the area where the attack harms and adapting the system's mission also makes it possible to control the threat. System redundancy is a good example of contingency by adapting the mission.

Threat Recovery (the last block from left to right in the second line) is a combination of *Threat Assessment* and *Function Restoration* (blocks below *Threat Recovery*). It is about the ability of the system to resume a safe operation after a threat occurs and generates outcomes to the system's normal functioning. *Threat Assessment* includes the reconnaissance and analysis of the threat, assessment of the potential harm, and additional vulnerabilities. This assessment is needed to restore the function initially affected by the threat. Therefore, *Function Restoration* refers to the measures necessary to restore the system's operation. These measures have a high level of variability and depend on what type of attack occurred and how was the sequence of events and facts. The organization and systems are expected to be able to assess threats and have the flexibility to act toward recovery.

Threat Prevention (first block from left to right in the second line) was proposed to address risk management and the capability to assess the architecture and promote adaptation in the face of events. In order to know events, *System Monitoring* is essential. After events occur, with or without adverse outcomes, it is important to manage them by controlling and performing assessment (*Threat Management*). These activities can lead to an *Architecture Assessment* or a new/improved mitigation plan (*Threat Mitigation*). The four capabilities composing *Threat Prevention* are not independent or linear parts that occur as a simple flow of actions. Their behavioral aspect is highly coupled with other capabilities in the diagram.

The proposed representation in Figure 5.4 results from iterative work during the definition of mitigations, security controls, security state, and processes. Allocations to capabilities in further diagrams are a method to verify coverage and consistency. It allows the architecture designer to revisit definitions and best accommodate the representations. Moreover, the UAF views allow traceability relationships from resources and processes to capabilities. The following sections provide a few examples of how this model feature can support the architecture to achieve the desired security effectiveness.

5.4.4 Security States

Motivated by the Strategic State (St-St) view, which is used to capture effects that the implementation of capabilities is expected to deliver, a Security State view is proposed in this section. The existing UAF grid in ISO/IEC (2022) does not provide the *Security State* view. The security viewpoint is limited to Taxonomy, Structure, Motivation, Connectivity, Processes, Constraints, and Traceability. The security state diagram in Figure 5.5 intends to identify the states related to resilience engineering: avoid, withstand, and recovery.

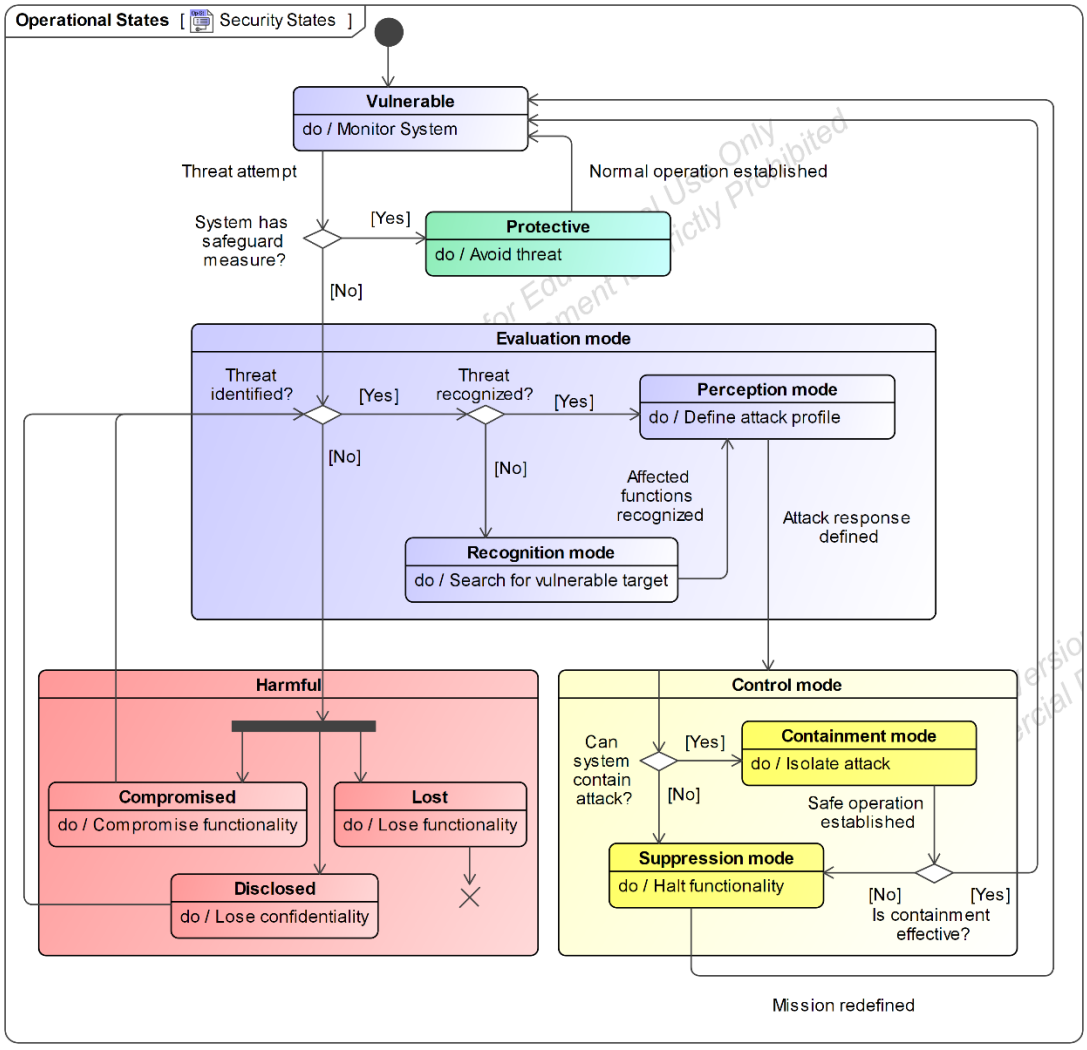

Figure 5.5: Security States

Given the unavoidable circumstance of facing evolving threats, protection is not a real and viable solution for the entire ecosystem (assets and operations). How can an organization or system cope,

recover, and learn from threats? How do we transition from an undesirable state into a controlled one? In which process should the effort be strengthened? Are the defined capabilities coherent with the transitions and behaviors of the security states? Those are questions that drive the diagram in this section.

The first state, applicable to all systems and operations, is *Vulnerable* (the first state at the top). Risks, hazards, and threats are inherent in any system. Safety and security are dynamic properties that complex systems must be designed to handle. Furthermore, recognizing that humans are an integral part of ecosystems and that their abilities and limitations must be taken into account in designing and managing systems is one of the resilient engineering principles (Nemeth & Holbrook, 2021). This state requires continuous and real-time monitoring, which traces to the capability of *Monitoring* (bottom left block in Figure 5.4). The *Monitoring* capability is an extensive ability that comprises physical, logical, and personnel entities.

When a threat is attempted, the best transition would be to a *Protective* state (second state from top to bottom in Figure 5.5). This means that the system is adequately prepared to avoid the threat. *Data Protection* and *Physical Asset Protection* capabilities are related to this state (bottom center blocks in Figure 5.4). *Protective* is a desirable state because it returns to normal operation without causing any adversity to the system. Data encryption, firewalls, verification layers, and controlling authorized access are examples of protecting data and physical assets.

When the system does not have adequate protection upon a threat attempt, it transitions to the *Evaluation mode* state (center state). Detecting a threat starts with knowing if an event happened and then recognizing its profile. *Threat Identification* and *Threat Diagnosis* capabilities (from Figure 5.4) allow the *Perception mode* substate (right side state inside the *Evaluation Mode* state) to define the attack profile and search for a response. If the system is not able to recognize the threat event, knowing the existence of the attempt, the other possible substate would be *Recognition mode* (bottom state inside the *Evaluation Mode* state). The flow within the *Evaluation mode* state shows the system's importance in being prepared for monitoring and performing screening during an attack. Furthermore, the capability *Threat Assessment* is also related to both substates within the *Evaluation mode* state.

The *Control mode* state (bottom right state) is entered when the threat is acknowledged and the response is known. The first option for controlling the threat is isolating the attack and resuming

safe operation. If the system has means to contain the attack, the *Containment mode* substate (right side state inside the *Control mode* state) is activated. Suppose the strategy is not effective, or the system does not possess the containment means. In that case, the *Suppression mode* substate (bottom state inside the *Control mode* state) is also possible. The other way of controlling the attack is by redefining the mission and halting the functionality that is being attacked. Redundancy of resources or suspending operations are examples of methods used to suppress the threat. The *Control mode* state represents the measures to withstand or to respond to an attack. The state is associated with capabilities like *Threat Containment*, *Mission Adaptability*, and *Function Restoration* (Figure 5.4).

If the system cannot detect any event, the transition moves to the *Harmful* state (bottom left state). This state is the most undesirable in the diagram. Not knowing a threat occurred can lead to catastrophic events. Once the state is active, there are three possibilities. *Compromised* substate (left side state inside the *Harmful* state) is when the threat affects one or more functionalities. Operating without knowing the system has compromised integrity can bring unsafe outcomes. *Disclosed* substate (bottom state inside the *Harmful* state) concerns the unauthorized disclosure of confidential information. Disclosing unauthorized data can range from jeopardizing national security to disclosing private customer information. For instance, if a flight plan is disclosed, it can facilitate other attacks with worse outcomes or even affect the organization's reputation and business. The third state is *Lost* (the state on the right side inside the *Harmful* state) and symbolizes when functionality is wholly lost. If an attacker can take control of a system and shut it off without being noticed, it can also bring catastrophic effects. *Compromised* and *Disclosed* states can transition to *Control mode* again. The system can and should detect the threat even after some time has passed since the first attempt. This could lead to the threat diagnosis and eventually a recovery and learning *behavior*.

The Harmful state represents the risks being consolidated in an objective fact. The *Lost* state is associated with the risk of *Loss of Availability* (from Figure 5.2). The *Disclosed* state can represent an event that produced a *Loss of Confidentiality* or a *Loss of Authenticity* (risks from Figure 5.2). Lastly, the *Compromised* state is when the risk of *Loss of Integrity* or *Loss of Authenticity* happens. *Loss of Authenticity* is a risk that occurs in both states because losing confidence in the validity of a transmission, a message, or a message originator can also compromise the system's functioning.

The state diagram is proposed to represent the primary states and the common transitions. Some specific behaviors or transitions require a more elaborated logic between states and substates. There are cases in which the threat attempt would be detected, and still, the protection exists and is effective. However, some protection systems avoid threats without recognizing attack attempts. Another example of a situation not detailed in the diagram is when an attack can hit different targets and present different profiles. This scenario could lead to controlling part of the threat and keep trying to evaluate another part. When the harmful state is active with compromising functionality for a while, and the system can detect the event, the diagram transitions to the *Control mode* state. However, irreversible harm could have been done, and the controlling state would deal only with new *targets*.

*T*he state diagram has limitations. Security states experience complex transitions and require more depth to cover various scenarios. Triggers and effects in security states can compel more elaborate notations. Nonetheless, the level of detail to increase the coverage of the diagram would affect the visualization and compromise the understanding aimed at this work. The intended purpose of Figure 5.5 is to support an understanding of how a system or organization can behave while facing its threat landscape. As described in the next section, the diagram helped define functions, mitigations, and processes.

5.5 Resilience in UAM Ground Operation

The security motivation and taxonomy views define *which* security control and risk mitigations are necessary. The UAF Security Process (Sc-Pr) view addresses *how* security controls will mitigate risks. Functions, processes, and resources are aggregated to elaborate the structure and behavior of the processes. *Security resource performers* comprise mitigations and security enclaves. Mitigations can be defined as resource elements or operational activities. *Functions* performed by those security resource performers will perform a *security process* that implements *security controls* for protecting enterprise assets to *mitigate* expected *risks*. Different views can describe operational behavior, structure, and exchanges required to exhibit capabilities.

The security architecture is often viewed as primarily concerned with safeguarding assets. This involves implementing security measures that align with established security control tactics,

techniques, and procedures, as well as adhering to relevant security policies, directives, and limitations. Operational and resource security mitigation can be defined and implemented to achieve these objectives (OMG UAF, 2022b). Despite the need to protect various assets, the security architecture must also provide countermeasures and means to withstand and learn from events. This section will focus on the UAM ground scenario to discuss how security processes support resilient operations.

5.5.1 Ground Security Processes

The first security process diagram (Figure 5.6) presents the functions necessary to perform mitigations. After the security structure and motivation were clear, security controls were defined to mitigate risks related to the ground operation. A *security control* (as the first line of blocks with the notation <<SecurityControl>>) is a prescribed safeguard or countermeasure for an information system to protect the confidentiality, integrity, and availability of the system and its information. In this step, the environmental context and the high-level operational concept are considered to have coherent security controls. In the diagram below, the security controls (are satisfied with one or more mitigation elements.

Below the <<SecurityControl>> blocks are the mitigation blocks defined for satisfying the security controls. <<ResourceMitigation>> represents a set of resource performers intended to address specific risks. <<OperationalMitigation>> represents a set of operational performers intended to address specific operational risks. In other words, it is possible to define mitigation based on function performance or operational activities.

The security control *Network Protection* (top left block) is satisfied by two mitigations: *Network Integrity Check* and *Network Protection Layer* (blocks under *Network Protection*). They are digital resources to enhance network protection. The purpose of these resources is to protect and monitor the network, as stated in the security control text. *Vehicle System Protection* (second block from top left to right) is a security control requiring two different mitigation types. Like the network protection layer, the <<ResourceMitigation>> *Vehicle System Protection Layer* is a digital resource that protects the vehicle's interfaces. In addition, an operational mitigation element is needed to completely satisfy the security control. The <<OperationalMitigation>> *Vehicle Integrity Check* is a set of elements (personnel, process, and systems) performing an activity.

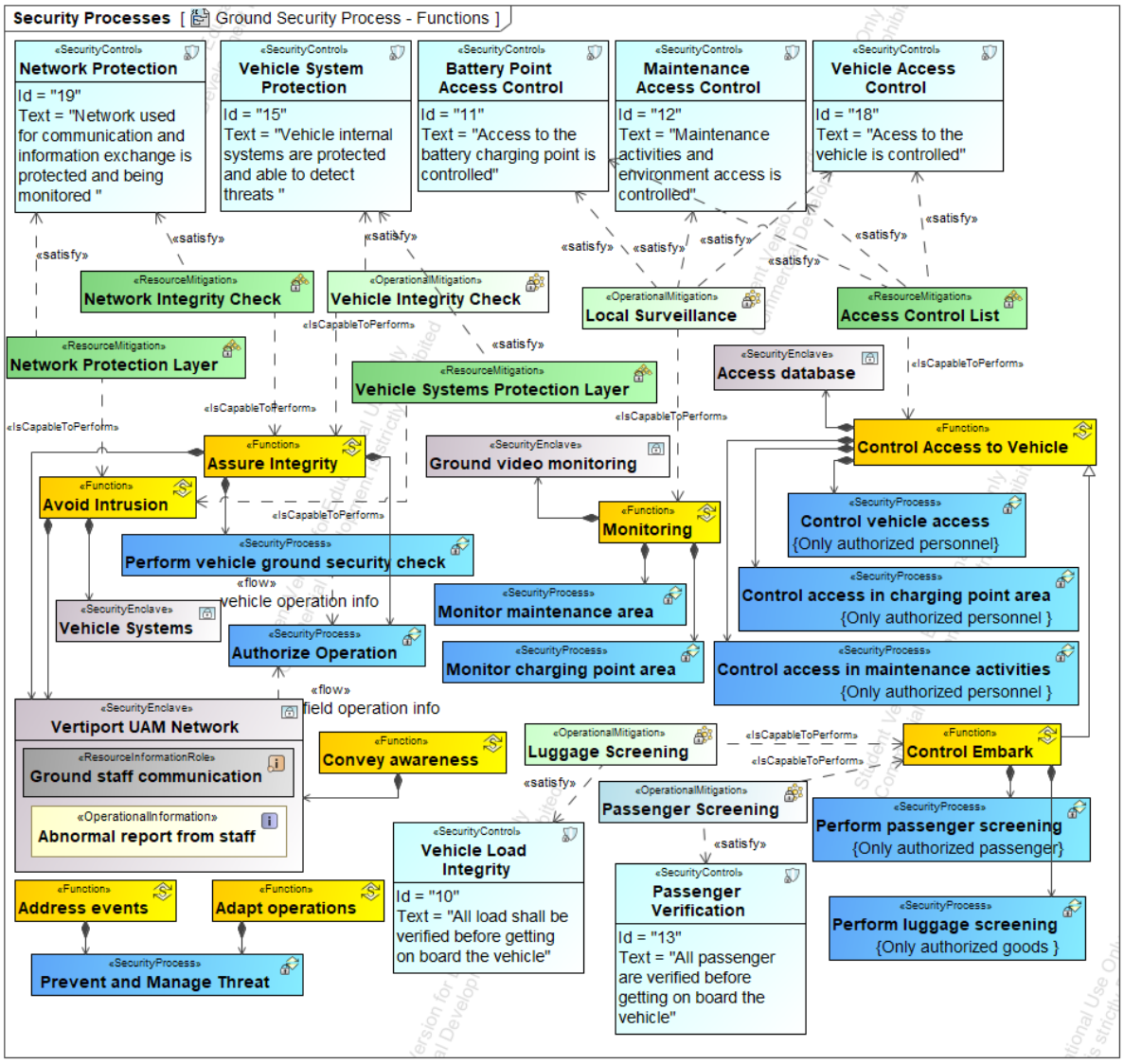

Figure 5.6: Security Processes (Sc-Pr) – Functions view

Two essential functions are common to the security control and mitigations mentioned above. *Avoid Intrusion* is a <<Function>> (block on the center-left side) performed by the *Network Protection Layer* and *Vehicle System Protection Layer*, two different resource performers. *Assure Integrity* (block near *Avoid Intrusion*) is performed by *Network Integrity Check* and *Vehicle Integrity Check*, a combination of resource and operational elements. When defining which processes deliver the function *Assure Integrity*, there are two security processes and one security enclave. A <<SecurityEnclave>> block represents a collection of information systems connected by one or more internal networks under the control of a single authority and security policy. The <<SecurityEnclave>> *Vertiport UAM Network* (big block on the left side) is a network for

communication and information exchange. Integrity checks must be planned within the network and can be further detailed in the resource architecture. *Perform Vehicle Ground Security Check* (<<SecurityProcess>> block in the center-left side) is a process to ensure that the vehicle is intact and nothing is affecting its integrity. Lastly, the security process *Authorize Operation* (block below the *Perform Vehicle Ground Security Check*) is the last integrity check before vehicle takeoff. It represents a comprehensive vision of the ground operation and is described in the activity diagram in section 5.5.2.

The same process of defining functions performed by mitigation elements was done for the other security risks. Access to the vehicle in the vertiport facility is a sensitive aspect of the security properties on ground operations. Concerns with unauthorized access during maintenance or battery recharging are legitimate, considering how the vehicle is vulnerable to malicious attacks. The vertiport is expected to settle in urban areas surrounded by the public and where the space is limited.

Another concern is regarding passengers and the embarking process. As a single crew, the pilot is exposed and vulnerable in the vehicle. A pilot or vehicle hijack is not locally constrained by protecting the crew with a cockpit door. Commercial flights count with airport security barriers, checking crew, passengers, and luggage through a series of processes and resources. However, the time spent in the embarking process, from when the passenger arrives at the airport to take off, is long and can take hours. Considering UAM flights are short (not more than 60 minutes), it may not be practical, or even acceptable from the business perspective, to have a long embarking process. Security and passenger experience must be considered in the ground operation. Current discussions are taking place to find a suitable solution for the UAM stakeholders. Regulatory authorities have yet to decide the ground standards for vertiport and UAM operations. Suppose authorities apply a similar approach to helicopter flights, where private transportation does not require passenger or luggage screening. In that case, it is crucial to understand the accepted risks and consequences. Alternatively, loyal passenger programs are also being discussed in a way to reduce the risk and still have a more agile embark and attractive transportation service.

The security process view is also used to introduce personnel elements and define which resource (*who*) is capable of performing which security process (*what*). The diagram in Figure 5.7 shows an example of the relationships between security processes, security enclaves, organizations, posts,

and capabilities. Processes are mapped to capabilities supporting the model's consistency with the enterprise's taxonomy.

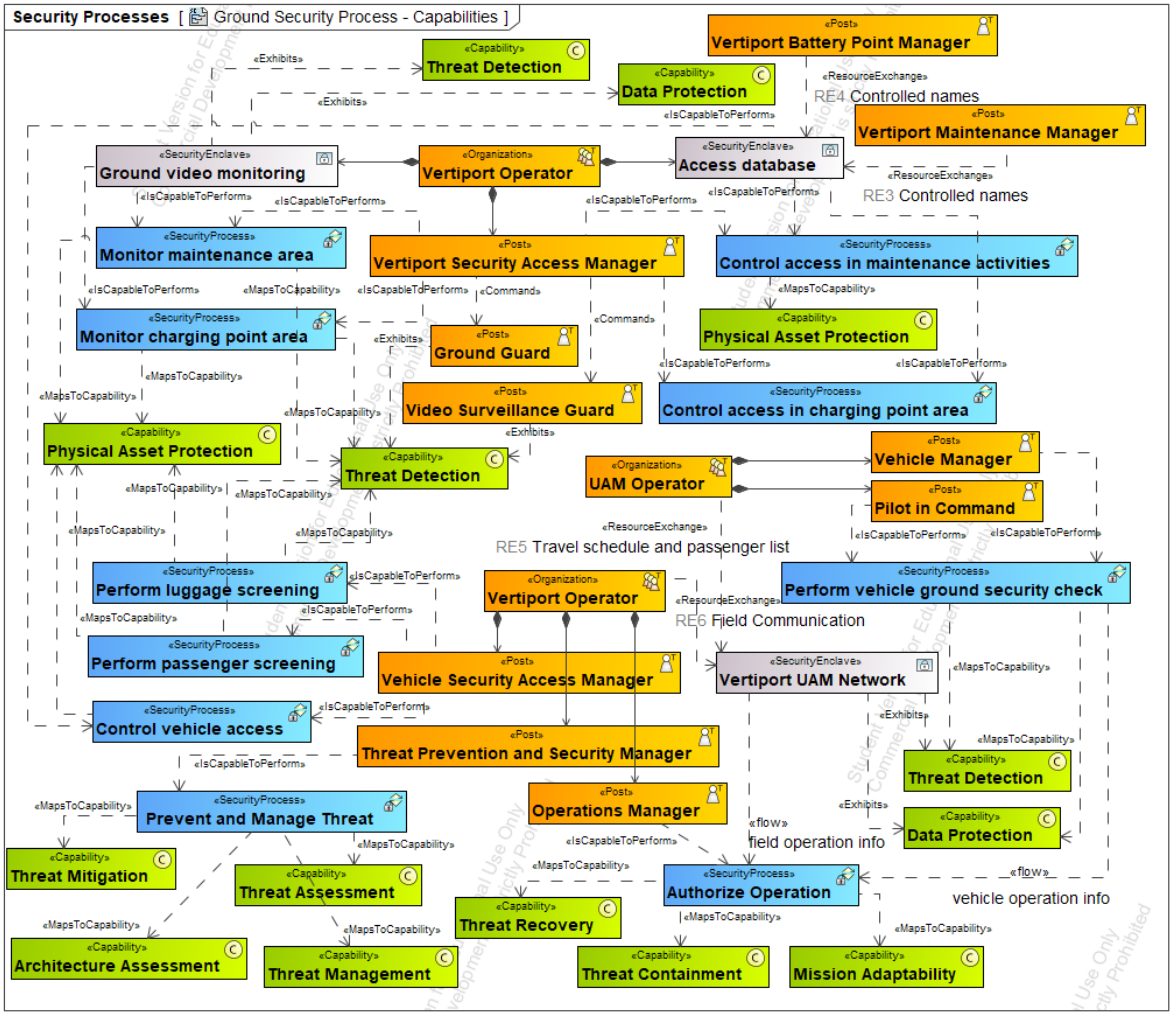

Figure 5.7: Security Processes (Sc-Pr) – Capabilities and Posts view

Relationships within the personnel domain are explored to represent different organizational levels performing security processes. Resources like organizations, posts, and security enclaves *perform* security processes. Figure 5.7 shows blocks <<Organization>> and <<Post>> (blocks in the center) linked to <<SecurityEnclave>> (same blocks defined in Figure 5.6 and presented in Figure 5.7). The dotted line with the notation <<IsCapableToPerform>> shows the resources' capability of performing processes. At the organization level, the <<Organization>> *Vertiport Operator* (block in the top center in Figure 5.7) is composed of posts (staff) and security enclaves like *Ground video monitoring* and *Access database*. People and systems are capable of performing

security processes at different hierarchy levels. For instance, the <<Post>> *Vertiport Security Access Manager* (block below *Vertiport Operator*) is the element responsible for the processes *Monitor maintenance area* and *Monitor charging point area* (<<SecurityProcess>> blocks on both of its sides). Still, two posts are commanded by the security access manager: *Ground Guard* and *Video Surveillance Guard* (<<Post>> blocks below *Vertiport Security Access Manager*). The combination of the entities linked to the mentioned security processes will exhibit the capabilities of *Physical Asset Protection* and *Threat detection* (<<Capability>> blocks in the center). Each post's responsibilities can be defined in detail, considering the structure and behavior explored in the process view. The UAF personnel viewpoint organizes data about organizations, posts, and responsibilities.

Resource exchange is another essential definition in this step. Identifying and understanding the exchange between resources is crucial for detailing the process flow of each security process. The security enclave *Access Database* can only perform the security process *Control access in maintenance activities* if it receives the proper *controlled names* (RE3 & RE4 on the top right of Figure 5.6) from posts *Vertiport Battery Point Manager* and *Vertiport Maintenance Manager*. The definition of the resource exchange can result in systems requirements, operational performance, or personnel responsibilities.

The effort to monitor and safeguard the environment is more evident in the ground scenario. The resources, functions, and processes focus on protecting the vehicle as the ultimate sensitive asset. Since the vehicle is on the ground, the ecosystem's behavior to secure the operation differs from during flight, when time is a critical resource. On the ground, the most critical boundary to avoid unsafe scenarios would be the flight authorization of an insecure vehicle. Most countermeasures and prevention rely on organizational processes and people's behavior. To address this scenario, the process *Authorize Operation* (block on the bottom right in Figure 5.6) has its flow detailed in the following section.

5.5.2 Ground Security Process Flow

UAF Security Process Flow (Sc-Pr) diagram represents the flow within a security process. The security behavior of the architecture can be defined, including process flows and their security measures of performance. Figure 5.8 shows an activity diagram to represent the behavior of the *Authorize Operation* security process. The activity diagram describes operational or resource-level

processes that apply (operational level) or implement (resource level) security controls to assets. In addition, the input and output for each action are specified consistently with the resource exchange defined previously.

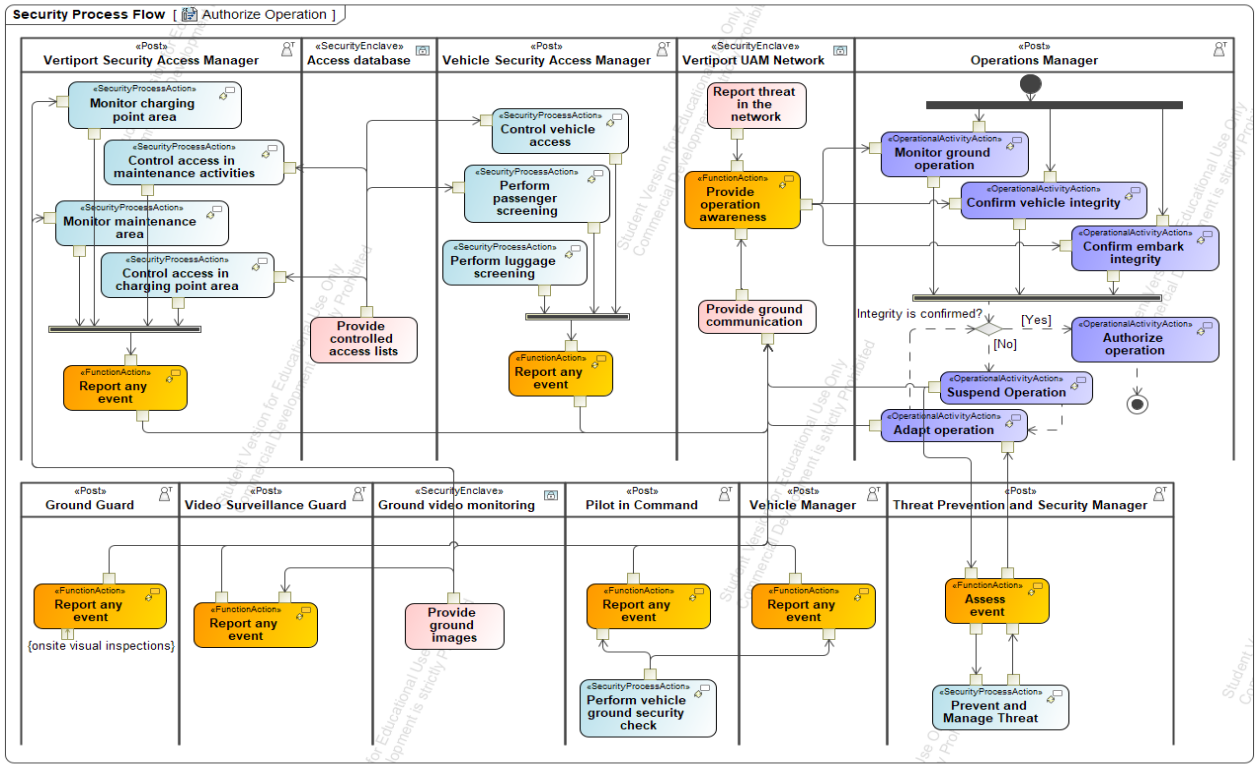

Figure 5.8: Security Process Flow (Sc-Pr)

The core process for *Authorize Operation* is represented in the last column from left to right in the diagram of Figure 5.8. The performer of *Authorize Operation* is the post *Operations Manager* (<<Post>> in the header of the last column from left to right). The activity starts in the initial black dot and follows the control flow (dotted line) inside the swim lane allocated to the *Operation Manager*. The first actions are related to context awareness and happen in parallel. *Monitor ground operation*, *Confirm vehicle integrity*, and *Confirm embark integrity* (<<OperationalActivity Action>> blocks) are actions that depend on other performers' information. The *Vertiport UAM Network* (<<SecurityEnclave>> column left to *Operations Manager*'s column) is a central resource in this scenario. Its function is to *Provide Operational Awareness* (<<FunctionAction>> block in the same column) to the operation manager. Additionally, there is a resource action of *Provide ground network* and *Report threat in the network* (blocks without notation in the same

column) performed by the network itself. All other posts perform the <<FunctionAction>> *Report any event* using the network as a communication resource.

Some actions are directly related to other security processes. The allocation of <<SecurityProcessAction>> elements into posts using swim lanes is consistent with the security process view in Figure 5.7. The relationship between resources and processes was defined in Figure 5.7 with the notation <<IsCapableToPerform>>. For instance, the <<SecurityProcess Action>> *Prevent and Manage Threat* allocated to <<post>> *Threat Prevention and Security Manager* (bottom right column in Figure 5.8) is an action resulting from the security process *Prevent and Manage Threat* (depicted in the bottom left of Figure 5.7). Lastly, resource actions (blocks without notation) are provided by security enclaves, like *Provide ground images* and *Provide controlled access list*.

The process flow performed by other posts is detailed in different diagrams. When all processes are defined, the output and inputs can be specified and called references among processes. The representation above is a sample of how different processes are related and dependent on each other. Using different elements to show the contribution of other resources in *Authorize Operation* was intentional. <<SecurityProcessAction>> <<FunctionAction>>, and resource actions are possibilities to explore the behavior of security process flow. Security process flow can and should be tailored to present the intended perspective.

The activity diagram of Figure 5.8 shows the extent of the operation awareness necessary to authorize a flight operation. Without the performance of posts realizing other processes and reporting events, the integrity of the ground operation could not be confirmed. Resources (staff and systems) are working to monitor and control the environment. Identifying threats is a collective and integrated performance. Using views with higher abstraction levels helps understand the ecosystem behavior towards the security goal. In addition, the usage of the process flow view includes requirements capture, the definition of roles and responsibilities, support task analysis to determine training needs, operational planning, and information flow analysis.

5.5.3 Resilient Performance on Ground

The security architecture elaboration presented at this point, starting from risk taxonomy (Figure 5.2) until the structure and behavior of security processes (Figure 5.6 to Figure 5.8), is an iterative

and recursive process. The analysis to achieve and sustain resilient performance supports the architecture elaboration. At the same time, the architecture resources affect the ability to perform resiliently, enabling and enhancing it in the best case. Resilient ecosystems are able to respond, monitor, learn, and anticipate adverse conditions. Additionally, resilience must be managed, which requires more than just monitoring and learning about the system. It also involves considering how the world responds or changes in response to the system's modifications and how these responses may impact the changes made. This recursive form of anticipation is the highest level of resilience management and must be considered to ensure optimal outcomes (Hollnagel et al., 2011). To address resilience in the ground operation scenario, the security states of Figure 5.5 presented in 5.4.4 were used as a reference to understand how the UAM ecosystem can avoid undesirable states or transition into controllable states.

Two high-level functions are associated with the *Protective* state in ground operation: *Avoid Intrusion* and *Control Access to the Vehicle* (<<Function>> blocks on the right and left sides of Figure 5.6). The first means that networks, information systems, and vehicle systems must be protected against malicious attacks and intrusion attempts. Systems and technologies can be designed to perform the protection for this case. Resource architecture details the measures defined for security protection. The other primary function is related to direct contact with the vehicle. The vehicle needs physical protection while on the ground as a physical asset. Sabotaging during maintenance, dangerous loads, unauthorized pilots, or malicious passengers are threats to flight operations. Controlling the embarking process is a way of controlling vehicle access and requires luggage and passenger screening, verification of pilot authorization, and local surveillance.

Monitoring in ground operations is a critical and central function necessary for evaluating threats. The security process and, consequently, the people involved in the ground operation are organized to monitor and report events effectively and efficiently. The action *Monitor System* in state *Vulnerable* of Figure 5.5 represents the system's monitoring capability. Without monitoring, the system remains vulnerable. The monitoring performance can also identify and recognize threats in the ground operation scenario. The human aspect, safety culture, and organizational culture lead to the monitoring performance and detection capability. Communication resources like the vertiport network and process adherence support the monitoring behavior. Another function is associated with the monitoring effort: *Assure Integrity* (<<Function>> block on the center-right of

Figure 5.6). When the vehicle performs pre-flight checks, or the operation's manager checks the integrity of other processes, an ultimate effort is made to monitor the environment and detect possible threats. Therefore, if the ground monitoring performance is deficient, the *Evaluation mode* state cannot move to the *Control mode* state and avoid the *Harmful* state, as presented in Figure 5.5.

Regarding controlling threats, the ground scenario responds differently than the flight operation. The ground staff is not as pressured by time as a pilot during a flight. There is always a possibility of suspending operations until safety is restored. The *Authorize Operation* process flow demonstrates how the organization can contain or suppress threats. If the integrity is not confirmed, the operation is suspended until the mission can be adapted and restored. The possibility of suspending the operation gives time for the organization to assess the threat and respond to it safely. The same may not be possible during the flight. In extreme circumstances, the flight could go to an emergency state and land as safely as possible.

The *Prevent and Manage Threat* process (<<SecurityProcess>> block on the bottom left of Figure 5.6 and Figure 5.7) supports assessing the threat during operation. An organized and effective risk prevention and management structure is the foundation of resilience. Planning is crucial to understanding risks and responding correctly. Monitoring and assessing is the key to learning about the effects on the operation. Monitoring is a capability that is exhibited collectively and depends on staff behavior and culture. Constantly adapting to the changes in the environment and anticipating them is necessary to reach the outcome desired by this process. Anticipation is only possible if the system's behavior is known through monitoring activities and with the engagement of the people involved in those activities.

Situation awareness, already addressed in Chapter 4, is essential for achieving security. As a collective cognitive process distributed at different enterprise levels, sharing information about events can improve the response capacity of the organization. Resilient performance is also related to non-security events. Learning from actual operation (work as done) can improve security and safety efficiency and make opportunities evident. Active management enables the learning and anticipation capability of the ecosystem. The action common to all posts in the activity diagram in Figure 5.8 is to *Report any event* (<<FunctionAction>> elements). Training people to observe and report all sorts of events, even non-threat or harmless events, can improve the capability of

monitoring and provide means to assess opportunities and actual threats.

A system can be considered resilient if it has the ability to adapt its performance before, during, or after events such as alterations, disruptions, and opportunities and, as a result, maintain necessary functions even in predicted or unforeseen circumstances. Security states, in conjunction with capabilities, provide a reference for analyzing the security process coverage and verification in terms of resilience. The abstraction of capabilities can be refined with the behavior of security state transitions. The state diagram's narrative can serve as a background scenario for defining effective processes. The matrix in Figure 5.9 shows the security traceability between states, processes, risks, and capabilities.

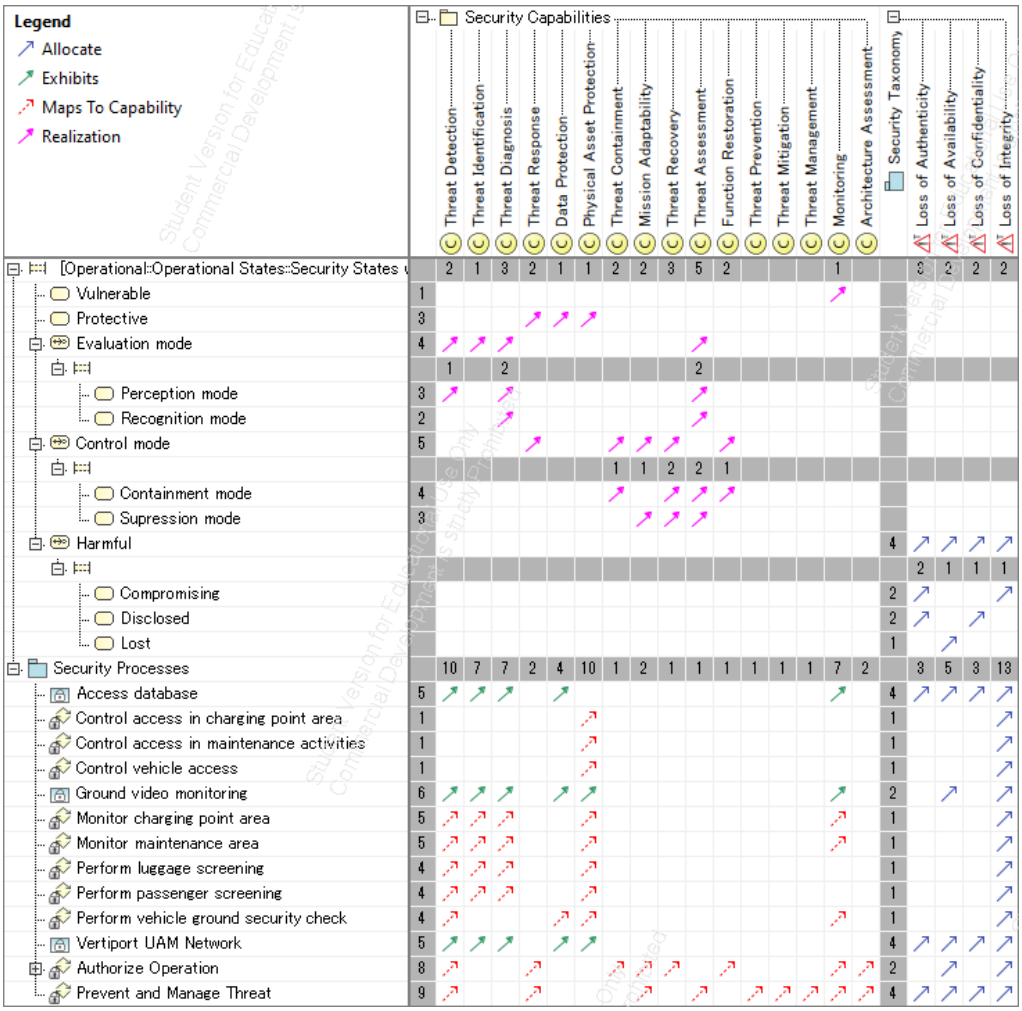

Figure 5.9: Security Traceability Matrix

The top part of the matrix is how the states relate to capabilities and risks, as explained in 5.4.4. The relationship used to trace the states to capabilities is the *Realization* (pink arrows). Realization is a specialized abstraction relationship between two sets of classes, used in this case for model stepwise refinement. States and risks were traced using the *Allocate* relationship (blue arrows), a mechanism for associating elements of different types or hierarchies at an abstract level. The *Harmful* state is the only tracing to risk element because it represents the consolidation of all risks. All other states are associated with detection, protection, response, and recovery capabilities. Some capabilities from the prevention structure are not traced to any security state. This gap was significant in defining the ground processes.

The bottom part of the matrix shows the relationship among security processes, capabilities, and risks. Security enclaves *exhibit* capabilities (green arrows), while the security process is mapped to capabilities (red arrows). The strong presence during threat detection and protection is coherent with the ground scenario. Controlling measures rely on the *Authorize Operation* process, given that monitoring and threat detection were realized. The *Prevent and Manage Threat* process was created to combine field information with proper assessment and support the responding capability.

Furthermore, as discussed earlier, risk prevention (with response planning and enablement) and resilience management must be performed. The *Prevent and Manage Threat* was simplified in the diagram as a single process. However, it represents an integrated and complex operational process. The *Prevent and Manage Threat* process represents the enterprise's mechanism to manage security states and achieve security goals. Protection, or using the *Protective* path (from *Vulnerable* to *Protective* state in Figure 5.5), can only happen if the enterprise is constantly monitoring and spending resources to assess threats and avoid them preventively. Using the *Evaluation mode* state to improve the detection capability and learn from threat behavior is driven by the exact mechanism. Likewise, the *Prevent and Manage Threat* process enables containment and suppression measures; consequently, the ability to control threats is possible. Besides the resources and process definitions involved in preventing threats, cultural aspects and individual behavior must be included if the organization needs flexibility and constant learning.

The allocation to risks on the bottom represents which processes or security enclaves are actively working to avoid or contingence the risks. *Loss of integrity* (risk defined in Figure 5.2) is the

primary target due to the nature of the ground operation. The availability can always be affected if the integrity is not confirmed. However, business interruption is less critical than ensuring safe operation.

5.6 Validation of UAM Security Views

A validation process was undertaken to ensure the accuracy and effectiveness of the security views. This process involved multiple stages of review and refinement, including expert validation, iterative feedback, and alignment with established security principles.

The validation process began by analyzing how the risk taxonomy is reflected in the NIST (2018) framework once it is a well-accepted standard for security in aviation and other domains. The definition of risk taxonomy provided a robust basis for checking the consistency and coherence of the security architecture. Subsequent views were elaborated using relationships defined in the UAF security metamodel (ISO/IEC, 2022), ensuring that the EA process for OMG UAF (2022b) was correctly followed. Relationships, notations, and semantics were verified against the UAF standard, further enhancing the model's validity.

Given that security is a structured approach in UAF, the validation effort concentrated more on model checking. The security traceability matrix supported the analysis, discussions, and definitions for resilience topics. The security state diagram, a novel contribution with no precedent in the UAF standard, was validated by model experts and presented to groups to evaluate the proposal’s clarity. Moreover, the content presented in this Chapter was peer-reviewed and published in the IEEE Open Journal of Systems Engineering.

The resilience in UAM operation was validated according to the intended purpose of the viewpoint. The evaluation was based on the ground scenario and the integration of systems, operators, and processes to adapt and recover when a security threat was identified. The resilience discussion was validated by evaluating the coverage and consistency among processes and operators against security states.

The success of the modeling effort was measured by achieving views with coverage, coherence, and consistency. The UAF has fulfilled the purpose of modeling a consistent architecture for the

UAM system-of-systems (SoS) and supporting the analysis, specification, and design of UAM security processes and controls. Moreover, the model provided insightful outputs to understand security behavior and structure. In the UAM ground operations, resilience principles were applied to define posts and functions related to the necessary security processes. In addition, security enclaves and the relation between systems and operators were included in the architecture.

Multiple iterations followed, with discussions involving various professionals. Experts in the following fields validated all diagrams: UAM Operation (UAM Navigation Systems engineer), Cybersecurity (Cybersecurity Specialist), Security Modeling (Senior Model-Based System Engineer), and Resilience Engineering (Human Factors Engineer). A cybersecurity expert supported the development of these views and co-authored the published article (Hoffmann et al., 2023b), contributing significantly to the validation process. A group of systems engineering researchers and practitioners at SDM also validated these findings. Group discussions helped evaluate the goals of the security viewpoint, ensuring that the findings and recommendations driven by the architecture elaboration were robust and applicable.

Several interactions occurred to refine the idea conveyed in each diagram and answer questions that could result from ambiguity or inconsistency. In addition, uncertainties were discussed to better address security with the available information from the UAM ConOps and assumptions.

CHAPTER 6

Safety Culture Concern in the UAM System of Systems

6.1 Introduction

Managing risks and maintaining safety at an acceptable level in a complex and dynamic context like UAM requires a proactive and ongoing process. A safety management system (SMS) is a systematic approach to managing safety within aviation organizations. ICAO (2016) considers that SMS encompasses the organizational structure, policies, procedures, and practices that enable an organization to effectively identify, assess, and mitigate risks to ensure the highest level of safety.

Safety culture refers to the shared values, attitudes, beliefs, and behaviors within an organization or industry that influence safety-related decisions and actions. It is the product of individual and collective attitudes toward safety and the organization's commitment to fostering a safe environment (Reason, 1997; Dekker, 2006; Woods et al., 2010). Safety management and safety culture are closely intertwined and complementary. An effective safety management system provides the framework and tools for identifying, assessing, and mitigating risks. Continuous learning from safety events depends on a culture of trust and transparency. Thus, Dekker (2007) observed that just culture is crucial for encouraging open communication and reporting safety concerns. It allows stakeholders, including pilots, operators, regulators, and the public, to collaborate effectively in identifying hazards, analyzing incidents, and implementing corrective actions to enhance safety standards (GAIN, 2004).

This Chapter aims to understand the structure and perspectives of safety management that would enable a just culture in the UAM operations. As a socio-technical concern, the safety culture depends on the UAM safety management framework, which encompasses organizations, operational procedures, safety standards, regulatory authority, management, and systems.

Therefore, we will explore several safety management perspectives to address a safety culture with trust, ownership, and accountability values. The primary research question about this Chapter is RQ4: "How can the UAM ecosystem develop and maintain a safety culture that fosters trust and accountability among front-line workers?". In order to guide the results of this Chapter, the question was broken down into three:

- RQ4.1: How does the organization balance stakeholders with different interests to achieve trust and share risk information? Refer to the results in 6.2.
- RQ4.2: What processes and relationships support values like trust, ownership, and accountability to the front-line worker as a potential reporter? Refer to the results in 6.4.
- RQ4.3: How can we achieve a consensus on acceptable and unacceptable behavior among organizations of the UAM ecosystem? Refer to 6.5.

The theoretical foundations and past findings on safety management, safety culture, and just culture presented in Chapter 2's literature review were used to understand the problem space and the proposed solutions in this Chapter. The diagrams presented in this Chapter were created per EA methodology, utilizing the Unified Architecture Framework (UAF) version 1.2, as explained in Chapter 3. Additionally, it is noteworthy that most of the content of this Chapter was published in the MDPI Systems Journal in May 2024 in the article called "Exploring Safety Culture in Urban Air Mobility: System of Systems Perspectives Using Enterprise Architecture" (Hoffmann et al., 2024a).

This Chapter presents the results of the safety management viewpoint to address the safety culture socio-technical concern. It is organized as follows: First, the safety culture problem is analyzed in 6.2, and the solution space is envisioned in 6.3. The architecture elaboration for safety management perspectives is then presented in 6.4. In 6.4.1, safety management drivers are identified according to the problem defined previously. The functions and capabilities are specified for each stakeholder in 4.4.2, and the structure and interactions of each stakeholder are elaborated in 4.4.3. Next, we present a unified safety committee proposal in 6.5 and debate novelties and reflections on the safety management perspectives in 6.6. Lastly, validation of the views presented in the Chapter is explained in 6.7.

6.2 UAM Safety Culture Problem Space

Defining the problem of safety management and enabling a just culture in future UAM operations requires a systemic approach to address internal and external factors. The first step is looking into different perspectives and understanding the forces that drive the environment. Opposite interests within an organization and with external entities are dynamic and must be understood. The relationship among these entities is part of the problem, and acknowledging the boundaries behind each interest is crucial for achieving a balance. To explore the systems dynamics of safety management in UAM, the analysis was organized into three macro axes: administrative, economic, and operational.

The *administrative* axis represents the first aspect (see first column of Figure 6.1). It concerns the rules and regulations governing licensing, operational procedures, and regulatory compliance. At one end, the regulation authority pushes the organization with rules, inspections, and audits. The objective is to protect the public, ensuring the highest level of safety in aviation operations. It means establishing and enforcing aviation safety regulations, guidelines, and standards. This study focuses on the utilization phase, where the service will be provided to passengers. The enforcement then relates to air traffic management, maintenance practices, and operational procedures. The undesired state of this gradient is a reckless and negligent operation. In the opposite direction, there is the perspective of just culture. It is about the movement towards reporting events without fear of blaming. The goal is to learn about events and avoid operational silence, in which the organization is unaware of risks and near misses because operators are not reporting them. The enforcement of the regulation is associated with fear of blaming, which in turn makes operators less willing to report issues (Dekker, 2006). Hence, it is not possible to establish a just culture if the regulatory force is adjusted for punishment purposes only.

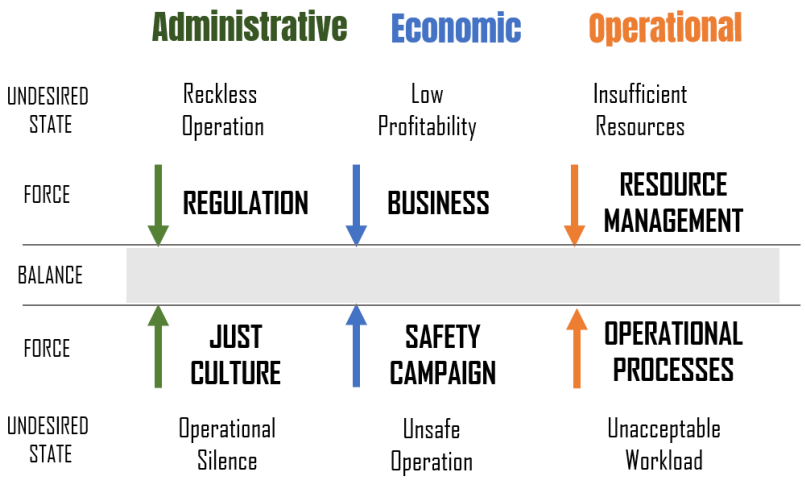

Figure 6.1: Safety Management Stakeholders and their Interests

In the *economic* axis (second column), a business interest protects the profit and viability of the operation. Most of the time, the top-level management represents this interest, constantly looking for productivity and avoiding a state of low profitability (or nonprofit). Efficiency is pursued, and a strategy to increase profit is usually implemented. In the opposite direction, there is the perspective of a safety campaign that aims to promote safety awareness among workers. In this case, the interest is aligned with the SMS component *safety promotion* and, in practical terms, aims to educate workers to make decisions that would not jeopardize the operation's safety. The slogan "safety first" can directly impact productivity when the operation is delayed, interrupted, or canceled. The balance problem about the operational axis is also called the "dilemma of the two Ps," in which conflicting goals exist: production (delivery of services) or protection (safety) (ICAO, 2018).

The last axis represents the *operational aspect* (third column of Figure 6.1). The operational processes should be defined to achieve an acceptable workload. If work processes are poorly designed or lack optimization, it can contribute to an excessive workload. In-efficient workflows, unclear task assignments, or redundant steps can all contribute to increased workload demands on workers. Moreover, unrealistic time constraints or tight deadlines can create a high-pressure environment and increase the perceived workload. An unacceptable workload can compromise operational safety and is the undesired state of this force. The other side of this axis is the resource management. Its purpose is to provide sufficient human, system, and training resources. Those

gradients can be opposites if a process is defined with unrealistic resources or if the best resource is provided, but the operational process is unacceptable.

The gradients were organized in three axes to ease the identification of dynamic forces that coexist in safety management. They represent internal and external factors that affect the safety culture and its performance (Clarke, 2006). However, the gradients are not independent, straightforward, or disconnected. Each one of the forces is influenced by and wields influence over other forces. For instance, safety campaign has a direct relationship with the just culture gradient. The reporting culture results from many other processes and values that the safety campaign promotes. Another example is when the business force manages the budget and controls the expenses, constraining resource availability. Figure 6.1 introduces opposite forces that compose the problem of managing safety to enable a just culture. It will be used to discuss the perspectives and viewpoints in 6.4.

6.3 UAM Safety Culture Solution Space

The front-line worker is any operator in direct contact with the operation. The worker can be a maintenance staff member, a traffic controller, a pilot, or any other role performing operational processes. They are also the centerpiece of our proposal. Their presence in daily operations and knowledge about field operations are the primary sources for generating valuable information in improving safety. Near misses, and even mistakes are symptoms (not causes) that can be investigated and assessed if the front-line worker feels safe to report them (Dekker, 2006). Reporting an event is an act of trust and ownership (Dekker, 2007). There is an individual and collective behavior behind reporting culture. Figure 6.2 represents the high-level concept of just culture from the front-line worker's perspective.

The operator must have direct access to a reporting system, and his/her direct manager has no other power influence than to build trust and support the habit of reporting. The fear of being scolded by a superior can discourage reporting. Power relationships must be carefully established to avoid influencing the decisions of the front-line workers, who are usually vulnerable. High-level management must sponsor safety practices and behavior. Values, especially trust, in the organization depend on the alignment among power, discourse, and actions from top to bottom. Similarly, the team or group that will receive, analyze, and sometimes investigate the event needs

direct access to the front-line worker. It is also vital that this group is from a separate division and has no relationship with the operator in terms of hierarchy. The engagement of the front-line worker in the assessment of events (and other safety-related processes) is also crucial for building ownership.

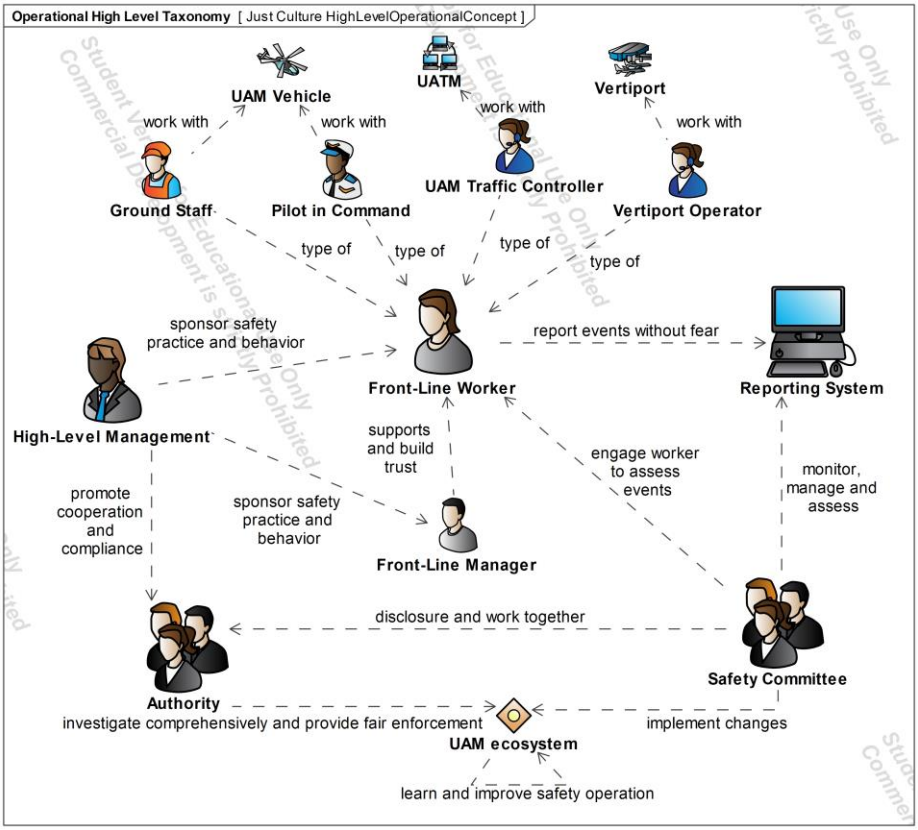

Figure 6.2: Front-line Worker's Perspective in a Just Culture Environment

Trust is the principal value of this concept. The front-line worker not only trusts that a fair assessment will be based on comprehensive perspectives rather than blaming individuals but also trusts that the reporting process for learning is effective. The front-line worker must realize that the information provided in the report is useful and will turn into a learning experience. Suppose the operator is not involved in this process or is not able to see changes and improvements. In that case, the reporting becomes only bureaucracy, which is spending time without purpose.

The authority is an external entity but has a significant role in the context of just culture. Establishing an agreement for disclosure and cooperation between the authority and the safety committee is vital to developing trust as a value among all workers. The goal is to learn, and

bringing everyone to the table means broadening perspectives and having the means to perform investigations comprehensively and provide a fair assessment.

6.4 UAM Safety Management Enterprise Views

The architecture elaboration process defined by ISO/IEC/IEEE (2019a) p. 47 aims to "describe an architecture in a sufficiently complete and correct manner for the intended uses of the architecture." The views presented below intend to provide visualizations and support the analysis needed to answer the research questions. In other words, the diagrams propose different organizational levels' perspectives and provide a means to understand the individual and collective contribution to the just culture in the UAM ecosystem.

The intended users are the stakeholders identified in the previous section and depicted in Figure 6.1. The architecture objective is to understand the structure and perspectives of safety management that would enable a just culture in UAM operations. To this end, this section elaborates on organizational views for enabling a just culture despite different stakeholders' interests. The objective is also aligned with the research questions intended to be answered by this Chapter.

6.4.1 Safety Management Drivers

The first step in the model development is to define the drivers. *Drivers* in UAF are factors that have a significant impact on the activities and goals of the enterprise. Drivers also relate to the purpose of an enterprise. From the forces (as presented in Figure 6.1) or stakeholders' interests defined in the problem space, we have identified six drivers:

- Regulation Gradient: In the Administrative axis, the regulation must not allow reckless operation;
- Just Culture Gradient: In the Administrative axis, the safety culture must avoid re-porting trust issues;
- Business Gradient: In the Economic axis, the business gradient must protect the viability of the operation;
- Safety Campaign Gradient: In the Economic axis, the safety campaign must offer

protection from unsafe operation;

- Workload Management Gradient: In the Operational axis, the operational processes must keep the workload within acceptable levels;
- Resource Management Gradient: In the Operational axis, Resource Management must keep the resources within sufficient levels.

Defining these drivers is key because they are the foundational elements guiding the architecture's development. Each driver represents a core interest or concern of the stakeholders, which must be addressed to ensure the successful and sustainable operation of the UAM ecosystem. These drivers help align the architecture with the enterprise's strategic goals and operational needs.

From a safety management perspective, understanding and incorporating these drivers into the architecture ensures that the system can meet regulatory requirements, foster a safety-oriented culture, maintain economic viability, manage operational workloads, and ensure resource availability.

6.4.2 Safety Management Functions and Capabilities

The personnel process view in UAF concerns functions that have to be carried out by organizational resources. The following figures represent how the drivers are implemented in terms of functions, who performs those functions, and how organizational capabilities are achieved.

Figure 6.3 represents the relationships in the administrative axis. The *Regulation Gradient* (<<Driver>> element on the top left) is realized when the function *Oversee Airworthiness* (<<Function>> on top center) is implemented. A set of subfunctions is defined as composition elements that provide more information about the regulatory act. For instance, *Issue Certification*, *Provide Policies*, *Monitor Compliance*, and *Enforce Legislation* (<<Function>> elements at the top) are parts of *Oversee Airworthiness*. Consequently, the *Regulation Authority* (<<Organization>> element below *Oversee Airworthiness*) is the resource capable of performing the functions. Inside the organization level, there are some primary resources represented as parts that are also performers: *Airworthiness Specialist*, *Accident Investigator*, and *Certification Specialist* (<<Post>> elements linked to *Regulation Authority*).

The same applies to the opposite force: *Just Culture Gradient* (<<Driver>> in the left bottom of Figure 6.3). The <<Function>> *Empower Event Reporting* realizes the Just Culture gradient. In this case, although the *UAM Operator* (<<Organization>> element on the right side) is the operational performer of UAM services and the organization behind the function *Empower Event Reporting*, the elements linked with the <<IsCapableToPerform>> dotted line are its parts. It means that different levels within the *UAM Operator* represented as <<Post>> elements are directly engaged with the reporting function and the subfunctions listed at the bottom of the diagram. The model aims to explore individual contributions, and every post is capable of performing the reporting function. Safety awareness can be promoted with directive activities for which the safety team is responsible. Yet, promoting trust, accountability, and ownership is also an individual act, and each post should perform it.

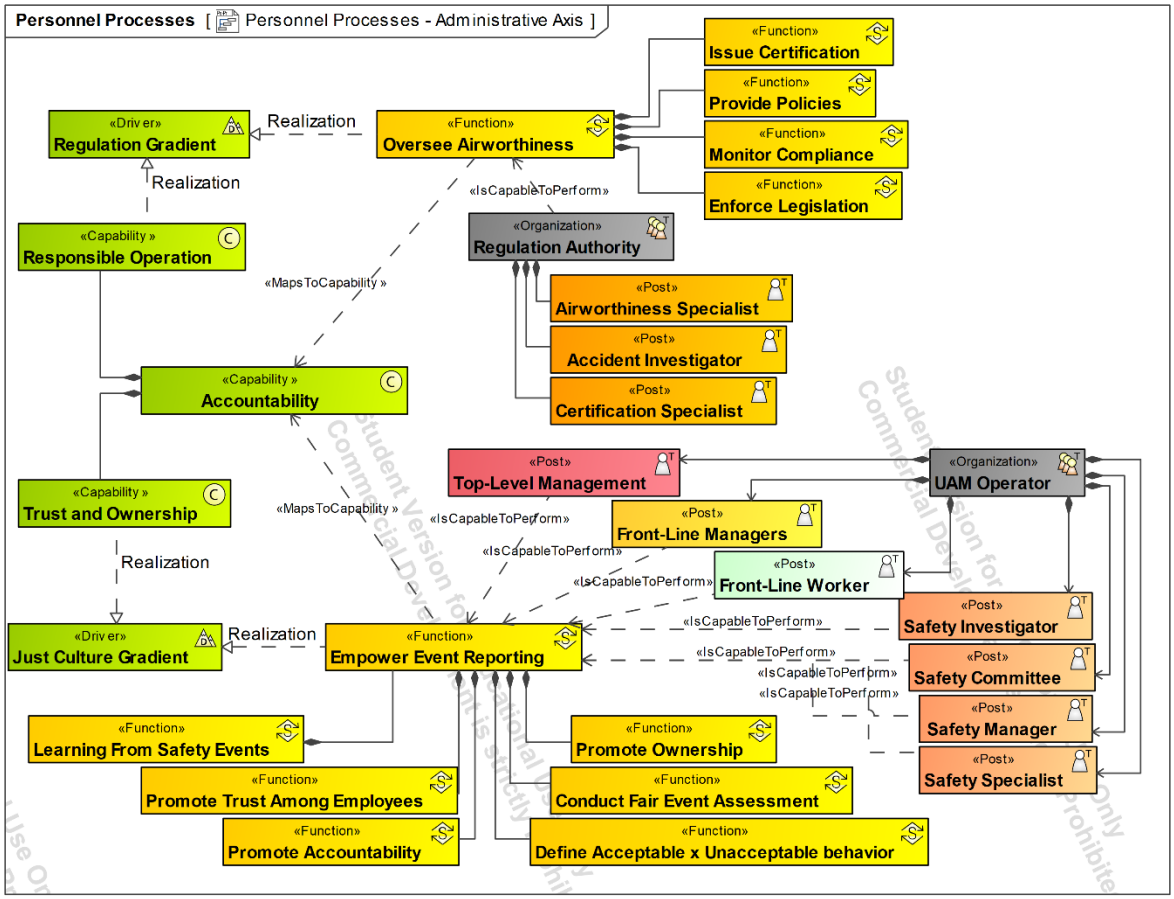

Figure 6.3: Safety Management Functions from the Administrative Perspective

The balance between regulation and just culture forces requires the involvement of the authority and the UAM operator to achieve the capability of *Accountability and Fairness* (<<Capability>> in the middle of the diagram). This means that enabling an environment without fear of reporting is only possible if regulations are enforced fairly. Moreover, achieving a responsible operation requires accountability and safety awareness. Balancing stakeholders' interests is possible if the enterprise develops capabilities according to the boundaries of each gradient. The <<Capability>> elements on the left side of Figure 6.4 represent the healthy combination of opposite interests in terms of capabilities. *Accountability and Fairness* capability is a combination *of Responsible Operation* and *Trust and Ownership* capabilities. Both capabilities realize opposite drivers: Regulation and Just Culture.

The economic axis balance is represented in Figure 6.4. In this case, only one organization is responsible for performing functions that realize both drivers: *UAM Operator* (<<Organization>> element in the middle). However, different organizational levels within the *UAM Operator* can perform the functions that will implement *Business Gradient* and *Safety Campaign Gradient* (<<Driver>> elements on the left side). *Top-Level Management* (<<Post>> above the *UAM Operator*) looks after operational viability and is responsible for maintaining profitability. The authority for safety matters, called in this diagram *Chief Safety Officer* (<<Post>> below the *UAM Operator*), is capable of performing the *Promote Safety Awareness* function. Top-level management plans for global strategies, while the safety team defines safety strategy. A relationship between those organizational levels and functions must be coordinated to achieve *Sustainable Operation* (<<Capability>> in the left middle). The capabilities on the left side of the diagram are also harmonized to balance opposite concerns: *Profitability* realizes the business interest, while *Safety Awareness* realizes the Safety Campaign interest. In the next section, we explore the resource exchange elements between organizational levels that can address complementary functions to achieve a balanced capability.

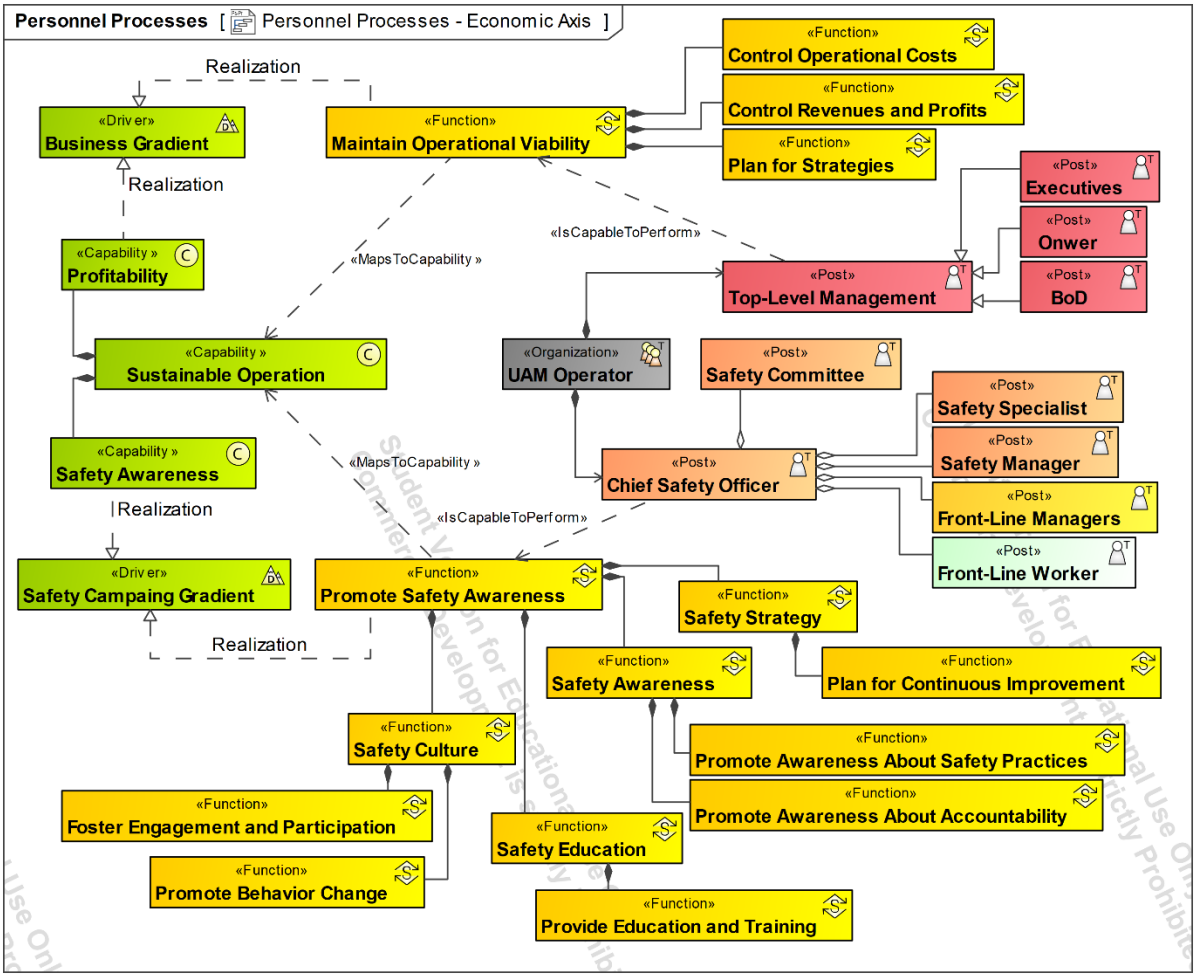

Figure 6.4: Safety Management Functions from the Economic Perspective

The last diagram in Figure 6.5 is for the operational aspect. It represents the balance between defining operational processes considering an acceptable workload and, complementarily, providing enough resources according to the same operational processes. Managing resources and workloads is a highly coupled activity, although different capabilities are being delivered. Defining enough resources depends on process definition. Managing workload also depends on the resource's definition. From the operational perspective, the organization wants to avoid defining processes with a workload that is too high or too low. In both cases, unappropriated workloads can affect the safety performance of a process. At the same time, resources must be provided per the process's workload. Lack of resources (personnel, systems, or training) can increase the workload or even prevent the activity from occurring, compromising its performance. This balance is represented by the capabilities *Acceptable workload* and *Sufficient Resources* (on the left side of

Figure 6.5). The enterprise must realize both capabilities to achieve *Safe Operation* (<<Capability>> in the center).

Achieving complementary capabilities means realizing opposite drivers from the operational axis. The high-level functions that realize those drivers are *Ensure Acceptable Workload When Performing Operational Processes* and *Provide Sufficient Resources* (<<Function>> linked with a dotted arrow to <<Driver>> elements). The list of subfunctions that compose the high-level function provides more details on how the different perspectives can support each other. Matching the functions specified for realizing both drivers is essential and strategic. For instance, functions like *Define Operational Processes According to Resources* (fifth <<Function>> on the right side's list) and *Define Resources According to Operational Processes* (first <<Function>> on the left side's list) can raise the necessary alignment between different interests. The resource capable of performing functions on the operational axis is the *Safety Team* <<Organization>>, which is part of the *UAM Operator* <<Organization>> and has a different hierarchical structure than that of the front-line workers.

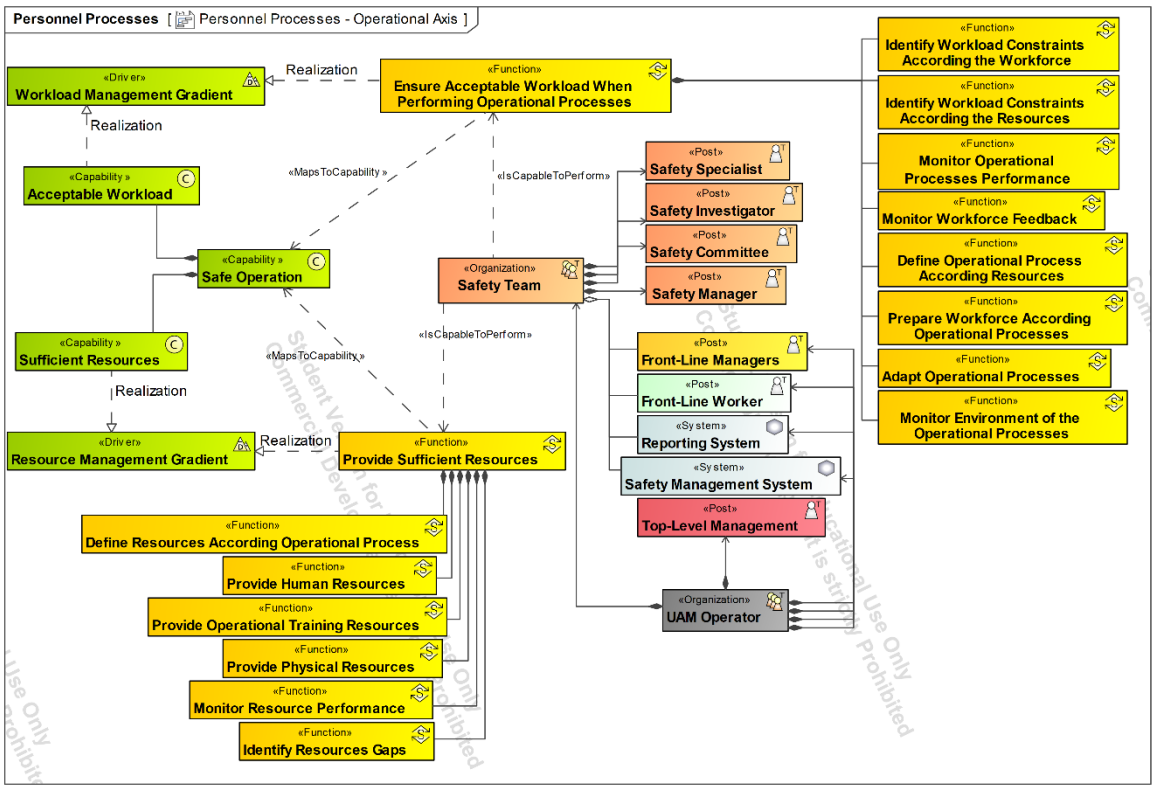

Figure 6.5: Safety Management Functions from the Operational Perspective

The structure within *Safety Team* (<<Post>> elements at its right side) and *UAM Operator* (<<Post>> elements above it) are represented in the diagram as essential parts involved in both functions: *Ensure Acceptable Workload When Performing Operational Process* and *Provide Sufficient Resources* (<<Function>> elements above and below *Safety Team*). The operational axis depends on actual field data to plan, adapt, and improve operations. Moreover, the front-line workforce is a critical resource that provides input for adjusting workload levels and resource gaps.

To reiterate, the above personnel processes diagrams show the implementation of drivers in terms of functions and capabilities and the individuals or entities responsible for performing those functions. From the operational viewpoint, it is possible to specify which activities will implement each function, including methods, parameters, and measurements. Different posts will perform the same function in different ways. The perspective of each organizational level at contributing with a high-level function and, therefore, a capability is valuable to disseminate ownership and awareness. Knowing how each agent in the ecosystem acts towards a joint capability is meaningful for developing a comprehensive perspective.

Capability is defined in UAF as an enterprise's ability to achieve a desired effect realized through a combination of ways and means (activities and resources). The personnel process views above show how stakeholders with different interests can achieve balanced capabilities that meet the UAM's interest as an enterprise.

6.4.3 Safety Management Structure and Interactions

The personnel structure view concerns the organizational structure used to support capabilities. It shows organizational structures and possible interactions between organizational resources. Once we have defined the capabilities that will balance the drivers and how (functions) will be achieved, we can look into the organization-level perspectives. The following diagrams represent the three main organizational levels' responsibilities and resource exchanges for exhibiting their capabilities.

The first is the *Top-Level Management* perspective. In our model, the top-level management can be represented as *Executives*, Body of Directors (*BoD*), or *Owner* (all <<Post>> elements in the top left of Figure 6.6). The diagram below shows a set of responsibilities that the highest level in the organization must have. Ensuring operational viability, allocating funds for safety promotion, developing strategic safety plans, making safety-committed decisions, and facilitating cooperation

and collaboration for safety are duties allocated to the highest level (represented as <<Responsibility>> elements). Moreover, workforce perspectives around the organization's governance should not be disregarded. Fostering a just culture and being accountable are also responsibilities with which the power and discourse of the top-level management must be aligned.

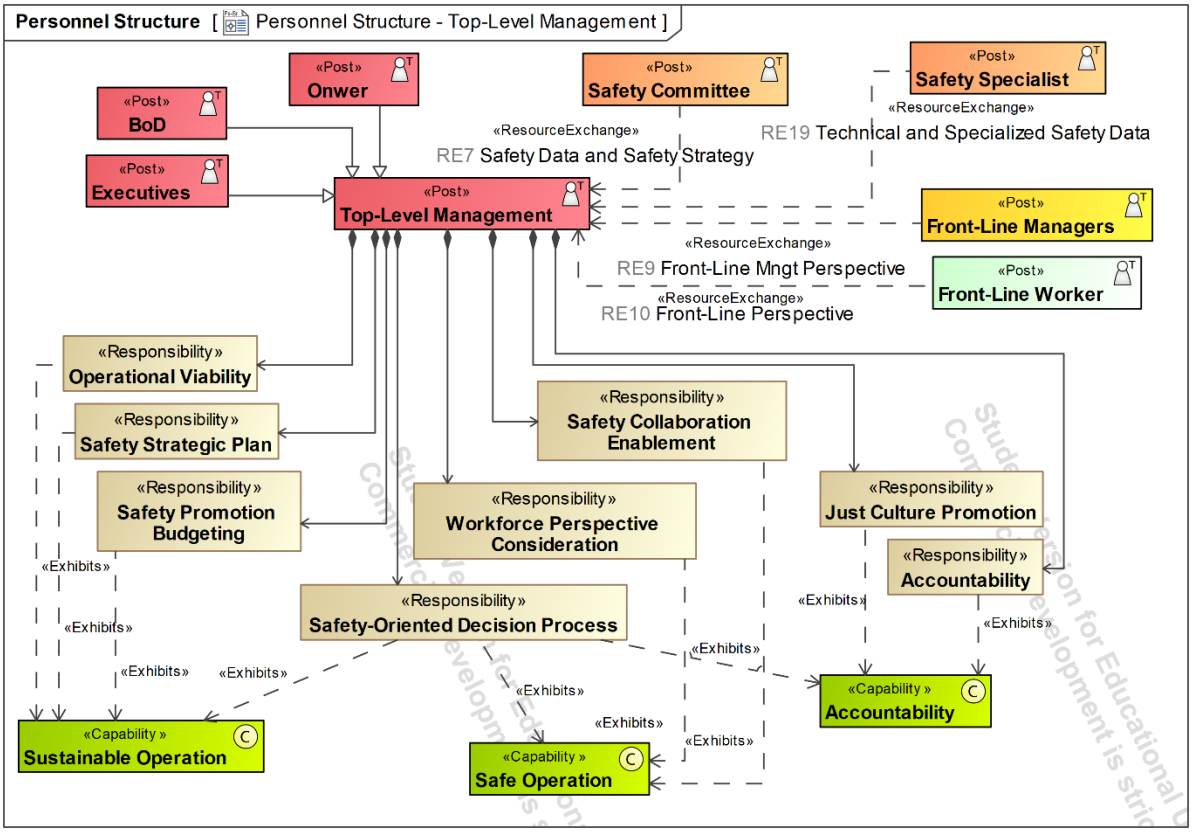

Figure 6.6: Top-Level Management Engagement

The exchanges between the top and other organizational levels are on the diagram's right-top side (represented as dotted lines with <<ResourceExchange>> *RE* notations). *Safety Committee* <<Post>> shall provide safety data and strategy (RE7); *Safety Specialist* <<Post>> feeds technical and specialized safety data (RE19); *Front-Line* level (managers and staff <<Post>> elements) provide their valuable perspective (RE9 and RE10). Without these resource inputs, the top-level management cannot meet its responsibility and contribute the necessary capabilities. The resource exchanges proposed by the model are not desirable interactions but a condition (requirement) to develop the strategic capabilities defined earlier.

The next level explored in Figure 6.7 is the safety division's perspective. Safety core duties such

as defining operational safety guidelines, safety promotion and communication, and resource and workload management are defined according to the capabilities driven by the safety campaign and operational gradients. Regarding the just culture gradient, a focus on managing the reporting system and performing a fair investigation is defined to promote trust and accountability. According to the model language, responsibility *exhibits* capability. Nevertheless, this relationship is not straightforward in actual operations. Operational processes can include more than one responsibility; likewise, responsibility can be shared in different processes. Responsibilities like *Ensure Front Staff is Engaged in Safety Decisions* (fourth <<Responsibility>> in the left side of the diagram) can be performed in multiple activities from safety division posts. They will impact all the capabilities, not only *Sustainable Operation*. The representation in the diagrams does not show all <<exhibit>> relationships to keep the visualization clean.

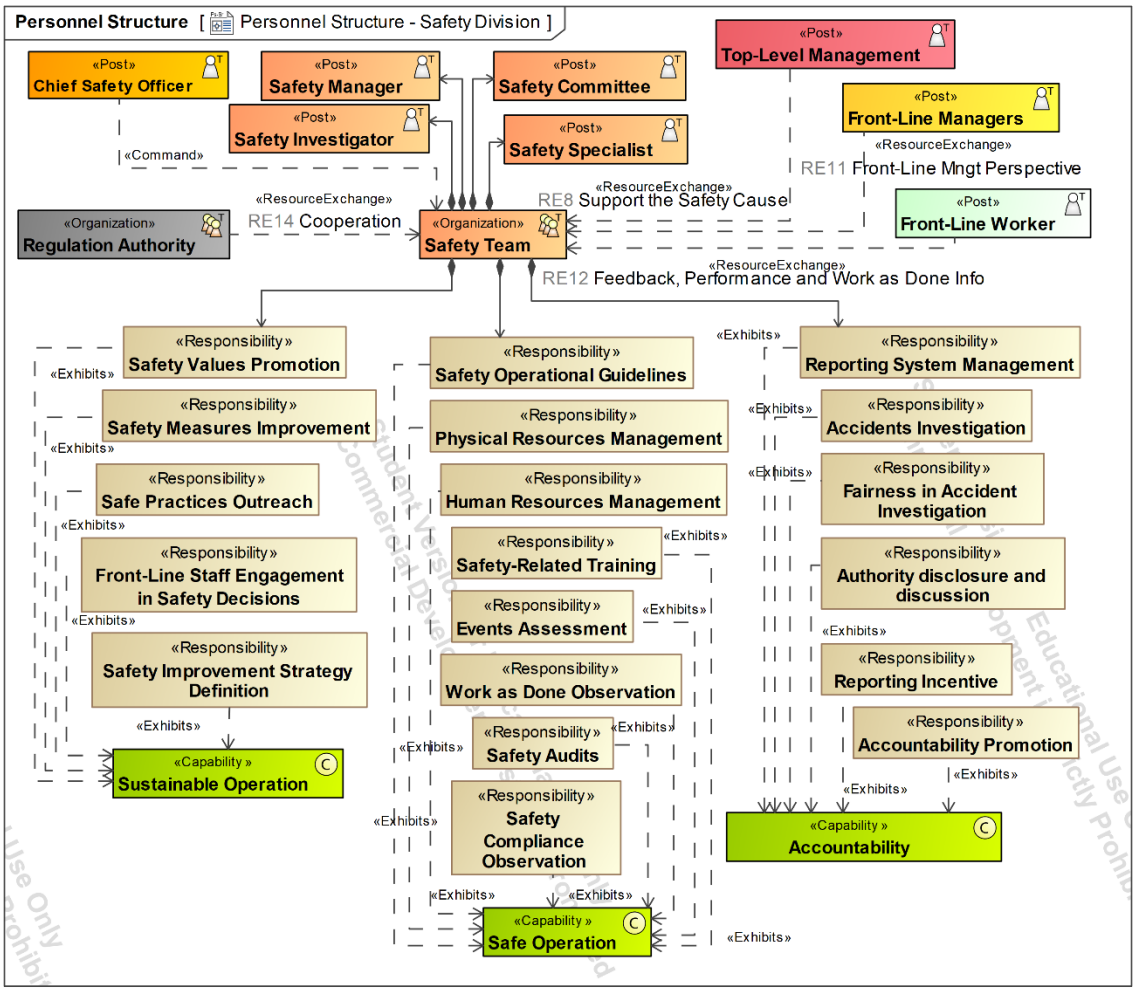

Figure 6.7: Safety Division Engagement

There is an external and essential connection with the *Regulation Authority* (<<Organization>> in the top left) regarding resource exchange. Without cooperation (RE14) between authority and operator, the consensus of acceptable and unacceptable behavior will hardly exist. Cooperation also includes an agreement for disclosure, discussing new practices, and adapting the existing standards. Top-level management offers extensive support (RE8), and *Front-Line Managers* provide their perspective (RE11). The *Front-Line Staff* provides a key resource exchange for the safety division. Feedback, performance data, and work-as-done information (RE12) are essential for all the other activities and responsibilities of the safety division.

The last view represents the front-line perspective in Figure 6.8. The *Front-Line Staff* (<<Post>> element in the middle) must develop *Operational Ownership* (third <<Responsibility>> in the left side). *Safety Guidelines Validation* (first <<Responsibility>> on the left side) and *Event Assessment Support* (last <<Responsibility>> in the middle) place the staff inside the safety process and bring them knowledge, voice, and accountability. Reporting inadequacies in workload and resources (<<Responsibility>> elements in the middle) will feed the safety division team with valuable information.

The daily operational information from the front-line staff is the safety currency that will drive safety management and provide material for learning. Reporting events and encouraging reporting (<<Responsibility>> elements on the right side) is the responsibility of every person involved in the operation. However, it appears in the front-line perspective because they are the ones seeing and handling the operation. Secondly, they are also vulnerable in terms of hierarchy and power.

The front-line manager has power over the front-line staff expressed by the relationship <<Command>> (dotted line below <<Post>> *Front Line Managers*). The hierarchy and power can discourage the reporting of events and mistakes. The front-line staff must feel comfortable reporting and discussing events with an external entity like the safety division (as in the *Event Assessment Support* <<Responsibility>>). Moreover, the resource exchange RE17 (at the top right) represents this connection between front-line workers (staff and managers) and the safety team. *Safety Practice Guidance and Partnership* (RE17) is crucial to building ownership, accountability, and trust.

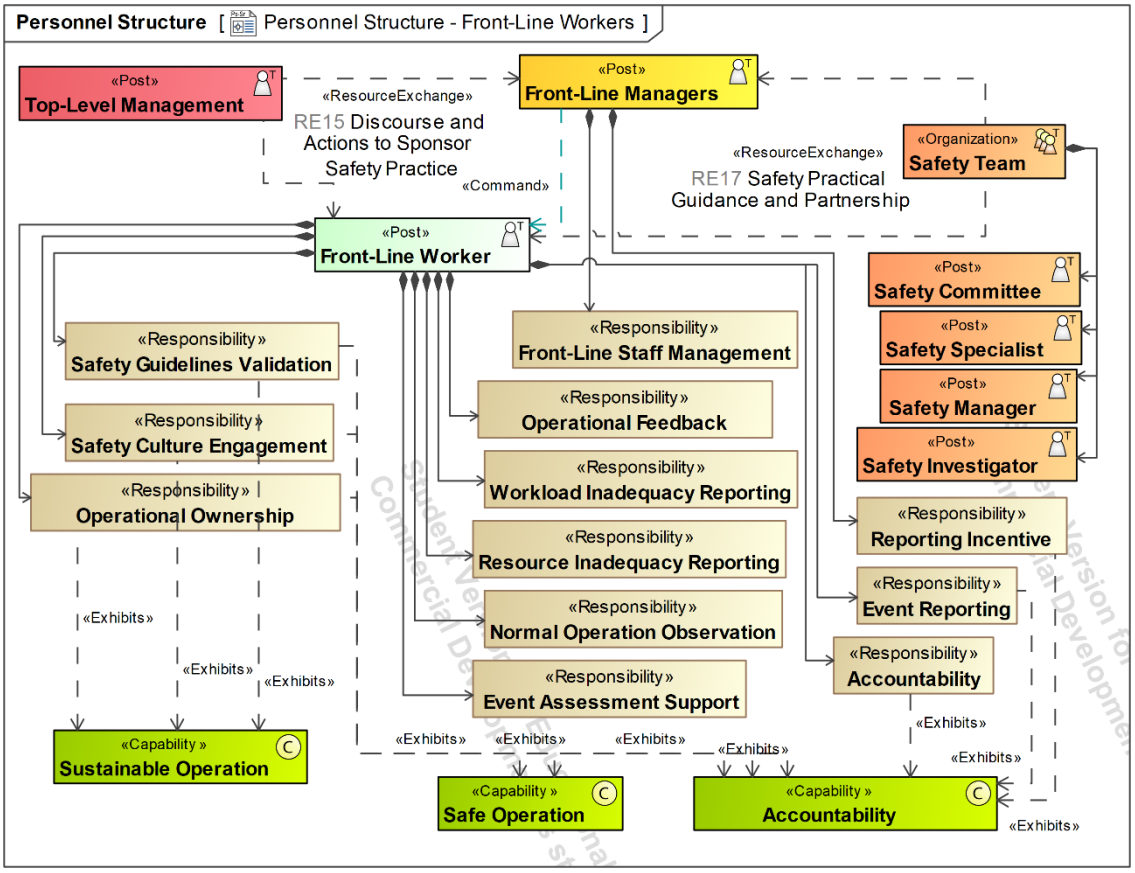

Figure 6.8: Front-Line Engagement

6.5 UAM Unified Safety Committee Proposal

Unlike civil aviation, which is usually centralized in big airports, the UAM ground infrastructure will be granulated in various vertiports over urban and suburban areas. The envisioned vertiport network will also have different units in terms of space, topology (on the ground or over buildings), and services (only takeoff and landing pods or with a complete service station for battery charging, maintenance, and parking areas). The distribution will also be significant for providers and operators: different vertiport owners or operators, with diversified staff or third-party workers and different operational processes. This is in addition to multiple UAM operators and different vehicle technologies demanding specific ground services.

Another relevant aspect of the distribution and operational landscape of UAM is the convergence of the air and ground transportation sectors. Air travel in dense urban areas would require

integrated mobility solutions, including accessibility and connectivity to ground transportation. The air industry is dominant in terms of safety protocols and standards. Many front-line workers, managers, and staff in UAM operations will likely come from aviation backgrounds, where a strong safety culture is typically ingrained. On the other hand, individuals working in ground transportation, such as vertiport operators, ground staff, and service providers in Mobility as a Service (MaaS), may have different levels of recognition or familiarity with aviation safety practices. This difference in safety awareness and training could potentially lead to a mismatch in safety expectations and practices within the UAM ecosystem.

Education and the environment need to be considered to address this issue. First, the UAM industry must establish comprehensive training programs and safety protocols that bridge the gap between the air and ground transportation sectors. This includes educating ground transportation workers and service providers about aviation safety standards, emergency procedures, and risk mitigation strategies. Collaborative training initiatives and cross-industry knowledge sharing can help align safety practices across all aspects of UAM operations, ensuring a harmonized approach to safety management and enhancing overall safety outcomes in this innovative transportation sector. Secondly, safety management must provide an environment for learning and improving safety performance among all front-line workers.

There is an enormous potential for learning in the new UAM ecosystem. New situations will occur in a systematic and distributed manner. New systems and workers adjusting their performance add another layer of uncertainty to the UAM operations. How can the UAM ecosystem, with all its entities and relationships, learn effectively and efficiently? How can a just culture and all the encouragement for reporting support this learning? The discussion in this section aims to address both questions and propose an environment to enable learning in the UAM ecosystem.

The diagram in Figure 6.9 shows the leading <<Organizations>> involved in the UAM ecosystem: *UAM Operator, Vertiport Operator, UATM Operator, Regulation Authority, Service Providers—Third Party*, and *Professional Association*. Enabling a just culture at the ecosystem level involves multiple organizations. Thus, there is a cultural factor that needs to transcend the boundaries of the organization. The primary base for enabling a just culture is the behavior consensus of what is acceptable and unacceptable. In the model's representation, it means that the *Behavior Consensus* is a competence that operators (organization-level) and the regulation authority must have. The

dotted lines with the notation <<RequiresCompetence>> pointing to the <<Competence>> *Behavior Consensus* at the center of Figure 6.9 illustrate this need. We propose the UAM Safety Committee as a unified organization capable of developing and implementing such competence. The realization arrow pointing to the *UAM Safety Committee* (<<Organization>> at the bottom right) synthesizes the purpose of the strategy discussed in this section.

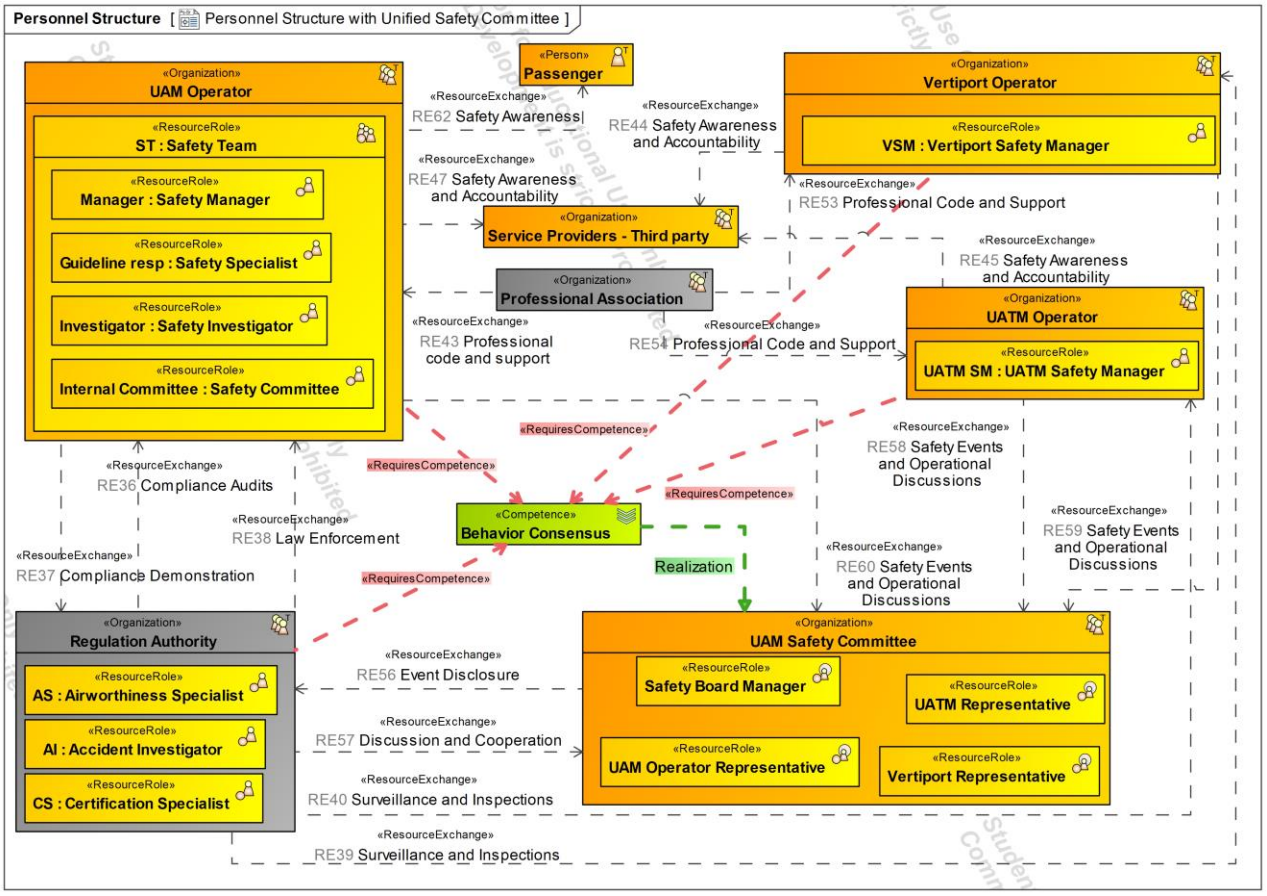

Figure 6.9: Unified Safety Committee Proposal

This committee would have representatives (see <<ResourceRole>> inside the UAM Safety Committee box) from all organizations at different levels, including front-line workers, to ensure their voice and ownership value. The event disclosure (RE56) from the *UAM Safety Committee* to the *Regulation Authority* is part of their cooperation agreement. The internal events that fall under a minor level (upon agreement) should stay in each organization and be handled according to its internal policies. Cases requiring a higher attention level are the ones that are brought to the unified

committee. When involved, the *Regulation Authority* should participate in relevant discussions (RE57) towards learning and improving operations.

All regulatory processes like surveillance, inspection, audits, compliance demonstration, and law enforcement (RE36, RE37, RE38, and RE39 in the bottom left) are kept between the *Regulation Authority* and each *Operator*. Boundaries for accountability are essential for the regulation and can coexist with a fair assessment discussed between the authority and safety committee. The operators provide safety events and actively participate in operational discussions (RE58, RE59, and RE60 above the *UAM Safety Committee*). The purpose is to create a systemic view with different perspectives of the problem and contribute to better solutions and improved safety. Participation builds ownership that should occur at every level, from front-line daily discussions to a unified safety committee board.

Third-party workers are usually a challenge for organizations regarding culture and values. This becomes even more critical with the expected diversity of organizations entering the UAM arena, including small organizations without an aviation background. It is essential to include all providers in safety awareness and accountability (RE44, RE45, and RE47 pointing at the *Service Providers—Third party* box). Likewise, the *Passenger* (<<Person>> in the top) is another part of the operation and should be instructed on safety awareness (RE62 below *Passenger*). Everyone should know they are part of a whole new operation, and its safety is an individual and collective commitment. Lastly, the *Professional Association* (<<Organization>> in the center) is relevant for creating a professional code and supporting front-line workers (RE43, RE53, and RE54 outputs of *Professional Association*). This support is significant in encouraging the front-line worker to report events and can increase their trust level concerning fair assessment.

The ultimate goal of a just culture is learning from events. Information about actual operations, including successful practices, near misses, and hazard events, is *the asset* for UAM safety. Having a shared space for discussing events in such a distributed and diversified operation provides an opportunity for assessing this information. Nonetheless, the proposal is for an ecosystem-level solution, and there are also significant challenges. Achieving a consensus with so many players, including authorities debating how to define safety standards, is arduous. Giving space and a voice to front-line workers is also challenging and requires excellent organization, management, and efficiency. In every environment that expects horizontal and collaborative work, some practices

flow smoothly, and others do not fit. The recommendation is to start the consensus discussion early on and evolve with the maturation of the UAM. Avoiding building a just culture could compromise the necessary learning and bring even more challenges for public acceptance in case of accidents.

The unified safety committee proposal was discussed and presented for the UAM ecosystem, which comprehends different organizations and governance systems. The systemic approach is novel and reflects on empirical studies with pilots and managers about the line between acceptable and unacceptable behavior (McMurtrie & Molesworth, 2021). Differences in perceptions of what is considered acceptable or not were found. Gray areas regarding interpretations, technical and non-technical assessments, and decision-making were highlighted. Finally, insights about the uncertainty among pilots and managers regarding disciplinary measures and accountability underscore the need for a unified approach, as the UAM Safety Committee proposed.

6.6 Discussions on the UAM Safety Management Perspectives

The architectural views presented in the previous section depicted stakeholders' interest under two schemes: at the enterprise level and the group engagement level. The first type of diagram, personnel processes (Figures 6.3 to 6.5), defines enterprise functions that map to desired enterprise capabilities. Meanwhile, the second type of diagram, personnel structure (Figures 6.6 to 6.8), defines group responsibilities towards all strategic capabilities. The synthesis of operational structure, enterprise drivers and capabilities, and roles and responsibilities provided different perspectives of safety management. Although the enterprise approach of this study is unique, the results and insights can be reflected in other literature. This section will highlight some insights related to research findings on just culture in aviation.

The first point is the construction of values like accountability and ownership. Accountability is present in all the organization-level perspectives of Section 6.4. Noticeably, the value of accountability does not have a mistake-owner connotation. Pointing fingers and blaming are barriers to a just culture. Instead, accountability brought by a deep sense of ownership of processes, decisions, and operations is the value a safe operation and just culture seeks (Dekker, 2007). Being accountable in the sense of knowing how safety is a collective commitment and a systemic behavior that depends on each one of the ecosystem pieces. Encouraging and establishing a deep

sense of ownership and accountability is crucial for fostering a culture where pilots and front-line staff feel empowered to report safety incidents without fear of blame or reprisal.

The second point concerns trust as a result of establishing accountability and ownership. Having different engagement levels aware of the whole safety effort allows individuals to take their share and behave collectively towards a common goal: safety. The responsibility behind the process for each organizational level was defined, considering drivers and individual perspectives. Front-line staff reporting events depends on values like trust, built from ownership and accountability. This aligns with the survey performed with a group of pilots on the study presented by McMurtrie & Molesworth (2021), revealing that fear of reprisal from the employer (airline) emerged as the leading reason for failing to report or under-reporting safety information. The lack of confidence in just culture among airlines highlighted the importance of addressing reprisal concerns and fostering a culture of trust and transparency within aviation organizations to encourage voluntary reporting and enhance safety outcomes. In a subsequent work, McMurtrie & Molesworth's (2022) research exposed trust issues among pilots. The perception of reprisals for voluntary reporting and the fear of punitive actions can create barriers to reporting and hinder the development of a just culture.

Another point is the power relationship between front-line workers and their direct management. The reporting system, event investigation, and assessments were intentionally proposed in a different hierarchical structure, highlighting the need for direct access to reporting systems without fear of reprisal. The evidence touches upon power dynamics and hierarchies within organizations, which can influence the mentality of reporting and the willingness of front-line workers to report safety events. This resonates with findings from Schuit & Scott's (2021) research regarding differences in perceptions of disciplinary measures and accountability among pilots and managers. In a just culture, understanding why procedures were violated should be investigated regardless of the outcome, emphasizing the need for a systemic approach that values accountability and transparency at all levels of the organization. Additionally, the safety division's responsibilities were emphasized in effectively addressing events because they directly impact how front-line workers trust the process. This strategy echoes pilots' concerns about timely feedback and the perception that appropriate actions are not always taken upon reporting safety concerns, as revealed in previous surveys (Schuit & Scott, 2021).

The next consideration is regarding organizational attitude toward fostering a just culture. In the enterprise architecture views presented, engagement groups can be applied to any organization directly interacting with the operation. Front-line workers, top-level management, and safety divisions are common categories of personnel, and their roles and responsibilities are suitable for achieving the enterprise's strategic capabilities. The organization can build those values by planning resource exchange while considering front-line-worker voice, power, discourse alignment, and regulatory cooperation. Similarly, recommendations from previous surveys conducted by McMurtrie & Molesworth (2022) suggest that airlines should develop clear frameworks for acceptable performance and remedial actions following safety events. When airlines embrace the principles of a just culture and pilots understand the significance of their incident reports, it creates fertile ground for preventing future incidents more effectively (Sieberichs & Kluge, 2021).

The last point to discuss is adopting EA as a method of elaborating and providing visualizations for the results. Considering that UAM has operational and safety challenges that are being discussed and planned to operate in the future, preparing for safety management is a recommended strategy. Enterprise architecture can facilitate communicating with different stakeholders and converge to shared goals, facilitate architectural analysis and decision-making processes, and support large and complex enterprise transformation changes (Guo & Gao, 2020). The findings of Sundberg et al. (2023), whose study focused on the strategic value of EA in government agencies, support the EA's role in preparing for safety management in UAM operations. By leveraging EA principles, organizations could effectively communicate with various stakeholders and align efforts toward common goals in different domains. EA is already practiced (and sometimes mandated) among federal organizations and government acquisition processes, providing a communication pattern for better understanding and collaboration (Heikkilä & Penttinen, 2007).

Moreover, EA can facilitate large-scale enterprise transformation changes necessary to successfully implement UAM stages that are aligned with governmental UAM initiatives. Finally, in the safety culture concern, the communication factor has been investigated, and evidence shows the positive impact of safety communication on employees' safety performance and safety culture, particularly in high-risk industries (Zara et al., 2023). The findings also underscored the need for businesses to focus on safety culture variables, especially in stressful working environments, to

improve safety performance. Thus, using EA in safety management strategies can enhance coordination, collaboration, and effectiveness in systematically addressing safety concerns.

6.7 Validation of UAM Safety Management Views

The safety management architecture was validated with a multidisciplinary team comprising experienced systems engineers with a background in aviation and safety, a senior systems engineering researcher, and a safety researcher and practitioner. Safety researchers provided theoretical foundations, while experts in modeling techniques discussed and refined the architectural views presented in this article. This collaborative effort involved a series of iterations and discussions to enhance the clarity and effectiveness of the proposed solutions. Subsequently, the work was presented to systems engineers at different hierarchical levels to gather valuable feedback and insights. Additionally, validation exercises were carried out with commercial pilots and safety practitioners to ensure the practical applicability and relevance of the proposed solutions.

The process of understanding the problem and proposing solutions was recursive and iterative in nature. Modeling, particularly in complex domains like aviation safety and system engineering, often involves implicit knowledge that may not be readily apparent. Therefore, verifying the clarity and usefulness of ideas through peer review and feedback from industry experts was critical to ensure that the proposed solutions meet the expected standards and effectively address real-world challenges.

With respect to the modeling effort, the author performed a consistency check and semantic analysis considering the elaboration process and modeling framework. Although not all views, model aspects, and elements are presented above due to resource limitations, the enterprise motivation and strategy were defined according to UAM's just culture goals. From the defined goals (mission and values), the strategic capabilities are then defined and associated with goals. The strategic capabilities are the base for defining the functional architecture, resource architecture, and personnel structure. Thus, verification and validation were conducted through a set of analysis activities, including element associations, tracing, and coverage after multiple iterations and corrections. Language verification was also performed to check the semantics.

The stakeholder's validation (external) was essential in evaluating the effectiveness of the

proposed architecture. It validated that the architecture aligns with stakeholder requirements and expectations. Experienced systems engineers, safety practitioners, and pilots were invited to understand the research and the different architectural views. The discussion carried out by the multiple perspective groups aimed to challenge the architecture elaboration, the ideas represented by diagrams according to the safety theories, and practicality in the UAM's future operations. Different feedback was received, which included improving the diagram presentation, correcting resource exchange naming and flows, including new elements, and modifying responsibilities. The discussions with multidisciplinary teams helped the conceptual modeling process and, most importantly, the qualitative assessment of the proposed solutions.

Lastly, before the MDPI Systems Journal publication, the peer review process also provided comments and suggestions that added value to the findings and architecture views.

CHAPTER 7

Sustainability Concern in the UAM System of Systems

7.1 Introduction

In pursuing sustainable urban mobility, integrating electric Vertical Takeoff and Landing (eVTOL) aircraft within Urban Air Mobility (UAM) emerges as a promising pathway. This paradigm shift aligns with the broader aviation initiative, notably the commitment to achieving Fly Net Zero by 2050, championed by the International Air Transport Association (IATA, 2021). At the forefront of this movement, UAM envisions itself as an environmentally friendly alternative, offering zero CO2 emissions during operations by utilizing fully electric aircraft.

While the inherent eco-friendliness of eVTOLs is a decisive aspect, the accurate measure of sustainability extends beyond the flight phase. The sustainability socio-technical concern comprises environmental and social impacts embedded in UAM services. The research focused on the passengers' sustainability awareness of mobility alternatives. Thus, the UAM transportation of passengers, referred to herein as pUAM (passenger UAM), is used to evaluate the adoption of UAM service. In other words, the user being aware of the eco-efficiency of the UAM service and choosing it represents the pUAM adoption in this study. In summary, the study assumes that sustainability goals for the UAM will directly impact its operational sustainability.

While CO2 emissions are just one part, the broader idea of eco-efficiency encompasses the balance between multiple impacts and values. Eco-efficiency, defined as the ratio between the product or service value and the environmental influence produced (WBCSD, 2000), is the guiding principle for the presented analysis. The sustainability viewpoint investigated the problem and discussed the solution using causal loop analysis to comprehend the intricate relationships influencing public perception and, ultimately, public acceptance and adoption. Through this lens, the Chapter aims to

unravel the complexities that either enhance the value proposition or minimize the environmental and social impacts associated with UAM passenger transportation.

The research aims to answer the question RQ5: “What are the social, economic, and environmental impacts of integrating UAM into urban environments, and to what extent can UAM operation be eco-efficient for passenger transportation?”. As a socio-technical concern, sustainability in UAM transportation encompasses environmental stewardship, social equity, economic viability, and technological innovation, requiring a systemic approach that integrates ecological resource management, community impacts, financial sustainability, and advanced technological solutions to create a balanced and enduring urban air mobility ecosystem.

By exploring the sustainability viewpoint and emphasizing the holistic understanding of UAM’s operational impact, this Chapter seeks to empower users to make informed, eco-efficient choices when navigating the evolving landscape of pUAM.

The theoretical foundations and past findings on environmental and social sustainability presented in Chapter 2’s literature review were used to understand the problem space and the proposed solutions in this Chapter. The diagrams presented in this Chapter were created per EA methodology, utilizing the Unified Architecture Framework (UAF) version 1.2, as explained in Chapter 3. Additionally, it is noteworthy that most of the content of this Chapter was presented at the 34th Annual INCOSE International Symposium in July 2024 and published in the article “Evaluating the Eco-Efficiency of Urban Air Mobility: Understanding Environmental and Social Impacts for Informed Passenger Choices” (Hoffmann et al., 2024b).

The rest of the Chapter is organized as follows: In 6.2, the sustainability problem and its aspects are presented and discussed. Causal loop analysis for the sustainability problem is introduced in 7.2.1. Then, solution space is defined in 6.3, elaborating on environmental sustainability in 7.3.1 and social sustainability in 7.3.2. The architecture elaboration starts in 6.4 by setting the context for user awareness in 7.4.1 and the strategic motivation for the enterprise in 7.4.2. Closing this section, value streams and capabilities are defined for pUAM eco-efficiency in 7.4.3. Next, a proposal on how to inform the user about mobility eco-efficiency is discussed in 7.5. Finally, the validation of the sustainability viewpoint is presented in 6.7.

7.2 UAM Sustainability Problem Space

Sustainability in UAM is a critical socio-technical concern that requires a comprehensive approach, integrating technological advancements with societal and environmental considerations. The Organization for Economic Co-operation and Development (OECD, 2008) defines eco-efficiency as the effectiveness of ecological resources to meet human needs. In UAM passenger transportation, eco-efficiency involves optimizing transportation operations to achieve the highest possible benefit for individuals and society while minimizing environmental impact.

Eco-efficiency in mobility systems refers to maximizing resource use efficiency, reducing emissions, and minimizing the overall ecological footprint of mobility services. It includes adopting sustainable technologies, such as electric vehicles and renewable energy sources, to minimize carbon emissions. Beyond environmental considerations, the social impact of UAM is also critical. The goal is to balance pUAM's adoption with social and environmental aspects, ensuring that transportation services meet societal needs while contributing to long-term environmental sustainability.

UAM sustainability encompasses multiple dimensions, including environmental, social, and economic aspects. Environmentally, it focuses on reducing greenhouse gas emissions, minimizing noise pollution, and preserving natural habitats. Socially, it considers the impact on communities, including equitable access to transportation, public health, and safety. Economically, it can be summarized as the viability of UAM operations and the profitability for service providers.

Key stakeholders in the UAM sustainability problem space include a) UAM Operators and Service Providers that must adopt and implement eco-efficient technologies and practices in their operations; b) Government and Regulatory Bodies responsible for setting environmental standards, providing incentives for sustainable practices, and ensuring compliance with regulations; c) Local Communities and the General Public are directly affected by the environmental and social impacts of UAM and are vital in supporting sustainable practices; d) Environmental Organizations that advocate for sustainable practices and monitor the environmental impact of UAM operations; and e) Technology Developers and Manufacturers, which are handling innovations in electric propulsion, renewable energy, and sustainable materials play a crucial role in enabling eco-efficient UAM solutions.

The problem dimensions in UAM sustainability are multifaceted. UAM must minimize its ecological footprint by reducing emissions, managing noise pollution, and conserving natural resources, all part of the environmental impact dimension. This requires the integration of electric propulsion, renewable energy sources, and sustainable materials. In addition, the social dimension is also part of the problem. UAM should contribute positively to communities by providing equitable access to transportation, enhancing public health and safety, and minimizing disruptions to daily life. Ensuring that all societal groups benefit from UAM services is essential.

Moreover, adopting sustainable technologies must be economically feasible for UAM operators. It includes managing the costs associated with electric vehicles, renewable energy infrastructure, and sustainable materials while ensuring long-term profitability. The last aspect concerns regulatory compliance because UAM must adhere to environmental regulations and standards set by government bodies. This includes meeting emission targets, noise regulations, and other sustainability-related requirements.

Analyzing UAM's impacts and benefits is the essence of the sustainability problem. The dimensions and dynamics between them are complex and interconnected. The causal relationships in impact are not simplistic and depend on service adoption. Therefore, the definition of the problem space for sustainability will use additional support from causal loop analysis, which is explained in the next section. By evaluating what constitutes UAM's eco-efficiency and its relationships, we can identify key leverage points for enhancing sustainability.

7.2.1 Causal Loop Analysis

The comprehensive understanding fostered by systems thinking is essential to address complex and interdependent issues. Systems dynamics, a discipline grounded in systems thinking principles, models and analyzes the dynamic nature of systems over time. Causal loop diagrams, at their essence, employ feedback loops to visually represent how changes in one variable ripple through the system, impacting other variables either positively (reinforcing) or negatively (balancing) (Anderson & Johnson, 1997). By emphasizing interdependence and cyclical feedback, these diagrams enable researchers to unveil underlying patterns that steer systemic behavior.

In the context of pUAM, causal loop diagrams have been chosen to analyze relationships among social and environmental factors influencing the adoption of this novel transportation mode.

Adopting a conceptual and preliminary approach, the analysis focused on qualitative assessments, recognizing that simplifications would need further elaboration in subsequent analyses. The initial objective was to pinpoint critical factors and influential relationships. Figure 7.1 encapsulates the analysis overview, identifying aspects directly or indirectly impacting pUAM adoption. These aspects, representing variables that may change over time, formed the basis for understanding the influence of relationships uncovered during the analysis.

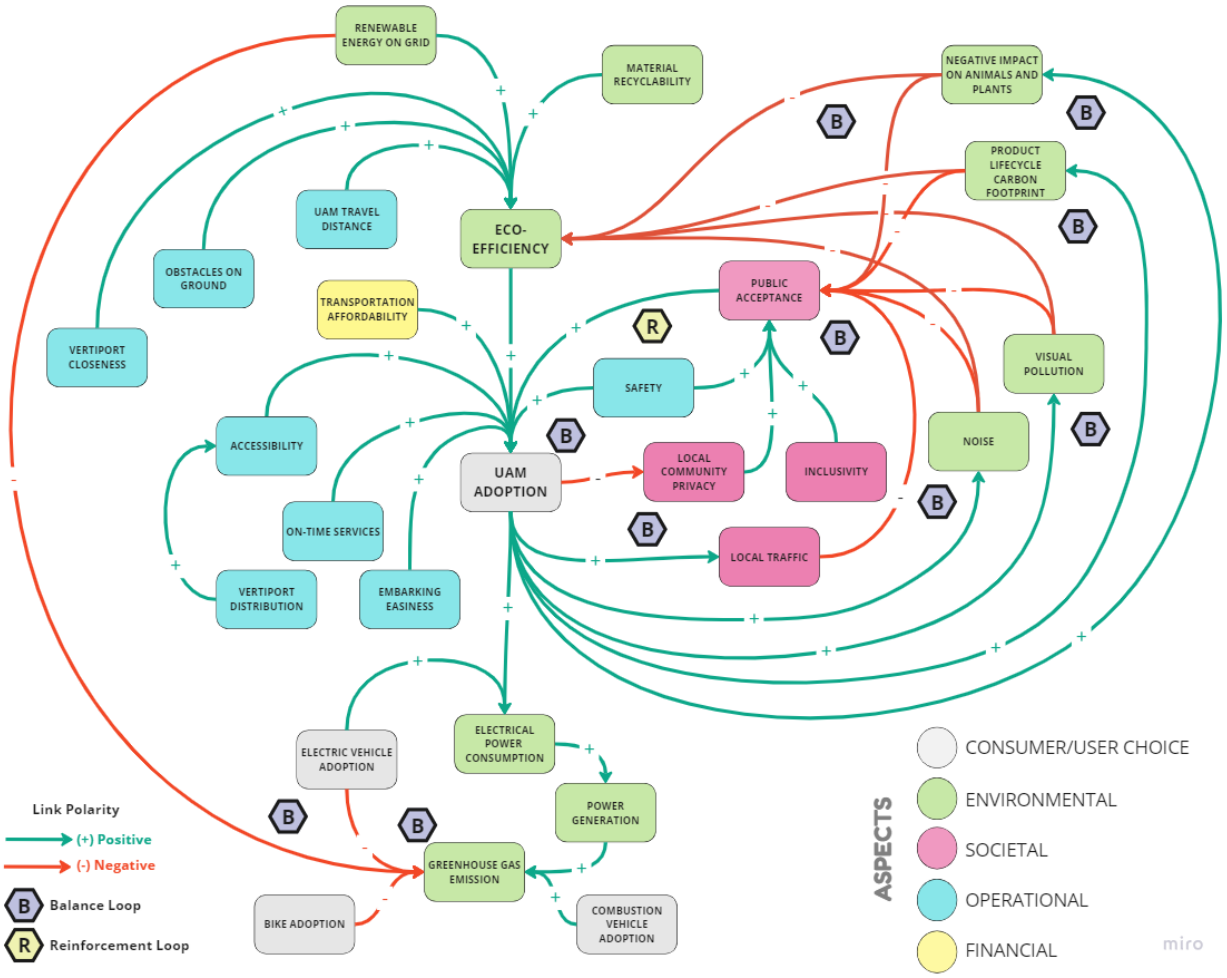

Figure 7.1: pUAM Causal Loops

To streamline the analysis, variables were categorized into five aspects: Consumer/User choice, Environmental, Societal, Operational, and Financial. The *Environmental* category addresses the direct and indirect impact of pUAM operations on the environment, while *Consumer/User Choice* delves into the adoption of pUAM and other mobility modes. *Societal* elements represent impacts on communities residing in areas of pUAM operation. *Operational* factors are intrinsic to pUAM

operation and determined by the location's peculiarity and the operator's strategy. The *Financial* aspect is tied to the pUAM business model, influencing and being influenced by other operational factors.

Although the economic dimension is part of the problem, business and financial aspects are indirectly covered in this research through public acceptance. Environmental and social sustainability is the premise for UAM adoption, consequently impacting business sustainability. Strategies proposed in the following sections align with values to sustain UAM operation but do not specify operational costs, efficiency, and pricing strategy. Operational definitions depend on the location and its specifics. Therefore, UAM's economic viability analysis is outside the scope of this Chapter. *Affordability* (in Figure 7.1) is a strategic value for the user when choosing UAM and is a mere symbol that financial aspects are part of the UAM adoption loop.

7.3 UAM Sustainability Solution Space

Causal loops map the relationships between factors affecting UAM sustainability. These relationships form feedback loops that can either reinforce positive outcomes or exacerbate negative ones. For example, a positive feedback loop might involve increased adoption of electric vehicles, leading to reduced emissions, improving public mobility, and encouraging further adoption of sustainable technologies. Conversely, a negative feedback loop might involve increased noise pollution, leading to public opposition to UAM operations, thereby limiting the expansion of eco-efficient mobility solutions.

The insights gained from causal loop analysis can drive the solution space for UAM sustainability. First, it helps to pinpoint key leverage points where interventions can yield significant benefits. Based on the identified leverage points, targeted interventions can be designed. In addition, causal loop diagrams highlight the most effective resource allocation areas. Resources can be used more efficiently by focusing on interventions with the highest potential for positive feedback. The analysis also underscores the importance of collaboration among stakeholders. For instance, solutions can be developed through partnerships between government agencies, UAM operators, technology developers, and local communities.

Continuous monitoring of interventions' impacts and effectiveness is essential. Causal loop analysis can help establish metrics and indicators for sustainability performance. Regularly reviewing these metrics allows stakeholders to adapt their strategies to address emerging challenges and capitalize on new opportunities.

With identified variables and relationships, two prominent loops emerged. The environmental loops outline the impact of pUAM operations on the environment and its subsequent influence on pUAM adoption. The social loops encompass relationships and the influence of the local community. Although business sustainability, pUAM adoption, and eco-efficiency correlate, the study concentrated on the environmental and social aspects in the following sections.

7.3.1 Environmental Loops

Figure 7.2 represents a distilled version of Figure 7.1, explicitly focusing on environmental factors. The core emphasis of the analysis lies in understanding the impact of eco-efficiency on the adoption of pUAM and how external factors shape and are shaped by this dynamic relationship. Two primary feedback loops concerning the utilization of pUAM have been identified. The first loop centers on the causality of greenhouse gas (GHG) emissions and eco-efficiency grade (left side loop in Figure 7.2). Notably, lower GHG emissions associated with pUAM contribute to a higher eco-efficiency grade, thereby enhancing the prospects for pUAM adoption.

Conversely, increased pUAM adoption may lead to heightened electrical power consumption, given the full-electric operational nature of pUAM concepts. This, in turn, influences the demand for expanded electrical power generation, potentially resulting in increased greenhouse gas emissions due to the need for higher operational activity of existing and new power plants. The power grid from which the energy is consumed plays a critical role in the loop. The amount of renewable energy on the grid can reduce GHG emissions and increase the eco-efficiency.

Similarly, the UAM product life cycle carbon footprint reinforces the GHG emissions and impacts the eco-efficiency. Establishing UAM operations involves raw material consumption, construction activities, and the mobilization of personnel, among other factors. Material recyclability, including battery disposal, is an opportunity for intervention on this balance loop and increase the overall eco-efficiency.

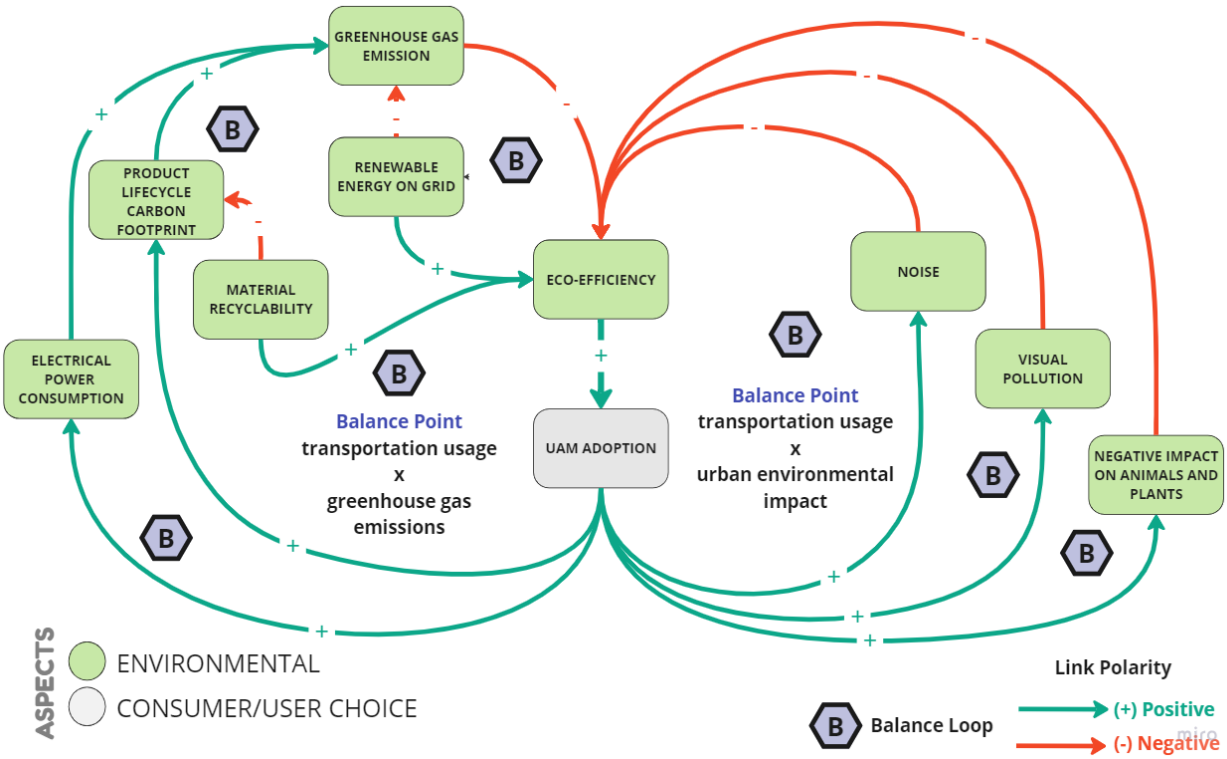

Figure 7.2: pUAM Adoption and Environmental Impact Loops

The second loop (right side) delineates how environmental factors influenced by pUAM operations impact the eco-efficiency grade. Assuming an increase in pUAM adoption, the local communities housing vertiports (pUAM terminals) may witness an escalation in ambient noise due to increased local traffic and the operational noise of eVTOL vehicles. Visual pollution may also intensify as numerous vehicles traverse the area. Also, heightened operations potentially threaten local biota (animals and plants). For instance, birds and other animals may be exposed to increased noise and air disturbance during the takeoff and landing of eVTOLs. These three factors collectively contribute to a degradation of the eco-efficiency grade, exerting an opposing influence on pUAM adoption. Similar to the greenhouse gas emissions loop, interventions in the urban environmental impact loop must be identified to maximize the eco-efficiency grade and, consequently, promote pUAM adoption.

7.3.2 Social Loops

Figure 7.3 illustrates the interplay of social and operational facets in shaping the adoption dynamics of pUAM. Commencing the analysis with operational factors, the proximity of vertiports

to users, termed vertiport closeness, directly impacts adoption. Users are more inclined to utilize the service frequently when the distance to vertiports aligns with the proximity of their residences and routine activities, such as work or study. Accessibility, meaning the ease individuals can access vertiports, directly influences adoption. Enhanced accessibility to vertiports and eVTOL vehicles broadens the pool of potential users, elevating the likelihood of adoption. The routing strategy devised for the pUAM service equally wields a direct impact on adoption, especially if it is optimized for cases where traveling via UAM is more environmentally sustainable than ground transportation modes. Trips, where ground route alternatives are longer due to an obstacle or distance, have more chance to increase the eco-efficiency of using eVTOLs. Optimizing vertiport locations and routes can be relevant to offering greener transportation and increasing the service's attractiveness.

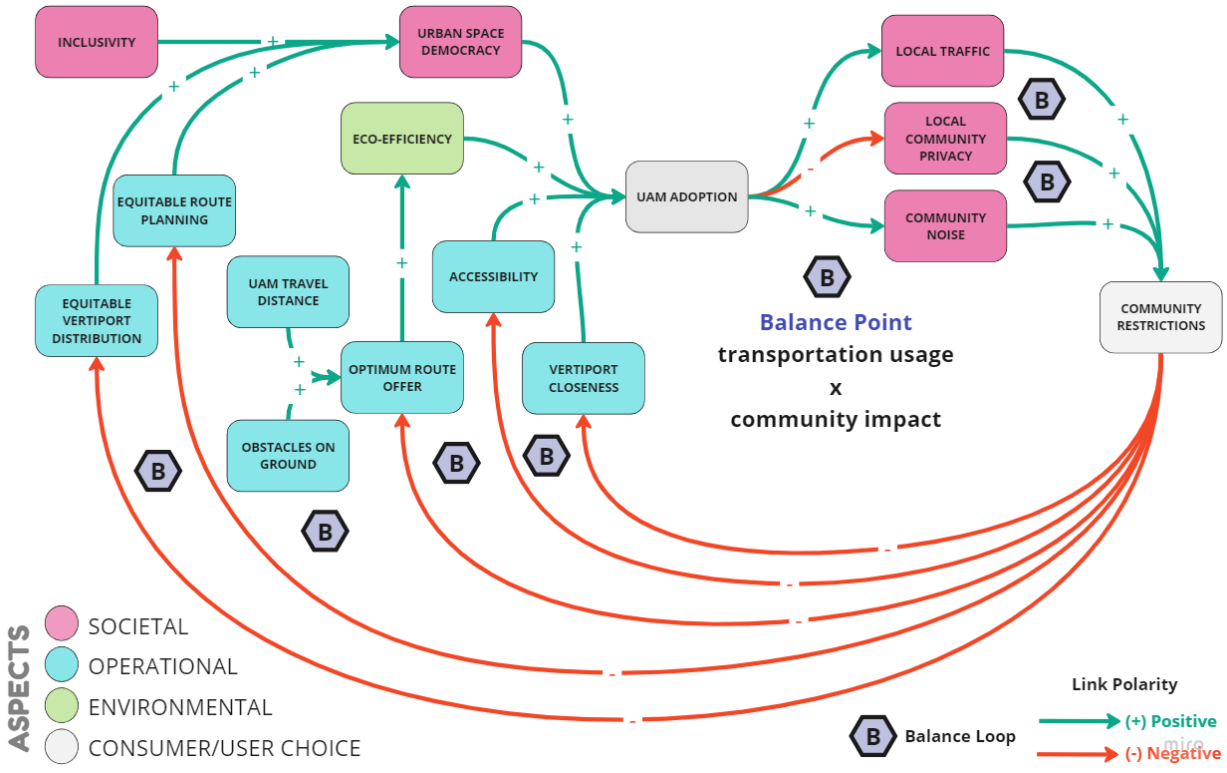

Figure 7.3: pUAM Adoption with Operational Aspects and Social Impact Loops

Democratizing access to the pUAM service is also relevant for its adoption. Inclusivity in providing services to impaired mobility passengers is a challenge that should be overcome for democratic transportation. Social and economic inclusion must be considered as well. A service

that caters not only to individuals with higher economic resources, often residing in upscale properties on the outskirts of city centers, but also extends its reach to less economically privileged communities, enhancing the service's appeal across society. Key drivers for this democratization include equitable route and vertiport planning, as well as connecting areas with the lower economic privilege to locations central to economic activities.

Operational factors are susceptible to the perceptions of communities, introducing a potential feedback loop where community attitudes influence imposed restrictions on pUAM operations. This influence can be positive or negative, with increased restrictions degrading the previously examined operational factors. These perceptions and resultant restrictions are, in turn, directly impacted by factors influenced by the operational level of pUAM, such as local traffic, privacy concerns, and noise.

Operational efficiency is part of the loop and can contribute to its positive value. Offering more efficient mobility includes optimizing flight operations, maintenance practices, and resource management. It suggests implementing advanced technologies and efficient operational protocols to minimize waste and energy consumption. For instance, deadhead flights should be avoided since the UAM could impact the environment while transporting one person or none. Similarly, route planning and vertiport distribution can decrease the value of the eco-efficiency ratio.

In conclusion, interventions on social aspects should be strategically designed to balance the counter forces within the loop, aiming for optimal pUAM adoption. Ideally, the service should remain attractive to society and businesses despite evolving constraints.

7.4 UAM Sustainability Enterprise Views

The views presented below provide visualizations and support the analysis needed to answer the research questions about UAM sustainability. The diagrams focus on the strategic view of the UAM ecosystem, providing an integrated approach to combining drivers, challenges, and goals. Since the relationships between those elements can be conflicting or consonant, the sustainability viewpoint concentrates on strategic motivation.

The intended users are the stakeholders identified in the previous section and represented below

in Figure 7.4. The architecture objective is to provide strategies to minimize or maximize specific relationships to enhance the overall eco-efficiency of pUAM operations. To this end, this section sets the contextual scenario for sustainability user awareness and then elaborates on strategic views, capabilities, and value streams. The objective is also aligned with the research questions intended to be answered by this Chapter.

7.4.1 pUAM Sustainability Context for User Awareness

Contextual awareness is imperative to making informed decisions throughout the systems engineering lifecycle, from requirements definition to system validation and adaptation to changing conditions (INCOSE, 2023). In the sustainability problem, defining and understanding the pUAM context provides us with essential information about stakeholders, boundaries, user needs, external interfaces, and the larger socio-economic and environmental urban landscape. Contextual information is fundamental to modeling the interactions between the system and its environment, ensuring that the designed system aligns with the overall objectives and functions seamlessly within its operational surroundings.

The UAF High-Level Operational Concept diagram describes the resources and interactions required to meet an operational scenario from an integrated ecosystem point of view. It is used to communicate overall quantitative and qualitative system characteristics to stakeholders. Figure 7.4 illustrates the main agents of the pUAM ecosystem organized from the sustainability viewpoint. People, organizations, systems, services, environment, and concerns are represented all together in the diagram.

The starting point, or the central motivation, is the *User* (on the left side), who has *sustainability awareness,* which supports decisions about mobility choices. Users can choose between *Ground Transportation* or *pUAM,* which also requires ground transportation for vertiport access and egress. Energy consumption relationships are represented at the top of the diagram. Some ground transportation (like cars, buses, trucks, trains, etc.) uses combustion engines and directly generate greenhouse gas emissions. Some are electrically powered and consume energy from the *energy grid*. Energy grids vary according to countries or regions and are usually a combination of *renewable resources* or *other resources.* The latter contributes to the greenhouse gas emission of the energy grid. Hybrid vehicles are in the middle of the two ground transportation categories. Hybrid and other types of transportation were not represented in the diagram to keep it clean.

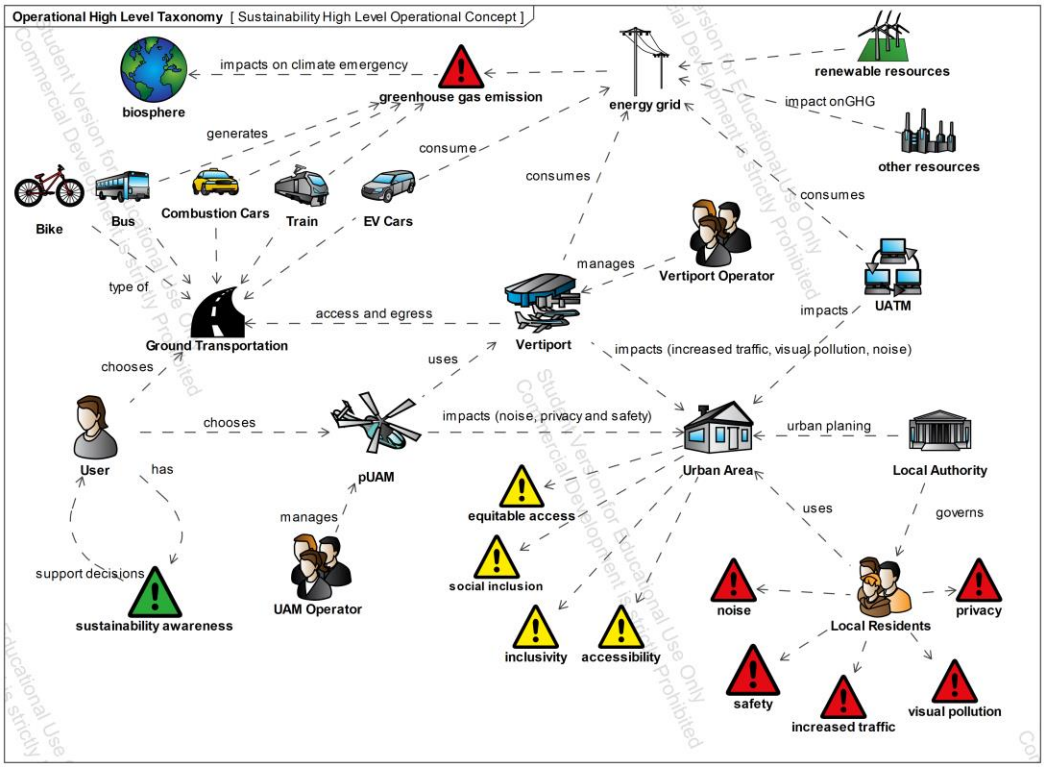

Figure 7.4: High-Level Operational Concept for Sustainability User Awareness

The *pUAM* vehicle (in the center) uses the *Vertiport* for ground operations, including charging the battery and performing maintenance. Therefore, its operation also consumes the *energy grid*, generates *greenhouse gas emissions*, and impacts the *biosphere*. Not to mention, other logistics for the vertiport operation may rely on combustible vehicles or general electricity to keep the systems running. Likewise, the Urban Air Traffic Management, *UATM* on the right side, consumes electricity to keep the traffic network functioning and all communication required during UAM operation.

The last part of the contextual diagram is about the urban space. The *Urban Area* (in the center) is impacted by *pUAM* vehicles, *Vertiport*, and *UATM*. The social concerns related to the urban environment are *equitable access* and *social inclusion*, which refer to the democracy of the urban space, *inclusivity* of any impaired mobility group, and *accessibility*, referring to the public ease of accessing transportation services. The *Local Authority* is responsible for *urban planning* and governs *Local Residents* (users of the urban areas). The community concerns are *noise*, *safety*, *increased local traffic*, *privacy*, and *visual pollution*. The contextual diagram does not expect to

represent all the relationships and complexity that the sustainability problem suggests. Still, a picture of the whole scenario helps navigate through the following model views.

7.4.2 Strategic Motivation for pUAM Eco-efficiency

The enterprise's strategic motivation starts with the definition and architecture of drivers and challenges. This step aims to identify elements that drive the UAM ecosystem to provide passenger transportation while addressing sustainability challenges. Stakeholders of this view include UAM strategic planners, operators, program managers, authorities such as local governments and regulators, and society. Their common concern is what the enterprise needs to do to achieve UAM's goals, which are driven by infrastructure, technology, or any other situation presented by sustainability challenges. The strategic motivation diagram proposed in Figure 7.5 represents the architecture for strategies to address the UAM eco-efficiency presented earlier. The causal loop analysis evaluated environmental and social elements to understand the critical balance points for pUAM sustainability. The operational concept diagram (Figure 7.4) framed those elements in the context of pUAM sustainability. In the following section, we define the sustainability strategy for the UAM as an enterprise, considering the challenges posed by sustainability elements and the operational context.

The <<EnterpriseGoals>> elements represent the UAM's operational ambition towards sustainable passenger transportation. *UAM environmental impact awareness* (in the center) is defined purposefully to place the society's need for sustainability. Similarly, *UAM social impact assessment* (on the left) and *UAM perception & acceptance* (on the bottom) are defined goals considering society as the primary stakeholder. As users and habitants of the biosphere, sustainability is urgent and imperative for every human being. The fourth goal is *Sustainable Urban Mobility Plans* (on the right), which concerns the planning and integrating mobility solutions in the population's best interest.

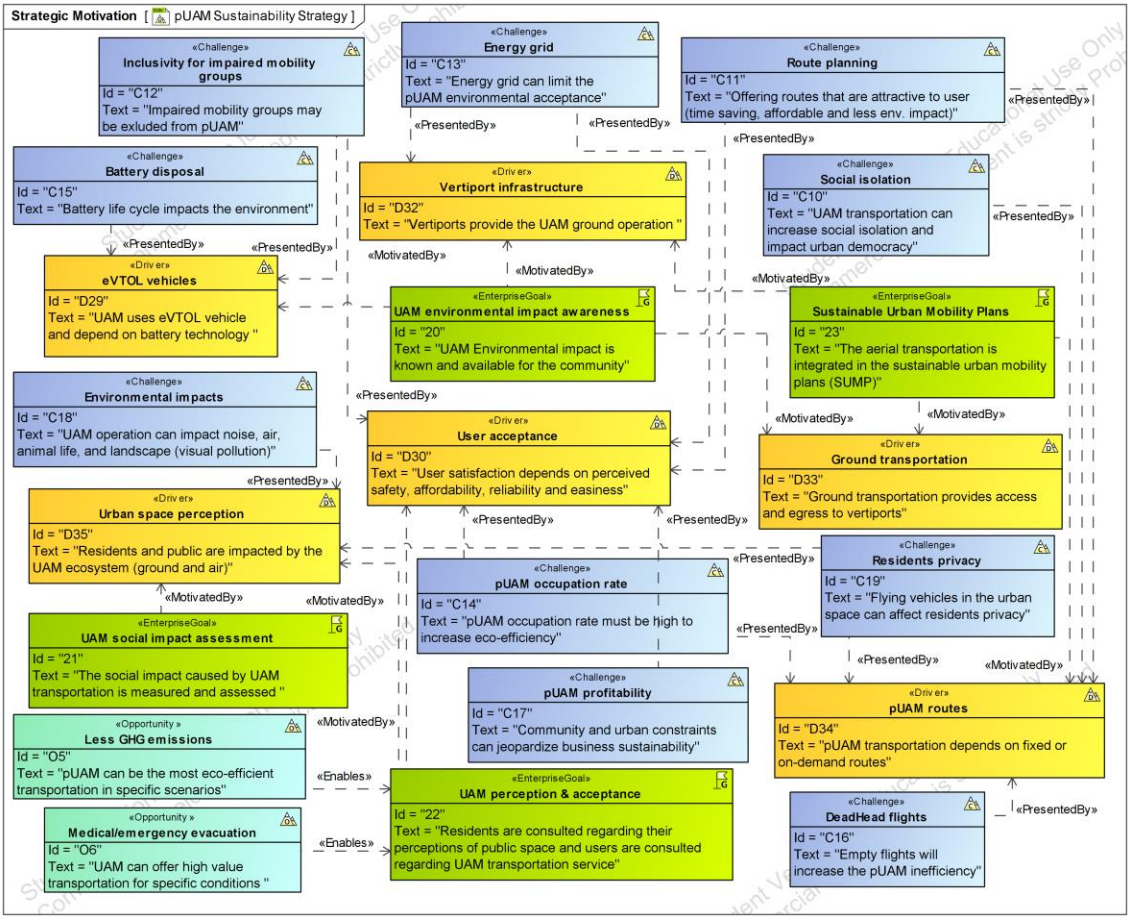

Figure 7.5: pUAM Sustainability Strategy (Strategic Motivation diagram)

Drivers established by UAM technology are *eVTOL vehicles* (<<Driver>> on the left) and *Vertiport Infrastructure* (on the center top). eVTOL vehicles work with battery technology, which is relevant to carbon footprint reduction but also brings concerns about *Battery disposal* (<<Challenge>> above *eVTOL vehicles*). The vertiport infrastructure provides UAM ground operation services, and its location is a key element for the benefits and drawbacks of community perception and UAM transportation accessibility. *Ground transportation* (on the right side) is another driver that complements the UAM mobility network from end to end. Passenger transportation assessments shall consider ground and aerial routes to include multiple aspects regarding the quality of the service and, ultimately, to forecast the carbon footprint of each solution. Therefore, *pUAM routes* (on the bottom right) are about the aerial on-demand or fixed routes. The two last drivers are related to the public. *Urban space perception* (on the left side) addresses how the population perceives the impacts of UAM ground and air operations. In *User*

acceptance, the passenger or potential passenger evaluates the UAM services. The satisfaction and willingness to use it depends on perceived values such as safety, affordability, accessibility, reliability, and easiness.

Drivers motivate goals and are associated with dashed lines and the notation <<MotivatedBy>>. The relationships between drivers and goals are not straightforward and simplistic; they are expected to have drivers motivating more than one goal or many drivers motivating a single goal. The same applies to <<Challenge>> elements. Challenges are presented by drivers, or in other words, some challenges must be overcome to address a driver. For instance, the driver *User acceptance* presents five challenges (dashed line with <<PresentedBy>> notation pointing at the driver) since it is a sensitive attribute in this analysis. *Inclusivity for impaired mobility groups*, *Energy grid*, *Route planning*, *pUAM profitability*, and *pUAM occupation rate* are challenges that service operators must address with the participation of authorities and the community. Another example is the *Route planning, Residents' privacy,* and *Deadhead flights*, all challenges associated with *pUAM routes* driver. Offering aerial routes that consider users' needs and are attractive, affordable, and sustainable is difficult for the UAM industry. Likewise, avoiding empty flights, usually in oriented mass movements for work shifts, is something planners need to overcome to maintain transportation efficiency.

Lastly, <<Opportunity>> elements are existing or potential favorable circumstances that can be advantageous for addressing enterprise challenges. Although opportunities are intentionally not the focus in this view, there are two examples of how pUAM can bring positive outcomes. *Less GHG emissions* (in the bottom left) represent the cases in which pUAM is the best option in terms of environmental sustainability. Longer ground distances, like when there are obstacles in the ground (mountains, sea, valleys, lakes, etc), may place pUAM as the best alternative for transportation, which means reducing greenhouse gas emissions on our planet. Other use cases like *Medical/emergency evacuations* can also benefit from pUAM due to the potential reduction in travel time.

7.4.3 Value Stream and Strategic Capabilities for pUAM Eco-efficiency

The next step from a strategic viewpoint is defining capabilities. *Capability* refers to an enterprise's ability or capacity to achieve a desired outcome. It is a high-level concept encompassing various elements, including people, processes, technologies, and resources, all working together to achieve

a strategic goal. Enterprise architecture modeling involves capturing and representing these capabilities to understand how different aspects of an organization contribute to its overall objectives. The significance of presenting the defined capability and achieving the desired effect can be visualized as the enterprise's value stream. *Value streams* are often integrated into enterprise architecture models to provide a comprehensive view of how different processes and activities contribute to organizational goals. This integration helps in strategic planning and decision-making. Figure 7.6 depicts the strategic diagram and shows the pUAM capabilities associated with drivers and value stream.

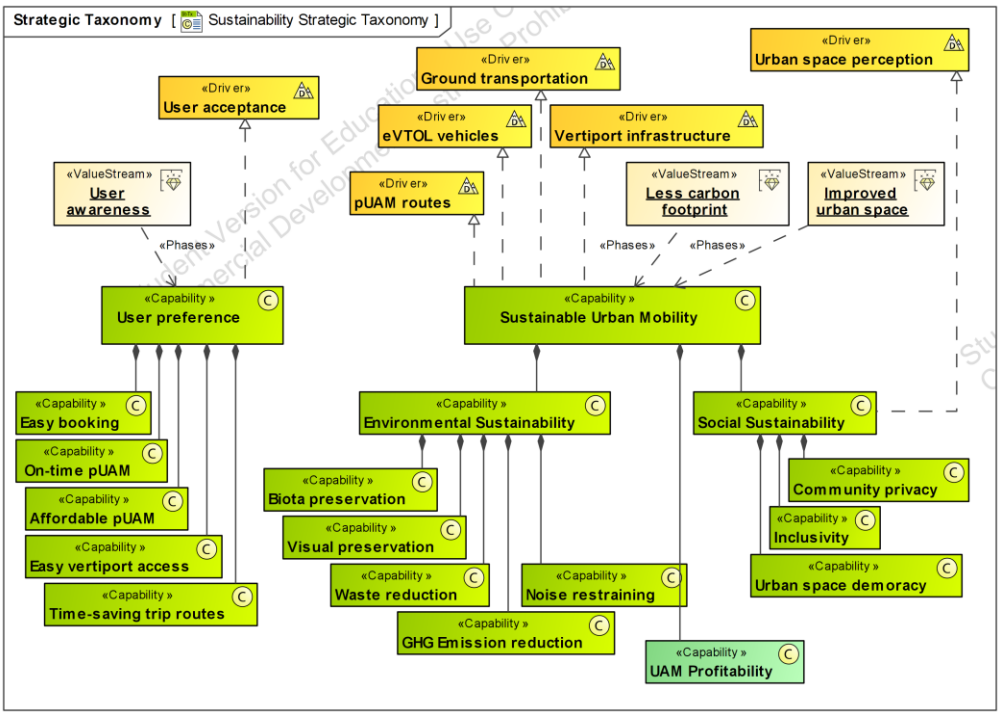

Figure 7.6: Strategic Taxonomy with Value Stream for Sustainable pUAM

We defined two primary capabilities that will structure the other level of capabilities: *Sustainable Urban Mobility* (<<Capability>> on the center) and *User preference* (<<Capability on the left). The UAM adoption parameter, used in the causal loop diagrams, is related to the *User preference* capability and has a central role in the strategic taxonomy. Note that all the capabilities defined in the strategic taxonomy were associated with the parameters analyzed in the causal loop diagrams for consistency check. The architecture proposed below is consistent with the approach of having a passenger that chooses pUAM knowing about its eco-efficiency. User perception depends on the UAM operation's capacity for *Easy booking*, *On-time pUAM* (reliable service), *Affordable pUAM*,

Easy vertiport access (accessibility), and *Time-saving trip route*. The driver *User Acceptance* is realized when the capability *User preference* is established, which maps to the <<ValueStream>> *User awareness*.

The other top-level capability is *Sustainable Urban Mobility.* It comprises *Environmental Sustainability, Social Sustainability,* and *UAM Profitability,* the second level of <<Capability>> elements below *Sustainable Urban Mobility.* Environmental sustainability includes managing the impacts related to the environment. *Biota preservation* concerns animal and plant lives. Vehicles flying in urban areas can affect birds, trees, or other living organisms. *Visual preservation* aims to avoid overloading the landscape with installations such as towers, antennas, vertiports, vehicles, and signs. *Waste reduction* relates to material recyclability and disposal. *GHG Emission reduction* concerns reducing the carbon footprint in the whole product life cycle and during operation. *Noise restraining* aims to control noise pollution, which can affect the quality of community life.

Social sustainability is composed of *Community privacy*, a problem that flying over urban areas or between buildings can cause to residents; *Inclusivity,* which should not exclude impaired mobility groups from a transportation method; and *Urban space democracy,* a combination of equitable access and social inclusion. Transforming pUAM into transportation for wealthy people by placing vertiports in rich neighborhoods can increase the distance between social groups and isolate society. Considering equitable access and including different social groups is vital to keeping the urban area a democratic space. The <<ValueStream>> mapped to *Sustainable Urban Mobility* capability is *Less carbon footprint* and *Improved urban space.* Both values align with the enterprise goals and are related to previously defined drivers.

Lastly, there is the UAM Profitability (<<Capability>> at the bottom of the diagram) as a symbolic representation that business sustainability is also part of the equation. pUAM services will only occur if the operators profit and sustain their business. Besides the challenges with city topology, transportation dynamics, and all operational settings for offering possible UAM flights, communities and authorities can impose significant constraints on operators. Finding the balance between value for society and economic viability is tricky and may not be feasible for all locations. pUAM might not be a good solution for all scenarios, but exploring the use cases that bring more value and less impact compared with what we currently have as transportation alternatives could be a good strategy.

7.5 Enabling Informed Users for a Sustainable Mobility

The choices people make as consumers carry consequential weight in shaping our planet's and society's future. As users of mobility transportation, we must approach our decisions with sustainability awareness. The impact of our transportation choices extends far beyond personal convenience, reaching into environmental preservation and societal well-being. By consciously opting for sustainable transportation alternatives, users exercise their power as consumers to promote eco-friendly practices and contribute to a cleaner, healthier planet. This collective shift towards sustainable mobility reduces the carbon footprint and fosters a positive ripple effect, inspiring industries and governments to prioritize environmentally conscious solutions. In essence, individual's choices as users become catalysts for change, propelling towards a more sustainable, harmonious coexistence with the world all inhabit.

Understanding aspects contributing to the pUAM eco-efficiency is valuable for the industry, urban planners, administrations, and regulators. Society is the stakeholder most interested in using the most eco-efficient mobility among available options. The biosphere is a critical resource and must be included in the ecosystem's perspective. Informing users about transportation's eco-efficiency gives them the possibility to make conscious decisions. The idea discussed in this section is incorporated in the use case diagram in Figure 7.7.

Handling awareness among users is a way of sharing responsibility at an individual level. If users know how much impact they cause when moving from point to point, they have the opportunity to contribute individually. There is no single truth about sustainability in mobility; it depends on the context, such as route, energy supply, time, occupancy, and traffic. A customized way to assess the contextual parameters and calculate the eco-efficiency of transportation would be relevant and valuable for society and mobility solution optimization. With eco-efficiency information about mobility solutions, the user can evaluate the alternatives available and make a conscious decision. Choosing the greenest alternative may not always be possible or desired due to the user's context, but it can increase the likelihood of greener solution adoption.

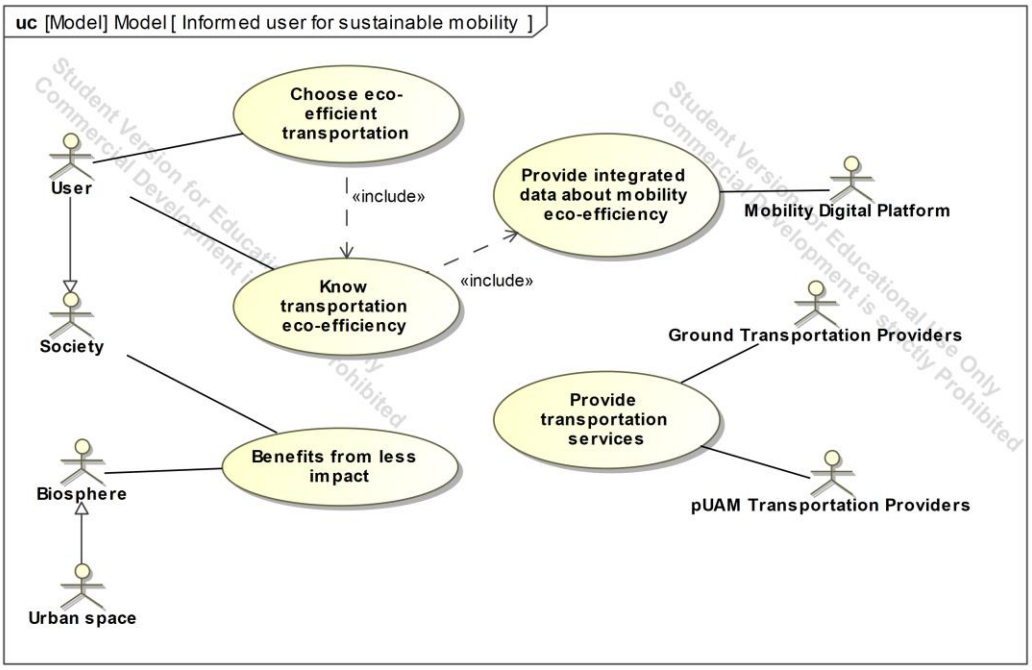

Figure 7.7: Informed user for Sustainable Mobility Use Case

The eco-efficiency awareness of the user is performed by the use case *Provide integrated data about mobility eco-efficiency* (top right side of Figure 7.7). The actor *Mobility Platform* represents the proposed integrated digital platform that connects transportation providers and mobility services to users' data and customized demands. The digital platform that calculates and informs the user about eco-efficiency converges with smart cities' goals. Mobility solutions refer to innovative and technologically advanced transportation and urban mobility approaches according to smart city initiatives. These solutions leverage digital technologies, data analytics, and connectivity to enhance the efficiency, sustainability, and accessibility of transportation within urban areas (Munhoz et al., 2020). Some aspects of mobility solutions in smart city projects include integrating transportation modes, data-driven decision-making, sustainability, environmental impact, user-centric approach, and digital platforms. Mobility-as-a-Service (MaaS) platforms envision applications offering a centralized digital hub for users to plan, book, and pay for various modes of transportation (Nemtanu et al., 2016). Eco-efficiency should be considered in the information provided by the smart city's digital platform and an agent for user awareness. Enabling consumer decisions for a better environment promotes the transformative potential of MaaS in fostering a culture of eco-conscious transportation.

7.6 Validation of UAM Sustainability Views

A validation process was undertaken to ensure the value and effectiveness of the sustainability viewpoint in UAM. The purpose of the sustainability viewpoint is to communicate a strategy to address and balance different UAM sustainability factors. Drivers, challenges, enterprise goals, and opportunities were proposed, accounting for the complex environmental and social impacts when users adopt UAM transportation.

The first step in the validation process involved using causal loop analysis to identify and map out the interactions and feedback mechanisms within the UAM ecosystem. These causal loops were essential in understanding the complex dynamics that influence sustainability. Each element and relationship within the causal loops was verified against established literature to ensure that the identified interactions were grounded in proven theories and empirical data. This verification process helped to enhance the credibility and reliability of the model.

Following this, the architecture model, developed using the EA standard, was employed to systematically structure and represent the sustainability viewpoint. The UAF strategic viewpoint provided a robust framework for organizing and analyzing the various components of UAM sustainability, ensuring that all relevant factors were considered and appropriately integrated into the model.

The causal loop analysis and the consistency with the strategic definitions in the model were validated by a sustainability and green technology researcher, who happened to co-authored the published paper (Hoffmann et al., 2024b). Moreover, discussions with architecture modeling practitioners scrutinized the model's views. These experts provided valuable insights and feedback, helping to identify potential gaps or inconsistencies in the model. Their expertise ensured that the model adhered to best practices in architecture modeling and accurately represented the sustainability concerns of the UAM ecosystem.

Researchers from different backgrounds participated in a group seminar and had the chance to visualize the diagrams and discuss the findings. As mobility users, most of them could share the perspective of a potential pUAM customer. The use case in which passengers can choose their mobility alternative with eco-efficiency information was well received, and the proposal's value was confirmed. Lastly, the content also received comments and suggestions from the peer-review

process of the 34th Annual INCOSE International Symposium, which added value to the findings and architecture views. During the oral presentation, comments from the audience demonstrated the need to deepen the research and provide more accurate data. It resonates with the research recommendations on developing a study case (in a specific location) with given parameters to quantitatively understand eco-efficiency according to its impact and values.

CHAPTER 8

Conclusion

In conclusion, the comprehensive evaluation of the UAM ecosystem highlights the interconnected nature of socio-technical concerns and their implications for achieving safe, secure, and sustainable UAM operations. This study examined four socio-technical concerns through the application of EA methodology. Key findings underscore the critical need for an integrated approach to achieving situation awareness, security, safety culture, and sustainability in UAM SoS. A summary of the research findings is presented in this Chapter.

In UAM, SA is a collective cognitive process that extends beyond individual actors to encompass various enterprise levels. Effective SA depends on personal skills, technology, workload, team communication, and interactions among human and nonhuman agents. Using the UAF, this study modeled the enterprise architecture to integrate SA elements and demonstrate their interactions. The model revealed that multiple enterprise levels influence SA and are crucial for safe UAM operations. The UAF's capability to organize information and processes consistently with enterprise goals enabled a detailed analysis of SA behavior and structure, providing insights for future research on operational tasks and workload.

The second aspect framed in the study concerns the UAM security and resilience performance in, particularly, UAM ground operations. The study defined security processes, risk taxonomies, and mitigation strategies by employing the UAF security viewpoint. The model emphasized a systemic approach to resilience, considering personnel, infrastructure, and daily operations. The UAF facilitated the integration of resilience capabilities, enabling the organization to monitor, respond, learn, and anticipate threats. The research underscored the need for comprehensive security measures that include physical, human, and organizational dimensions and suggested future research on security performance and diversified operational scenarios.

In the next socio-technical concern, establishing a just culture within UAM operations is essential for fostering a learning-oriented environment and enhancing safety performance. The work

highlighted the importance of trust-building, active participation in safety discussions, and fair enforcement of safety policies. Using UAF organizational viewpoints, the study explored the roles, responsibilities, and relationships necessary for a just culture. The findings emphasized the need for ecosystem-level consensus and stakeholder cooperation, proposing a unified safety committee to facilitate communication and learning within the UAM community.

Lastly, the sustainability and eco-efficiency viewpoint demonstrated that the environmental benefits of eVTOL aircraft depend on the source of electricity, energy efficiency, and life cycle impacts. The study evaluated the environmental and social impacts of UAM and proposed an enterprise strategy to address sustainability challenges. The UAF model mapped capabilities to support eco-efficiency and user preferences, suggesting that sustainable UAM services require careful planning and stakeholder coordination.

In summary, this study demonstrated that a comprehensive and integrated approach is essential for addressing the socio-technical challenges in the UAM ecosystem. The UAF provided a valuable framework for modeling complex interactions and supporting strategic, operational, organizational, and service architectures. The insights gained from this research contribute to advancing UAM safety, resilience, just culture, and sustainability, paving the way for informed decision-making and improved UAM operations.

8.1 Enterprise Perspective and Stakeholder Engagement Using EA Views

From an enterprise perspective, this research effectively utilized EA views to foster stakeholder engagement and comprehensively address UAM's socio-technical concerns. By employing the EA methodology and UAF as a modeling framework, the study provides a structured approach for analyzing the UAM SoS, facilitating clear communication and alignment among diverse stakeholders, including regulatory bodies, operators, and the community.

Addressing socio-technical concerns is often a difficult task with conflicting ideas and complex relationships. Communicating different perspectives for diversified publics or stakeholders is a current system engineering challenge. When decision-makers are a combination of technical, non-technical, administrative, regulatory, businesspeople, and users, conveying an idea and arguing about safety, security, and sustainability must be adapted and customized to achieve the desired

effect. This research's objective includes communicating with multiple stakeholders and supporting decision-makers by developing perspectives and viewpoints that can effectively engage and address the interests of various stakeholders.

The different perspectives were explored according to the objective of each viewpoint. For this reason, different aspects of the UAF were used in each socio-technical concern. For instance, the SA concern aimed to show how human aspects can limit or facilitate SA levels and how different enterprise levels can contribute to these processes. Therefore, mapping capabilities and constraints according to operational process flow were adequate for the first objective. While exploring service views and discussing SA as competence involving different operators and teams supported the second objective. The strategic and operational scenario could demonstrate the SA levels in practice during a flight, and the personnel taxonomy showed the organizational perspective of who requires SA for a safe operation.

From the security viewpoint, the technical side of risk taxonomy and security controls were the most suitable to show how security processes must be planned according to the UAM operational scenario. Moreover, security process views were used in two configurations to elaborate on resilience performance in the ground scenario. First, to demonstrate functions that the security process must fulfill at a higher level, and second, more definitions of which capabilities each security must deliver and which post or organization is capable of performing them. The abstraction level in each view was deliberately different to provide different perspectives and support the correct strategy to define the security process. In addition, a traceability matrix was utilized to show how processes or security enclaves are actively working to avoid or contingence the risks defined in the taxonomy. Likewise, with capabilities, the matrix allowed an easy visualization way to identify and understand which security processes are more critical to keep the operation protected and able to recover from a threat.

The strategy to explore safety culture focused on organizational perspectives within EA. Since the conceptualization analysis, stakeholders with different interests were part of the problem and must be addressed in the solution space. Then, drivers were mapped, and balanced capabilities were defined to accommodate different interests. For this reason, organizational views (personnel processes and structures) were used to show how organizations can work together towards a health safety culture. Moreover, just culture depends on behavior consensus and regulatory involvement.

Therefore, adding regulation authority into the discussion and considering it part of the UAM SoS in personnel structure view was crucial to discussing the unified safety committee proposal. Customized views were proposed for three different organizational levels. Top-level management, which engagement is crucial for integrating safety and security policies within the organizational strategy, safety divisions highlighting the importance of involving safety divisions in developing and implementing safety management systems, and front-line workers ensuring that safety concerns are reported without fear of retribution, enhancing overall safety performance.

Regarding sustainability, the EA aims to integrate the different challenges and drivers to achieve sustainability goals. Hence, focusing on strategic motivation after analyzing the causal relationships provided the enterprise's strategic perspective. Since the actual project's sustainability aspect depends on locality, regulation, operational setup, and community perception, the enterprise strategy is meant to serve as an agnostic roadmap that must be detailed and customized for a specific operation. For the informed passenger goal, the strategic taxonomy view was used to highlight the value streams and capabilities needed to achieve the desired effect. A use case diagram from SysML was added to this concern to represent how an integrated platform can support eco-efficiency awareness and be part of MaaS solutions.

The EA views offer different representations of UAM SoS. Each view frames a different perspective to communicate a message to a stakeholder. For each socio-technical concern explored in the research, specific stakeholders are also decision-makers and must engage differently. Using the UAF grid to present ideas best and reach the right stakeholders is part of the modeling conceptualization process. It is a result of the objectives defined in the solution space. In this sense, the research accomplishes its objective of communicating with multiple stakeholders and supporting decision-makers by developing perspectives and viewpoints that can effectively engage and address the interests of various stakeholders.

Finally, APPENDIX A elaborates on an alternative perspective using the UAF with a distinct purpose. This appendix includes a paper titled “Pilot’s roles in the Urban Air Mobility: individual capabilities for safety and security enterprise concerns” (Hoffmann et al., 2024c). This paper adopts a Human Systems Integration (HSI) approach to investigate the pilot’s roles and capabilities within the UAM ecosystem, contrasting the broader SoS-level exploration. The study focuses on the pilot as an individual performer, expected to control the vehicle and interact with multiple

systems and operators in UAM's early phases. By employing UAF, the paper discerns the pilot's strategic resource exchanges, responsibilities, and critical capabilities for situational awareness, security, and safety culture. The findings from the socio-technical concerns presented in Chapters 4 to 6 (Situation Awareness, Security, and Safety Culture) are applied from the pilot's perspective. This approach also underscores the value of EA visualization in providing different perspectives and fostering stakeholder engagement. The full paper and its elaboration are presented in APPENDIX A.

8.2 Summary of Results and Answers to Research Questions

The research questions guided the investigation of the socio-technical challenges in UAM, and the results provided findings that answered such questions. Following is a summary of the research answers that were elaborated and presented across previous Chapters:

RQ1→ What identifies the problem space for situation awareness, security, safety culture, and sustainability in UAM, and how can the solution space meet the diverse interests of different stakeholders?

For SA, the problem includes high operator workload and the need for better technology integration and training. The solution enhances communication systems, user-friendly interfaces, automated monitoring, and real-time data processing to support operators. Security concerns focus on vulnerabilities related to physical and cyber threats. The solution space includes advanced threat detection, comprehensive surveillance, robust encryption, and scalable, resilient systems that integrate seamlessly with daily operations. Safety culture in UAM emphasizes creating a just culture where incidents are reported without fear of blame. The problem space involves balancing regulatory compliance, business interests, and operational processes. The solution space focuses on building trust, fostering ownership, and ensuring fair assessment of safety events, strongly emphasizing front-line workers' perspectives. Sustainability in UAM requires minimizing environmental impact while ensuring social and economic viability. The problem space includes reducing emissions, managing noise pollution, and ensuring equitable access to transportation. The solution space involves adopting sustainable technologies, optimizing resource use, and promoting public acceptance through stakeholder collaboration and continuous monitoring of sustainability

performance. Overall, the solution space for UAM must address diverse stakeholder interests by integrating advanced technologies, improving human-system interactions, and fostering organizational processes that enhance situational awareness, security, safety culture, and sustainability. More details of problem and solution space were provided in Sections 4.2 and 4.3 for SA, Sections 5.2 and 5.3 for Security, Sections 6.2 and 6.3 for Safety Culture, and Sections 7.2 and 7.3 for Sustainability.

RQ2→ How does Situation Awareness behave as a collective cognitive process distributed at different UAM ecosystem levels, and how does it compromise the UAM safe operation?

SA in UAM operates as a collective cognitive process distributed across various levels of the UAM ecosystem, including physical and technological environments, organizational roles, operational flows, and human factors. This distributed nature of SA means it depends not solely on individual operators like pilots but also on the interactions and coordination among different organizational entities and roles. Knowledge, skills, and aptitude define SA competence and are essential for various UAM SoS organizational roles. For instance, pilots require SA to perform flights safely. However, other organizational posts, such as flight schedulers, training managers, and health managers, also contribute to maintaining and enhancing SA by managing pilot schedules, credentials, training, and health conditions. The process of acquiring SA is complex and encounters numerous challenges, such as high operator workload, effective communication, and integration of new technologies. These challenges are addressed through the Architecture Enablement process, which aims to develop and maintain the necessary capabilities, services, and resources to support SA. More details of SA results are presented in Sections 4.4 and 4.5.

RQ3→ Which security controls and processes are necessary for the UAM ecosystem to manage cyber, physical, and personnel security risks?

Security controls and processes must address a comprehensive range of threats and vulnerabilities, including cyber, physical, and personnel security risks in the UAM ecosystem. The security architecture involves implementing measures aligned with established security controls, tactics, techniques, procedures, and adherence to relevant security policies. Key elements include cybersecurity controls, physical security controls, personnel security controls, and operational security controls. In cybersecurity, network protection safeguards communication networks from cyber threats, vehicle system protection concerning vehicle interfaces through digital resource

layers, and operational integrity checks to prevent malicious intrusions. In the physical aspect, the integrity of vehicles on the ground is ensured through systematic checks before authorization for operation. This involves confirming vehicle and embark integrity and monitoring ground operations.

Moreover, access control involves managing and controlling access to vehicles and maintenance areas to prevent unauthorized entry and potential sabotage. This includes monitoring and controlling passenger embarkation processes to ensure safety without causing significant delays. Personnel and operational security include continuous Monitoring and Reporting, ensuring ongoing surveillance and reporting of potential threats and anomalies to maintain situational awareness and enable prompt responses. Integrating these controls and processes creates a robust security framework capable of addressing the diverse risks in the UAM SoS. The security architecture must harmonize technological systems, human factors, and organizational processes to achieve a cohesive and resilient security posture. Section 5.5 provided more details on security controls.

RQ4→ How can the UAM ecosystem develop and maintain a safety culture that fosters trust and accountability among front-line workers?

Several key steps are necessary to develop and maintain a safety culture that fosters trust and accountability among front-line workers in the UAM ecosystem. First, it is essential to establish comprehensive training programs and safety protocols that bridge the gap between the air and ground transportation sectors. This includes educating ground transportation workers and service providers about aviation safety standards, emergency procedures, and risk mitigation strategies. Collaborative training initiatives and cross-industry knowledge sharing can align safety practices across all aspects of UAM operations, ensuring a harmonized approach to safety management. Creating an environment that encourages learning and continuous improvement in safety performance is crucial. It involves implementing a just culture where front-line workers feel safe reporting incidents without fear of blame or reprisal. Such a culture supports the collection and analysis of safety data, fostering an atmosphere of trust and accountability. Establishing a UAM Safety Committee with representatives from all relevant organizations, including front-line workers, can ensure that diverse perspectives are considered in safety discussions. This committee can oversee the development and implementation of safety policies, promote a consensus on

acceptable behaviors, and handle higher-level safety issues collectively. Clear roles and responsibilities for all personnel involved in UAM operations must be defined and communicated effectively. It is essential to delineate the responsibilities of front-line workers, management, and regulatory authorities to ensure everyone understands their part in maintaining safety. Building trust involves establishing accountability and ownership of safety processes among all stakeholders. Front-line workers must feel empowered to report safety incidents, knowing their reports will be fairly assessed and acted upon. This requires transparent communication and consistent actions from management to build confidence in the safety system. Lastly, encouraging collaboration between aviation and ground transportation sectors can help harmonize safety practices and standards. By integrating the expertise of both sectors, the UAM ecosystem can develop robust safety protocols that address the unique challenges of urban air mobility. In addition, regular feedback also reinforces the importance of safety practices and demonstrates management's commitment to safety. More information on safety culture was presented in Sections 6.4 and 6.5.

RQ5→ What are the social, economic, and environmental impacts of integrating UAM into urban environments, and to what extent can UAM operation be eco-efficient for passenger transportation?

Integrating UAM into urban environments presents various social, economic, and environmental impacts. Socially, UAM affects local communities through increased noise, privacy concerns, and visual pollution due to the operation of eVTOL vehicles. These impacts can influence public perception and acceptance, potentially leading to restrictions on UAM operations if not managed carefully. Economically, UAM's viability hinges on its ability to be profitable by offering attractive routes for passengers while improving mobility solutions with minimum impact. Ensuring equitable access and service for all economic groups is crucial for widespread adoption and long-term success. Environmentally, UAM's eco-efficiency depends on factors such as greenhouse gas (GHG) emissions, energy consumption from the power grid, and the overall carbon footprint of the vehicle's life cycle, including battery disposal and recyclability. The eco-efficiency of UAM operations can be enhanced by leveraging renewable energy sources, optimizing vertiport locations and routes to reduce emissions, and incorporating sustainable practices throughout the vehicle's life cycle. However, increased adoption of UAM might lead to higher electrical power

consumption, potentially increasing GHG emissions if the power grid relies on non-renewable sources. The proximity of vertiports to users and accessibility are critical operational factors influencing UAM adoption, as convenient access encourages frequent use. Section 7.4 presented more information about UAM eco-efficiency.

RQ6→ How can different UAM ecosystem viewpoints and perspectives inform decision-makers, and what recommendations can be provided to balance diverse stakeholder interests while ensuring safety, security, and eco-efficiency?

Different EA perspectives were explored according to the objectives of each viewpoint. The solution drove a specific objective for each concern, and the model effort was planned to address critical aspects of the solution. The EA views were chosen using the UAF grid according to the idea or information planned to convey. There are multiple stakeholders, and even when they are present in more than one concern, or all of them, the type of communication is adapted using architecture visualization. The objectives and views used were explained above in 8.1. Recommendations to balance diverse stakeholder interests while ensuring safety, security, and eco-efficiency include: a) develop SA as a collective cognitive process involving multiple enterprise levels; and ensure effective SA by focusing on personal skills, technology, workload management, team communication, and interactions among human and nonhuman agents; b) employ a systemic approach to security, incorporating physical, human, and organizational dimensions; define security processes, risk taxonomies, and mitigation strategies using UAF security viewpoints; and develop security measures that enable the organization to monitor, respond, learn, and anticipate threats; c) establish a just culture within UAM operations to foster a learning-oriented environment and enhance safety performance; build trust through active participation in safety discussions and fair enforcement of safety policies; use UAF organizational viewpoints to explore roles, responsibilities, and relationships necessary for a just culture; and establish a unified safety committee to facilitate communication and learning within the UAM community; d) evaluate the environmental and social impacts of UAM operations and develop strategies to address sustainability challenges; focus on energy efficiency, the source of electricity, and the life cycle impacts of eVTOL aircraft; map capabilities to support eco-efficiency and user preferences, and integrate these into MaaS solutions; and use strategic motivation and causal relationships to provide an enterprise perspective that can be customized for specific locations.

8.3 Summary of Research Contributions

This thesis significantly advances the understanding of UAM by providing comprehensive enterprise architecture views that address multiple perspectives and research objectives. The contributions of this research were categorized into three main areas (as defined in Section 1.7).

First, the research extensively analyzed the UAM ecosystem, integrating various agents, including technological, regulatory, environmental, and human aspects. This systemic approach ensured that all socio-technical concerns were thoroughly examined, offering a complete picture of the UAM ecosystem's complexities. Next, each socio-technical concern was meticulously analyzed for its operational, environmental, cultural, and social impacts. The human integration aspect was central to the research, covering human limitations in situation awareness, operator engagement in security processes, organizational culture in safety management, and the societal benefits of sustainable UAM practices. Based on these insights, the study proposed strategies and recommendations to enhance safety, security, and sustainability within UAM operations. Lastly, the research developed views and perspectives to facilitate meaningful engagement with diverse stakeholders. This approach fostered a more inclusive and informed discourse on UAM, addressing the interests of various groups such as regulatory bodies, operators, and the community.

The research contributions are also classified into pragmatic and well-defined outcomes, each addressing specific research questions. A summary of the research answers is provided in Section 8.2. Furthermore, academic papers and articles were published in scientific journals, an international symposium, and conference as listed in Section 1.7.

Overall, the thesis advances the systems engineering field by demonstrating the effective use of the UAF to integrate diverse socio-technical concerns into complex SoS. This study highlights three key systems engineering aspects: System of System Engineering (SoSE), Human Systems Integration, and Architectural Decision Making (as in complex systems decision making). The research demonstrates a structured approach to integrating various socio-technical concerns within the UAM ecosystem by employing UAF and enterprise architecture methodologies. This comprehensive integration is a notable advancement, showcasing how systems engineering can address complex, multi-dimensional challenges by collectively considering technological, regulatory, environmental, and human factors. The research emphasizes the importance of

developing diverse viewpoints and perspectives tailored to different stakeholder groups. This approach enhances communication and engagement, ensuring that all parties, from regulatory bodies to operators and the community, are informed and involved in decision-making. This method sets a new standard for stakeholder interaction in systems engineering projects, promoting inclusivity and informed discourse. Finally, the detailed analysis of operational, environmental, cultural, and social impacts across various socio-technical concerns provides a robust framework for impact assessment in systems engineering. By placing human integration at the core and thoroughly examining human limitations, organizational culture, and societal benefits, the research advances methodologies for assessing and addressing the human element in complex systems.

8.4 Recommendations for Future Work

Building on the current research, several recommendations for future work can enhance the understanding and implementation of UAM systems. Firstly, detailing the structure and behavior of organizations and operational procedures within the UAM ecosystem is crucial. The UAF can be utilized to map out these elements, focusing on the viewpoint *Actual Resources* to represent real-world operations accurately. This approach can help evaluate pilot and controller workloads through detailed task analysis during different flight phases and scenarios. Future work can evaluate whether incorporating tactile displays and exploring parallel processing capabilities will aid in reducing cognitive overload and improving situational awareness.

Secondly, developing robust security measures must go beyond physical and human resources, including doctrine, organization, training, materials, leadership, personnel, and facilities. Future work should explore security performance metrics, define security enclaves' structure and connectivity, and specify technological resources. By leveraging UAF's capability to manage complex data through tables, diagrams, hierarchy views, matrices, and relation maps, researchers can better understand the interconnections within the UAM ecosystem.

Thirdly, a case study involving actual transportation providers, local authorities, and vertiport operators can provide valuable insights. This approach will help mature discussions, promote benchmark knowledge, and address challenges highlighted in the unified safety committee proposal. Regulators should develop transparent and standardized reporting and investigation

procedures for incidents and near-misses, fostering increased collaboration among regulatory bodies, UAM operators, vehicle manufacturers, and OEMs. Particular attention should be given to integrating small organizations and subcontractors into the ecosystem's safety culture.

Regarding the sustainability strategy, future work can investigate a case study involving actual location to evaluate sustainability parameters. Advancing the discussion of environmental and social impact can provide more insights and enhance the value and public acceptance of UAM. Additional research could elaborate on UAM integration with MaaS platforms at different levels. UAM transportation booking, eco-efficiency data, or public feedback about urban infrastructure, such as noise and traffic disruptions, can be investigated. In addition, exploring use cases that add value to society is recommended, such as emergency evacuation, disaster response, and medical goods delivery.

Future research should continue to explore the integration of advanced technologies, improve human-system interactions, and develop organizational processes that enhance SA, security, safety culture, and sustainability. Finally, implementing the proposed UAM architecture should follow the design definition process outlined in ISO/IEC/IEEE 15288 (2023) and consider the design of SoS processes defined in ISO/IEC/IEEE 21840 (2019c).

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APPENDIX A

This appendix presents the paper submitted and accepted at the 3rd Human System Integration International Conference authored by R. Hoffmann, H. Nishimura, and R. Calhau (Hoffmann et al., 2024c). This work used the findings of the socio-technical concerns presented in Chapters 4 to 6 (Situation Awareness, Security, and Safety Culture) and applied them to a different perspective, the UAM pilot as an individual performer. This paper's elaboration and results support the argument that EA visualization can provide different perspectives and foster stakeholder engagement. The full paper is presented below.

Pilot's roles in the Urban Air Mobility: individual capabilities for safety and security enterprise concerns

Abstract. Safety and security are cross-cutting concerns of the Urban Air Mobility (UAM) ecosystem and critical for its future operations. Addressing those concerns requires an integrated approach, including stakeholders, people, processes, systems, and capabilities. While previous research has explored safety and security at the System-of-Systems (SoS) level, this paper embraces the Human Systems Integration (HSI) approach to investigate the pilot as an individual performer. In UAM's early phases, the pilot is expected to be on board, controlling the vehicle and interacting with multiple systems and operators. This study employs the Unified Architecture Framework (UAF) to discern the pilot's roles and capabilities that are consistent with the UAM as an enterprise. Results include views combining strategic resource exchanges and responsibilities associated with each pilot role. Lastly, we analyze the relationships among roles and capabilities and discuss the pilot's critical capabilities for addressing situation awareness, security, and safety culture concerns. Leveraging the HSI approach allows for understanding the pilot's perspective, facilitating informed decision-making, and fostering a culture of safety and security throughout the UAM ecosystem.

A.1 Introduction

The UAM concept of operations (ConOps) envisions an ecosystem involving several key

components and stakeholders, all driven by a shared vision of transforming urban transportation. The UAM concept includes electric Vertical and Takeoff Landing (eVTOL) vehicles designed for short-distance urban travel, dedicated infrastructure such as vertiports, advanced technology for air traffic management and communication, regulatory frameworks, and integration platforms seamlessly coordinating different elements (FAA, 2023; Eve, 2022). Safety and security are fundamental considerations in UAM operations due to the challenges of integrating aerial transportation into densely populated urban environments (FAA, 2023; Bauranov & Rakas, 2021). UAM vehicles' proximity to the ground and other airspace users, coupled with the inherently dynamic nature of urban landscapes, necessitates robust safety measures to prevent accidents and ensure the well-being of passengers and ground occupants. Concurrently, the security of UAM operations extends to physical and cyber threats, as the increasing reliance on digital systems introduces potential vulnerabilities.

Addressing systemic concerns such as safety can benefit from a combination of top-down investigation and bottom-up analysis. This dual approach allows for a comprehensive understanding of the system by integrating high-level strategic insights with detailed, ground-level observations (Reason, 1997; Dekker, 2014; Leverson, 2012). Systems engineering, human factors, and organizational safety often emphasize the importance of both perspectives to achieve a holistic view of safety and operational effectiveness. The integration of human operational aspects in the UAM ecosystem is crucial for ensuring safety and security, particularly during the initial piloted phases. Understanding the pilot's roles and the challenges of single-pilot operations (SPO) is fundamental to developing task analysis and safety standards within the UAM ecosystem.

Prior research (Hoffmann et al., 2023a; Hoffmann et al., 2023b; Hoffmann et al., 2024) has adopted a holistic view to explore safety and security in UAM's future operations. The approach considered the UAM system-of-systems (SoS) and evaluated safety and security as cross-cutting concerns of the UAM architecture. Using enterprise architecture modeling and the Unified Architecture Framework (UAF), the investigation of safety and security was divided into three viewpoints: Situation Awareness (Hoffmann et al., 2023a), System Security (Hoffmann et al., 2023b), and Safety Culture (Hoffmann et al., 2024). Results included enterprise strategies, capabilities, functions, personnel structure, and operational considerations. Findings were provided from the

system-of-system perspective, or in other words, from the enterprise level.

This paper shifts the perspective and focus on the UAM pilot as an individual operational performance. The objective is to investigate how the pilot, as a component of the UAM ecosystem, behaves according to safety and security enterprise concerns. Using UAF to model UAM views, this study presents the pilot's perspectives, emphasizing its roles and capabilities. The rest of the paper is organized as follows: We present the safety and security challenges considering the UAM operational context and the human system's integration aspects concerning the pilot. Next, we briefly outline the study method and position it concerning past research. Then, we define the pilot's role for each enterprise concern and present dedicated views with individual capabilities, responsibilities, and resource exchanges. Lastly, we analyze the relationships among roles and capabilities, discuss the insights provided by the model, and present our final remarks.

A.2 Background

The human operational aspects within the UAM ecosystem play a vital role in the safety and security concerns. Human Systems Integration (HSI) gains even greater significance, particularly in the initial phases of UAM operation when the vehicle is piloted and human control manages traffic (FAA, 2023). Given the complex and dynamic nature of the environment in which pilots and controllers operate, effective decision-making processes are critical for ensuring safety in UAM performance. Safe UAM operations for passenger transportation involve two main sets of operational factors to consider: (1) those related to operations within shared airspace (Air Operator) and (2) those concerning personnel, including pilots, air traffic controllers, and maintenance staff (FAA, 1978). These factors present additional challenges due to UAM operations occurring at relatively low altitudes and within densely populated urban areas.

The ability of humans to make informed decisions relies on a solid understanding of the environment and the capability to steer clear of unsafe scenarios. Situation Awareness (SA) is defined as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and a projection of their status in the near future” (Endsley, 1995, p.36). In this context, a user-centric approach is indispensable to design systems conducive

to supporting SA, requiring the organization and operation of the UAM ecosystem to align with how users pro-cess information and make decisions. In Hoffmann et al., 2023a, we examined the SA behavior in the UAM SoS, showing it as a collective cognitive process distributed at different enterprise levels. Findings include UAF views from strategic, operational, personnel, and service aspects, combining systems, people, and processes committed to achieving SA.

The organizational and human operational aspects of the UAM ecosystem are also relevant for security considerations. The process of avoiding, withstanding, and recovering is not limited to systems and technology (NIST, 2021). Ensuring resilience involves not just systems and technology but also the people and processes within the system (Null et al., 2019). Personnel involved in UAM operations are susceptible to malicious events and play a vital role in maintaining security and resilience. Security events require informed decision-making and, consequently, a good strategy to achieve and maintain situation awareness. Therefore, designing systems and processes that support resilient performance must consider human factors (Holbrook et al., 2020). In the UAM context, a comprehensive work was presented by Hoffmann et al., 2023b proposing UAF views for security strategy, risk taxonomy, and security structure. Findings considered the UAM SoS level, including security controls and mitigations for different scenarios and vulnerabilities within the ecosystem.

Furthermore, the novelty and complexity of UAM services add considerations for providers and operators. Establishing a safety culture encouraging open communication and learning can pave the way for a sustainable operation. Managing safety and fostering learning is a challenge that involves organizational culture. The previous work of Hoffmann et al., 2024, revealed the challenges of implementing a healthy safety culture in the UAM ecosystem. The approach considered different enter-prise levels and highlighted the importance of the front-line worker's role in ensuring safe and efficient UAM operations.

Safe UAM operations depend on the complexity of multiple systems integration, operational procedures, and operators' capabilities. The pilot is a critical resource in the earlier phases of UAM and is expected to be on board the vehicle with complete operational control (FAA, 2023). Hence, discussing human aspects and operational tasks from the pilot's perspective is crucial. In this sense,

existing literature has explored Single Pilot Operations (SPO) with great concern (Wolter & Gore, 2015; Ebrecht, 2023; Li, Wang, Ding & Wang, 2022; Li et al., 2023). Although there are contributions considering single crew in commercial aircraft (Wolter & Gore, 2015; Zin et al., 2024), SPO is still not a consensus due to safety concerns by the aviation community. UAM operational procedures are still under discussion, and the pilot's task is unknown to this date. Understanding the UAM pilot's roles, responsibilities, and capabilities is key to discussing task analysis and safety standards (Edwards, Verma, and Keeler, 2019).

A.3. Method

The results presented in the paper are based on previous research findings that adopted the Enterprise Architecture (EA) methodology (ISO, 2019). Past work has generated enterprise, UAM SoS-level views to address safety and security concerns systematically. Enterprise views were defined using architecture conceptualization and elaboration processes (ISO, 2019). After investigating the problem space for UAM Situation Awareness (Hoffmann et al., 2023a), UAM Security Hoffmann et al., 2023b), and UAM Safety Culture (Hoffmann et al., 2024), the solution spaces were defined using UAM constituent systems and stakeholders. In the current work, the pilot's perspective is extracted from the cross-cutting concerns and defined as an individual performer. EA methodology is also applied, adding the human system's integration perspective for the UAM pilot.

The architecture modeling used the UAF version 1.2 (OMG, 2021). Elements, relationships, and views follow the UAF language and metamodel (OMG, 2022; ISO, 2022). The model elements and views were validated through consistency checks, traceability (with the enterprise-level elements), and discussions following the architecture evaluation process (ISO, 2019). The study aims to define and specify roles, capabilities, responsibilities, and critical resource exchange for the UAM pilot while being consistent with the UAM safety and security enterprise concerns. The architecture concerns covered in this research are Situation Awareness as a collective competence, Security, including physical and logical aspects, and Safety Culture, fostering a learning environment within the UAM organization.

A.4 Pilot as a Resource of the Enterprise

The UAM, as an enterprise, has concerns that affect the whole architecture. Safety and security are cross-cutting concerns that must be addressed from different architectural perspectives. UAF has a set of predefined viewpoints (ISO, 2022, p. 14) according to the key stakeholders and their perspectives and concerns. For instance, it is possible to explore organizational resource types in the *Personnel* aspect, including the human capabilities of organizations, teams, and people. From the *Operational* viewpoint, the logical architecture can describe operational behavior, requirements, and structures. The other important element in the UAF grid (ISO, 2022, p. 13) is called *aspects* (also known as model kinds). Different *aspects* are used to describe view specifications for different purposes. The *Motivation* aspect can capture the high-level strategy of the enterprise and is used to frame enterprise goals, opportunities, and challenges that drive different views of architecture.

While the *Strategic* viewpoint defines capabilities for the enterprise, including its taxonomy, composition, dependencies, and evolution, the resource viewpoint focuses on capability configuration, which is responsible for implementing the operational requirements. The combination of operational tasks, resource types, and human capabilities must be coherent and consistent with safety and security goals. Different resource types (systems, organizations, artifacts, natural) can realize different functions by exhibiting different capabilities. Thus, understanding how each resource engages in the enterprise is critical for determining the desired effect of the enterprise's capabilities and goals. Past research has proposed enterprise views for SA, Security, and Safety Culture. Figure A.8 outlines the pilot's perspective as an enterprise resource and how it was framed concerning previous work.

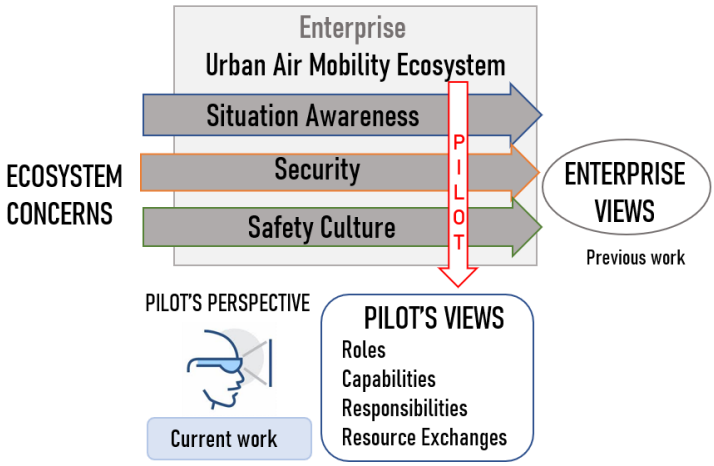

Figure A.8. Pilot's perspective as an enterprise resource

The *pilot* can be defined as a <<ResourcePerformer>> of the UAM enterprise and exhibits a *resource* kind of capability. It means that the *Pilot* is a resource that performs functions for the enterprise and implements operational activities defined in the operational architecture. Likewise, <<ResourceRole>> elements are defined as part of a greater resource performer. One resource may perform different resource roles, and different resource performers may perform one resource role. At a more specific level, the *pilot* can also be defined as <<Post>>, which is a type of <<OrganizationalPerformer>> (specific classifier of resource performer). The element *post* is part of the personnel viewpoint and exhibits *personnel* kind of capabilities. This distinction between kinds of capabilities is important because it relates to the individual ability to fulfill the resource capability. In the following sections, we will explore the roles and individual capabilities required of the pilot.

Pilot's roles

The strategy for addressing three enterprise concerns was defining three roles for the pilot. Figure A.9 shows the overview of the pilot's roles and main relationships and definitions in the resource, service, and operational architectures. The <<Post>> *Pilot in Command* presents three <<ResourceRole>> elements: (i) *Decision Maker*, (ii) *Safety Agent*, and (iii) *Security Agent* (in the center of the diagram). As depicted, the pilot is commanded by the *Pilot Manager*, another post of the same organization *UAM Operator* (at the top left). The *UAM Operator* implements the <<Service>> *UAM Transportation*, a high-level definition from the service architecture. The

operational architecture is summarized in the <<OperationalActivity>> *Fly Vehicle*, implemented by the pilot. Still on the left side, there are three main functions performed by the corresponding pilot's roles: *Make safe decisions*, *Report events*, and *Protect flight*. At the bottom of the diagram are the primary system's interactions performed by the pilot: Operate the *UAM Vehicle*, and input and follow up events on the *Reporting System*.

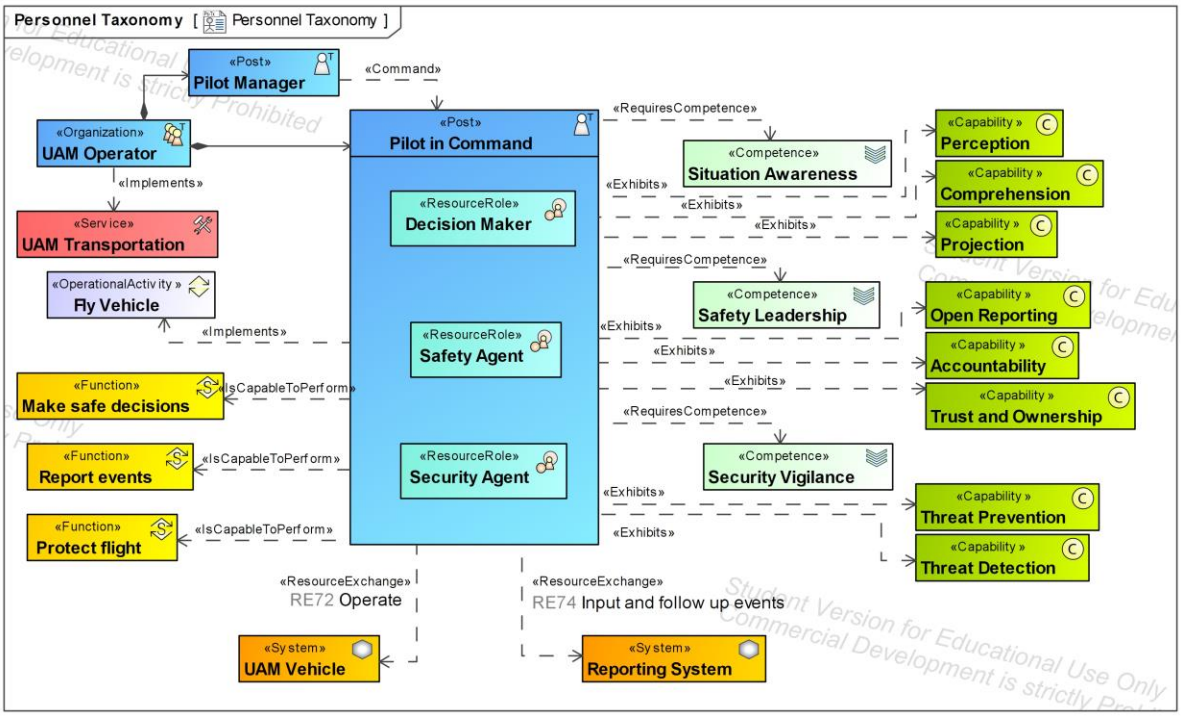

Figure A.9. Overview of Pilot's roles

On the right side of the diagram, there are three sets of required competence and capabilities exhibited by the pilot (each set corresponds to one specific role). In UAF, competence is defined as a specific set of abilities defined by knowledge, skills, and aptitude; capability represents the enterprise's ability to achieve a desired effect. In the *Pilot Resource Taxonomy* view (diagram above), the pilot exhibits capabilities defined by the resource architecture's specification (resource kind of capability). In other words, the pilot is being represented as a generic resource for the enterprise. Therefore, the pilot, in the role of a *Decision Maker*, is a resource that requires competence in *Situation Awareness* and should exhibit the capability of *Perception*, *Comprehension*, and *Projection*. When the role is *Safety Agent*, the competence required is *Safety Leadership*, and capabilities such as *Open Reporting*, *Accountability*, and *Trust and Ownership* are exhibited. Likewise, when the pilot is a *Security Agent*, the competence required is *Security*

Vigilance with *Threat Prevention* and *Threat Detection* capabilities. The scheme in Figure A.9 is a simplification of the taxonomy regarding roles, competencies, and capabilities. Remarkably, the roles and capabilities are not independent or disconnected from each other. For instance, being a safety agent requires perceiving the environment (*Perception* capability), or, developing security vigilance (competence) involves personal accountability and open communication. Competencies and capabilities in this view were defined at the enterprise level (from a previous study). The objective of Figure A.9 is to summarize the pilot's roles, main competencies, and capabilities that are considered when addressing the three enterprises' concerns. Detailed capabilities, at the individual level, are defined in the next section.

A.5 Pilot's capabilities, responsibilities, and exchanges

In this section, we will focus on each pilot's role. The diagrams below present the necessary individual capabilities, responsibilities, and exchanges for when the pilot performs its roles.

Pilot as a *Decision Maker*. When *Situation Awareness* is the problem to be addressed by the UAM ecosystem, the pilot must undertake the role of *Decision Maker*. Notably, SA is a competence required in other pilot's roles. The pilot makes decisions in multiple roles, in different scenarios, and for different purposes. This paper focuses on the SA problem during vehicle operation (pre-, post, and during flight). Thus, a definition notation was added (linked to the <<ResourceRole>> element) to make clear the operational frame of the decision-maker role. The ability to perceive, understand, and effectively respond to any event while controlling the vehicle makes the pilot a critical resource for the operation (Hoffmann et al., 2023a). The list of responsibilities related to the role of the *Decision Maker* (while operating the vehicle) is presented in Figure A.10 (bottom left). *Vehicle Health Status Monitoring*, *External Communication*, and *Stress Level Management* are some examples of the pilot's duties for maintaining a safe level of situation awareness. The necessary resource exchanges between the pilot, system (UAM vehicle), and other posts are on the top right of the diagram. Because shared information is key for situation awareness, reporting and communicating with other agents of the ecosystem is highly expected and required, as illustrated. Another crucial aspect to be monitored and assessed is the technical and personal condition of the pilot, also represented by resource exchanges and responsibilities.

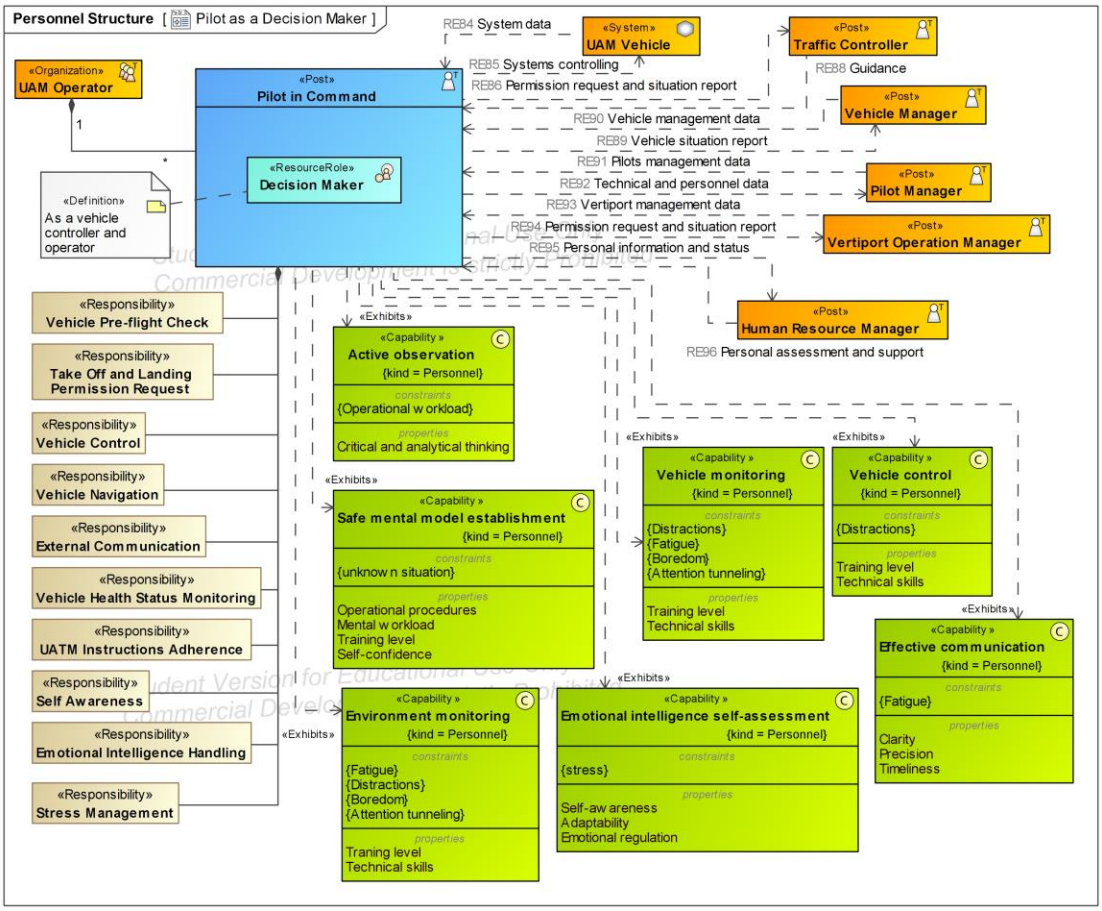

Figure A.10. Pilot as a Decision Maker (during vehicle operation)

In terms of capabilities, preparing, developing, and maintaining situation awareness requires a complex set of individual abilities that rely on training, practice, and also human aspects (e.g., personal conditions, attitudes, knowledge, skills, traits, etc.). As shown in Figure A.10 (bottom center/right), these human aspects that impact individual capabilities are represented using properties and constraints. As illustrated, properties support the capability strength, and, in the opposite direction, constraints impact them negatively. For instance, the pilot's ability to monitor the environment (capability *Environment monitoring* on the center bottom) depends on training and technical skills (defined as properties). Nevertheless, fatigue, distractions, boredom, and attention tunneling can impair the pilot's perception (defined as constraints). The same applies to the *Monitor Vehicle* capability (in the center). Moreover, *Active observation* (below pilot in command's box) requires analytical and critical thinking, which is fundamental for projecting scenarios (important ability of situation awareness). Operational workload can jeopardize the ability to observe and make sense of any possible threat. Emotional aspects, mental model, and

communication are equally explored with their properties and constraints.

Pilot as a *Security Agent*. The second role of the pilot concerns the security viewpoint. As a security agent, the pilot's role is to protect the flight by performing security processes before the flight (prevention) and adapting the operation if any threat occurs during the flight. Monitoring and reporting are equally significant in this role (as in the vehicle operator role). Figure A.11 depicts the responsibilities of the pilot with security matters. *Vehicle Pre-flight Check, Vehicle Integrity Verification, Passenger Screening Check,* and *Flight Plan Approval* are some activities charged to the pilot's security agent role. On the top right is the security process that the pilot performs and security enclaves used to exchange information. In addition, exchanges with posts like *Vertiport Security Access Manager, Vehicle Security Access Manager, Ground Guard,* and *Traffic Controller* are presented due to their relevance to protecting the operation. More details of those exchanges are in the diagram below.

The capabilities of the security agent's role, *Active observation, Vehicle monitoring,* and *Safe mental model establishment* are the same as exhibited by the decision maker's role. *Open reporting* (capability on the bottom right) is the ability to report events on time while assessing their criticality. Ethical lapse and complacency (constraints) can affect this capability in time or misjudgment. The specific capability for this role is the *Security process commitment* (on the center right). As a security agent, the pilot must be committed to protecting the vehicle and flight. This is represented by the *Security process commitment* capability in Figure A.11 (on the center right). In the case of this capability, field experience (for enhancing judgment skills) and unwavering attitude are represented as its properties, which are crucial to preventing any security threat. In addition, complacency (constraint) can affect security's commitment capability when the pilot becomes too experienced or familiar with his/her security processes and starts to develop an overly relaxed attitude toward tasks. Lastly, ethics also builds the individual's commitment to security matters. Ethical lapse is defined as a constraint because it can jeopardize the operation's security.

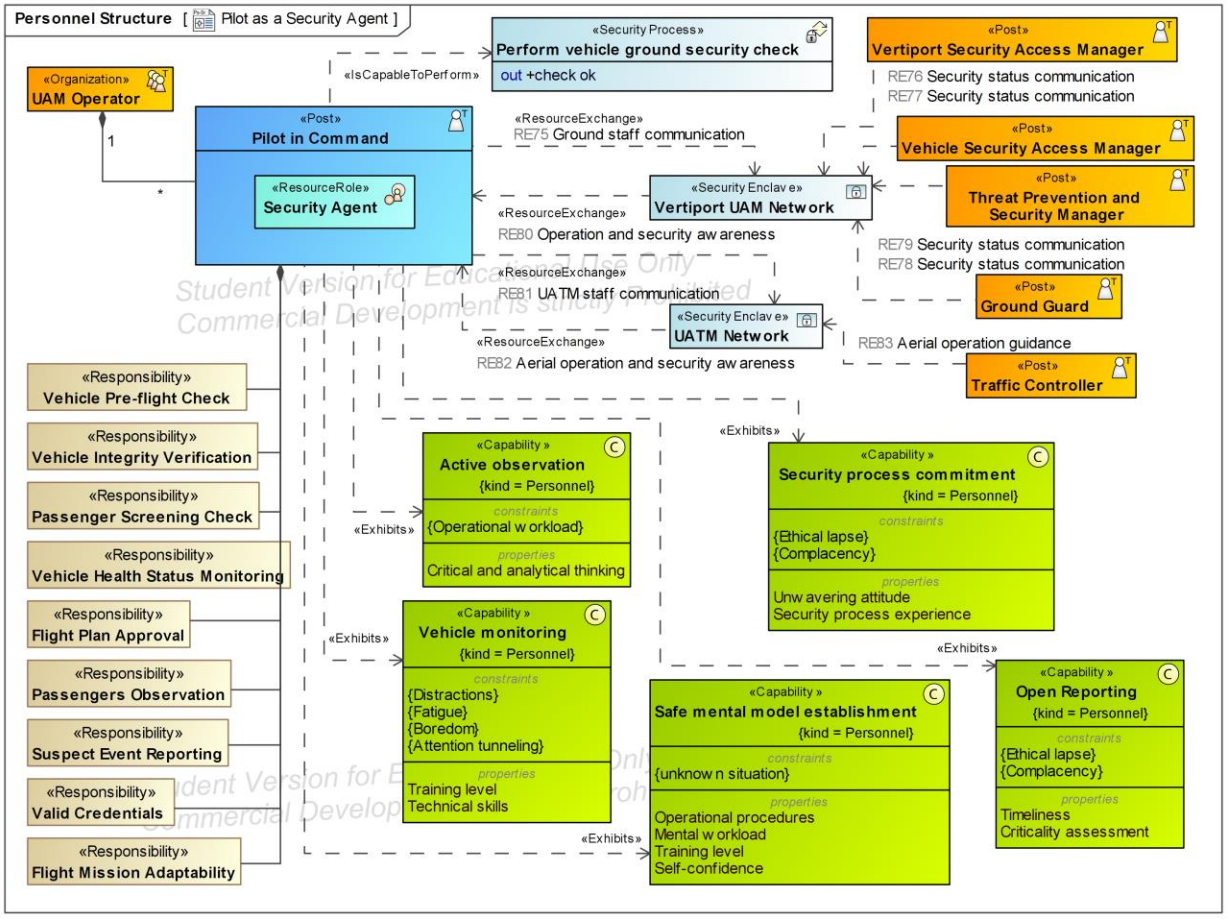

Figure A.11. Pilot as a Security Agent

Pilot as a *Safety Agent*. The pilot is a safety agent, the third role of the pilot, and an essential piece of the UAM safety culture. In this concern, trust and accountability are the leading aspects of developing relationships and processes for a healthy learning culture. Reporting is the main verb in terms of actions and responsibilities. *Event Reporting*, *Event Assessment Support*, *Resource* and *Workload Inadequacy Reporting* are responsibilities in Figure A.12. Likewise, being part of the safety guidelines and developing an ownership sense is crucial for accountability. In this role, the pilot is a *Front-Line staff* (<<Post>> defined from a safety culture viewpoint). Therefore, the pilot carries (<<import>> relationship in the center) the resource exchanges defined for a *front-line staff*. It means that operational perspectives, feedback, and co-participation are required for the pilot. More exchanges are detailed on the right side.

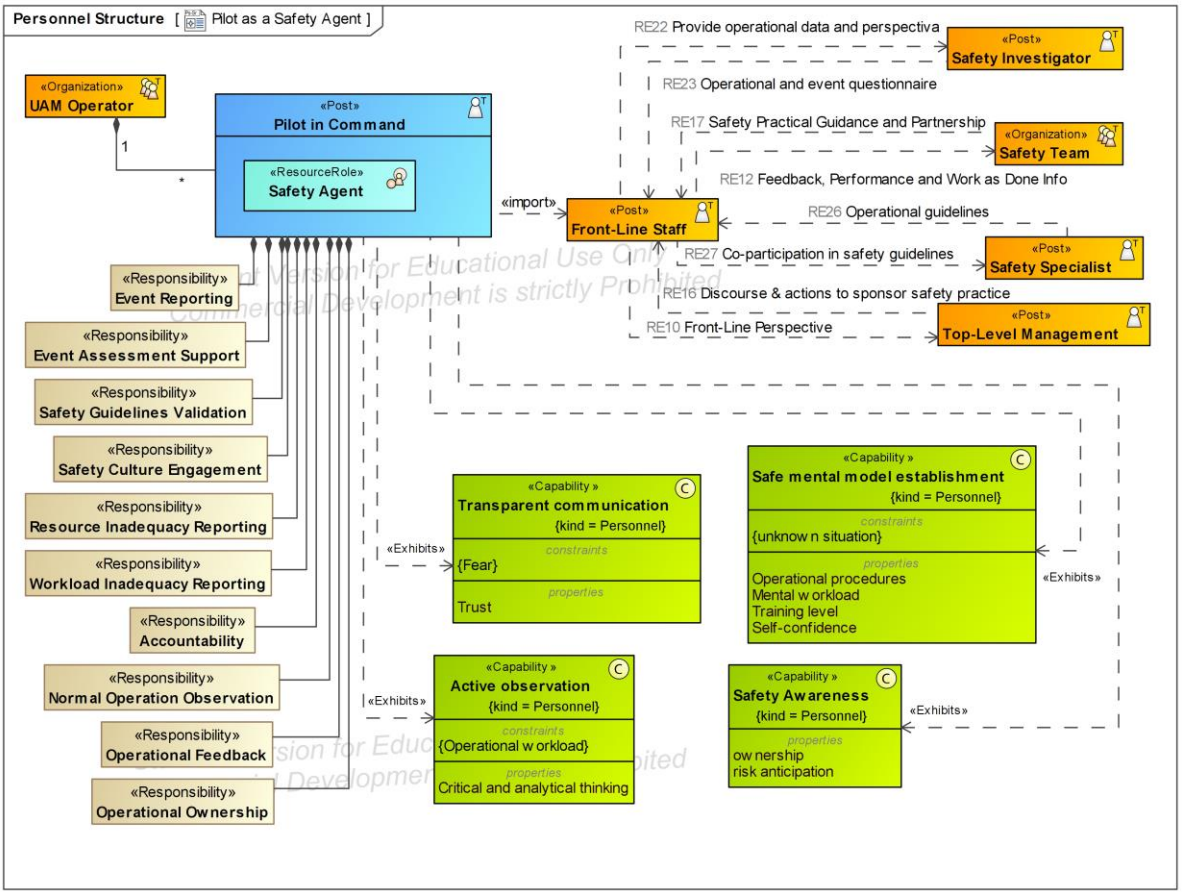

Figure A.12. Pilot as a Safety Agent

Active observation and *Safe mental model establishment* are shared capabilities, already described above. *Transparent communication* is the capability that allows the organization to know about events and learn from possible mistakes. Transparent communication is only possible if the employee trusts (property) that it will be used in the best interest of safety learning and does not fear (constraint) being judged and blamed. Furthermore, *Safety Awareness* (in the bottom right) is driven by ownership and accountability (properties). In this viewpoint, the *front-line staff* must understand the differences between honest mistakes, at-risk behaviors, and reckless actions. When the pilot is engaged in the safety culture and is part of the guidelines and decisions, he/she can develop ownership and accountability for his actions.

A.6 Discussion

The pilot's roles presented in the previous section are not disconnected nor independent. Behaviors, skills, and responsibilities overlay. The purpose of framing responsibilities,

capabilities, and exchanges in a personnel structure diagram is to facilitate the understanding of the pilot's performance in three different enterprise concerns: Situation Awareness, Security, and Safety Culture. Using model traceability and matrix features, we analyzed the relationships between roles and capabilities that will be summarized and debated in this section.

All pilots' roles share *Safe mental model establishment* and *Active observation* regarding individual capabilities. The critical nature of the SA competence explains this. Making safe decisions is relevant for achieving and maintaining safe and secure UAM operations. A mental model is a cognitive framework or representation of how something works. In the pilot's context, it is an internal mechanism that helps him/her understand safe behavior in UAM operation. Mental models are formed through education, experiences, and exposure to information. Situation awareness, security, and safety culture depend on individual and collective mental models and must plan for training, practice, and shared information systems. Likewise, the pilot must exhibit active observation, which includes being critical and analytical of the interacted environment and systems. Active observation and a safe mental model depend on each other. The pilot needs both to predict outcomes and make safe decisions, the desired effect of all three viewpoints.

The individual capabilities of the pilot as a decision-maker must be planned according to the organizational context and personnel aspects. Since previous work has delved into SA as an enterprise competence, we identified the properties and constraints of individual capabilities consistent with organizational enabling processes in this paper. For instance, training level is decisive for building a proper mental mode and for preparing the operator on monitoring skills, among other operational tasks. The organization and its resources must provide the pilot training needs in all its roles. The same applies regarding stress and emotional instability. The organization should be prepared to monitor and handle individual conditions on pilots that may affect their ability to make safe decisions. Therefore, continuous assessment and adaptation of organizational processes to meet the evolving needs of pilots are crucial for sustaining high standards in aviation operations.

Communication is another significant capability defined for the UAM as an enterprise. Communication has different facets when we move to the personnel domain and define individual

capabilities. Namely, the pilot must exhibit *effective communication* as a vehicle operator. Clarity, precision, and timeliness are properties for communicating while operating the vehicle. On the other hand, *open reporting* is the communication capability that the pilot as a security agent requires. Lastly, *transparent communication* is the type of communication that the pilot must exhibit as a safety agent. The strategic capability of the enterprise must be analyzed from the resource perspective. Different individual capabilities (specialized types of strategic capabilities) are defined for each pilot's function.

The need for a safe mental model, active observation, and effective communication is fundamental across various aviation environments. While the architecture was explicitly modeled for UAM operations, many of its principles are relevant to other aviation contexts, including single-pilot operations (SPO). The mapping presented in this paper is tailored to the unique requirements of UAM operations in the early phases, with one pilot onboard the vehicle. Still, the results have broader applicability to other aviation contexts and highlight the importance of aligning individual capabilities with organizational processes.

A.7 Final Remarks

The research presented in this paper framed the UAM pilot as an individual operational performer of the UAM ecosystem. The systemic approach was explored in previous work considering the whole UAM enterprise. In this work, we investigated the pilot’s perspective when performing different functions for the enterprise. We proposed three roles and provided specifications for responsibilities, exchanges, and capabilities. Using UAF modeling, we presented views combining individual-level elements following the enterprise-level architecture. Lastly, we analyzed the pilot’s capabilities according to its roles and discussed critical resources for addressing safety and security challenges.

The UAF has proven to be a suitable framework to synthesize the holistic aspects of a complex operation, and as presented above, helpful for exploring individual-level perspectives. Modeling eases the burden of dealing with complexity but also carries limitations. Inconsistency and incoherency can happen with conceptual representations, for such iteration and validation are encouraged. The diagrams presented in the results were scrutinized and validated by experts on

human factors, system engineering, and conceptual modeling.

Future contributions include analyzing how ontologies can improve the representation of individual and organizational capabilities in the UAM domain, as was proposed by Calhau & Almeida (2022). In this case, ontologies can allow zooming in on competencies/individual capabilities to better understand how their elements (knowledge, attitude, skill, and other human aspects) are related, as Calhau & Almeida (2022) did. Furthermore, concerning the zooming out on individual capabilities, ontologies can also help to improve the modeling of the phenomenon of emergence in EA, as Calhau et al. (2023) approached. In this instance, they can help answer questions such as: how do the SoS's capabilities emerge from the individual capabilities? How can capabilities of distinct human resources (e.g., Pilot and UAM Operator) be better combined? How can human aspects (e.g., attitude, knowledge, represented as capability's properties and constraints) impact the whole system?

Finally, recommendations include performing task analysis using operational activities and combining them with personnel and resource capabilities. In addition, other roles in the ecosystem, like traffic controller or maintenance staff, can benefit from the approach presented in this paper.

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