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FRAM APPLICATION FOR ANALYSIS OF THE CONCEPT OF EVTOL OPERATION IN URBAN CENTERS: CHALLENGES AND RISKS

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ABSTRACT

This article explores the application of the Functional Resonance Analysis Method (FRAM) in assessing the operational concept of Electric Vertical Takeoff and Landing (eVTOL) vehicles in urban environments. The study investigates the challenges and risks associated with urban mobility, focusing particularly on the potential impact of eVTOLs as an innovative mode of transportation. The increasing interest in autonomous or piloted aerial vehicles stems from the growing demand for air transport and the imperative to reduce CO_2 emissions. The article aims to provide qualitative analysis of operational risks associated with eVTOLs in urban settings. By adopting the FRAM methodology proposed by Hollnagel (2004; 2012), the study seeks to comprehensively understand interactions within sociotechnical systems and identify emerging failures that could compromise safety and operational efficiency. While these vehicles offer cost reduction, operational efficiency, and environmental sustainability benefits, they also pose challenges in terms of safety, reliability, decision-making, and societal acceptance. Studies underscore the need to balance the advantages of aerial vehicles with the complexities of urban infrastructure and existing air traffic management systems. The Concept of Operations (CONOPS) was defined through literature review. Using a standardized scenario, the operation was modeled using FRAM and function abstraction at different hierarchical levels. Findings highlight the importance of integrating diverse stakeholders and addressing uncertainties in urban air mobility planning. In conclusion, applying FRAM to assess the operational concept of eVTOLs provides a holistic perspective on the challenges and opportunities of integrating advanced aerial vehicles into urban transportation systems. By comprehending the intricate interactions within sociotechnical systems, stakeholders can make informed decisions to enhance safety, efficiency, and sustainability in future urban air mobility initiatives

Keywords: FRAM, Risk Assessment, Transportation, Ergonomics, Urban Mobility.

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1. INTRODUCTION

Encouraged by credit policies and tax reductions, the Brazilian vehicle fleet has shown continuous growth. According to the Brazilian Institute of Geography and Statistics (IBGE, 2022), the vehicle fleet in Brazil exceeds 115 million vehicles, a 3.2% increase from 2021, with annual growth trends since 2006.

However, the rise in the vehicle fleet and disorderly urban growth have led to numerous problems in large cities. These include decreased air quality, increased atmospheric emissions from fossil fuels (Karakurt & Aydin, 2023), vehicle traffic noise (Yang et al., 2020), impacts on local fauna (Pagany, 2020), high rates of accidents and fatalities (Vecino Ortiz et al., 2022), and stress and health issues associated with noise (Jimenez et al., 2023).

To encourage innovation and mitigate the problems of the previously mentioned current modes of transportation, and to promote improvements in urban mobility and transportation development in Brazil, there are public policies, especially National Urban Mobility Policy regulated by Law No. 12587 of January 3rd, 2012 (Brasil, 2012), but, also, disruptive technologies, such as eVTOLs (electric vertical take-off and landing), require technical analyses of operational risks and hypothetical scenario predictions due to system variability. Concerns already exist about pedestrian safety, noise, operational times, and altitude in relation to eVTOLs (Yedavalli & Mooberry, 2019).

This article maps the operation of eVTOLs in urban environments and presents a qualitative risk analysis of the process. It considers the main actors within the system and key influences and interactions among existing functions, using the Functional Resonance Analysis Method (FRAM) proposed by Hollnagel in 2004 and consolidated in 2012.

2. BIBLIOGRAPHIC REVIEW

2.1. eVTOL

The growing interest in the development of autonomous or piloted aerial vehicles is driven by the increase in air transport users and the goal of reducing CO_2 emissions. These vehicles are seen as alternatives to urban transportation, aiming for greater operational safety and cost reduction (Doo et al., 2021). However, challenges such as the need to combine the safety of civil aviation with the low operational costs of UAVs (Unmanned Aerial Vehicle) and issues of control and social acceptance are highlighted by Xiang et al. (2024).

Construction models and technical parameters are detailed by Zhang et al. (2024), while Qu et al. (2024, p.8) and Patterson et al. (2018) describe time estimates for flight stages and landing procedures, considering emergencies and vertiport changes, which are relevant for modeling using the FRAM method.

2.2. Risk Analysis in Socio-Technical Systems: Conceptualization and Limitations of Uncertainties

Risk analysis in socio-technical systems is essential for the success of these systems. Fragola (1996) and Zachmann (2014) trace the origins of risk analysis from navigation to its consolidation in the nuclear industry.

Amid the debate about the origin of risk analysis and management, it is undeniable that measuring, managing, or mitigating risks are fundamental actions for the success of any socio-technical system. These factors led to the creation of analysis methodologies to support decision-making by correlating the severity and impact of certain events with their probabilities of occurrence.

Before advancing into the concepts of risks, it is pertinent to clarify that the concept of safety discussed in this work does not refer to the absence of risks but to the existence of acceptable risks (see Aven et al., 2018, in Society for Risk Analysis Glossary). This clarification is of great relevance for understanding this work as it makes clear that uncertainties are inherent in any system, and human behavior and actions are a crucial component of this analysis (Hollnagel, 2002). Therefore, we assume that no system is free or immune from risks.

From a technical perspective, risk estimation is a process that allows the predictability of how and when undesirable events may develop (Luetge et al., 2014). This estimation depends on numerous factors and involves the existence of a risk source, an event and its respective consequence, and the uncertainties present in this function. These uncertainties can be stochastic, based on historical data and frequentist inferences, or qualitative approaches (when numerical data for direct probability estimates are unavailable), under which the strength of tacit and explicit knowledge must be considered (Flage et al., 2014; Amundrud et al., 2017).

In the context of eVTOLs, the lack of statistical history limits the analysis of standard operational scenarios (CONOPS) and following Amundrud et al. (2017) criteria it is assumed beforehand that there is no strength of knowledge for the uncertainties in this study. Furthermore, regarding the difficulties faced in any risk analysis of socio-technical systems that have not yet been implemented and consolidated, transparency in the evaluations conducted here is necessary to maintain the credibility of the work (Thekdi & Aven, 2023).

2.3. Functional Resonance Analysis Method – FRAM

The Functional Resonance Analysis Method (FRAM), according to Hollnagel (2012), evaluates systems by considering real interactions between components, adaptability, and human performance. FRAM can be retrospective, for accident analysis, or prospective, for modeling behaviors and risks (Patriarca et al., 2020). The methodology is widely applied in aviation, such as in incident analyses (Reiser et al., 2023) (Da Silva et al.,2023) and studies of critical variabilities in landings (Reiser et al., 2024). Examples of applications in other sectors include ship piloting (Guo et al., 2023) and medical care (Kaya & Hocaoglu, 2020).

3. METHOD

The first stage of the work consisted of defining the CONOPS (Concepts of Operations) for an eVTOL, which was developed according to the presentation by Fregnani (2022). The characteristics of the CONOPS are presented in the Table 1.

Table 1 eVTOL Standard Operating Concept Items and Descriptions.

Item	***Description***
Type of Operation	Urban air taxi, covering flights of 15 to 50km, on demand, between available landing points; Transport to airports (airport shuttle), including scheduled flights of 15 to 50 km, with defined routes between airports and selected points.
Study Vehicle Characteristics	Lift + Cruise; Low/Medium Cruise Speed; Short Range; Transition from/to hover; Simple design; Lower noise in cruise; Simple maintenance; Easier to certify (?)
Frequency and complexity of operation	Low
Infrastructure needed	Existing helipads, shared with helicopters
Automation Level	Pilot on board
Roles and responsibilities	Executive and legislative power; Government regulatory agencies; Local control and supervision (air traffic control, regulations, urban planning); Operating company; Pilots; Field maintenance; Passengers; General public
Air space	Dedicated air corridors for eVTOL operation

Item	*Description*
Operation profile	The flight phases can be summarized as: Taxi in: Preparation for takeoff, boarding of passengers; Take-off: Ascent with vertical propulsion (hover); Transition to climb: Transition point for horizontal propulsion; Climb: Ascent; Cruise: Flight at cruising altitude with horizontal propulsion; Descent: Descent with horizontal propulsion Transition to landing: Transition point for vertical propulsion; Landing: Vertical descent with vertical propulsion; Taxi out: Stopping the aircraft, disembarking passengers

Given the scenario and requirements defined by the standard operating concept, a scenario was modeled using the Functional Resonance Analysis Method (FRAM) proposed by Hollnagel (2012), using the FRAM Model Visualiser software, version 2.2.0, considering the hypothesis of system operation as designed.

This scenario aimed to illustrate the complexity of the system at different hierarchical levels, using Rasmussen's abstraction concepts (1997) and function allocations at temporal levels derived from the STEP (Sequentially Timed Events Plotting) method (Hendrick & Benner, 1987). The adaptations required partial applicability of these other models, reducing abstractions to 5 hierarchical levels, and assuming that events occur through complex interactions with emergent outcomes, under a systemic concept that cannot be detected through decomposing analysis into common cause-effect lines typical of sequential models, as classified by Wienen et al. (2017).

Thus, some functions have timeless assignments required for pre-operation regulatory purposes, as well as oversight and control activities that impact the process throughout.

4. RESULTS AND DISCUSSION

The scenario modeling of the entire system is presented in Figure 1, located at Appendix. The illustration model of the system through the adaptation of abstractions proposed by Rasmussen (1997) and temporal segregations existing in STEP (Hendrick & Benner, 1987) promotes a comprehensive understanding of the situation, which encompasses the characteristic interactions of sociotechnical systems and also graphically illustrates how the interaction between functions transcends the individual limits of each hierarchical level. Sklet (2002) mentions that the temporal scale does not need to follow linearity in the STEP model, being above all useful for maintaining a systemic understanding of the event. Herrera & Woljter (2009), in a comparison work between the use of FRAM and STEP in a retrospective context, highlight the virtues of FRAM in identifying emergent failures within an analysis that provides valuable information on 'what', 'how', and 'why' an event happened or could happen.

The negative aspects of this interaction refer to the limitation of existing levels and the technical difficulty of mapping all possible variabilities, a fact that underscores a possible negative correlation between the accuracy of the analysis and the size of the system sampling.

One of the strategies to increase the reliability of the analyses lies in the participation of experienced specialists in the process being mapped, in addition to the integration of various methodologies. Some evaluation methodologies emphasize organizational aspects and restrictions imposed by controls, with intra and inter-organizational interactions. The STPA model proposed by Leveson (2002) is an example of a prospective analysis that delimits hierarchical levels of actors and emphasizes control mechanisms and feedback but requires complementation to address human performance factors and system variabilities, which can be obtained through other methodologies (Thatcher et al., 2020).

The discussion on the layout and interaction of functions in the preliminary model may raise questions about the number of functions and the interactions between their elements. However, as this is a developmental stage of transportation mode, there are still no clear guidelines to accurately model an eVTOL flight, including the definition of actors and their respective roles and responsibilities.

One of the virtues of applying FRAM at this stage was to generate questions that will need to be discussed in the future, especially by high-level stakeholders who have various responsibilities for regulating the activity sustainably, safely, and efficiently. Practical examples are linked to

environmental licensing issues to mitigate noise and birdlife impacts, as well as situations related to labor legislation to regulate the working hours of professionals involved in this transportation and general infrastructure aspects required by this mode. Although it may seem contradictory, these questions and the graphical illustration of the system highlighted the complexity of implementing a new transportation mode in large urban centers and underscored the need for synchronization among various societal actors, a fact corroborated by Steen & Ferreira (2020).

In this context, Xiang et al. (2024) address important issues regarding organizational and legal aspects of eVTOL flight, and Laarmann et al. (2023) discuss certifications required in Europe, detailing the complexity of implementing eVTOL flights on that continent.

In Brazil, the complexity of air transportation is exemplified by the fact that since the promulgation of Law 11182 (Brazil, 2005), the National Civil Aviation Agency (ANAC) has been responsible for standardizing, regulating, and overseeing aeronautical services. On the other hand, airspace control is the responsibility of the Department of Airspace Control, under the Air Force Command (Ministry of Defense). In addition, environmental regulations and infrastructure are the responsibilities of the Ministry of the Environment and the Ministry of Infrastructure, respectively, and their affiliated agencies.

At intermediate and basal levels of abstraction, in addition to operational issues, the emphasis relates to the need to implement control measures against malicious activities, requiring broad-spectrum counterintelligence actions capable of mapping intentions and dangerous interactions, including functions performed at the 3rd, 2nd, and 1st hierarchical levels mapped. Amundrud et al. (2017) clarify that these assessments require high judgment capacity and constant applicability on a temporal scale for mapping uncertainties and vulnerabilities.

Therefore, the implementation of a new mode requires synchronized integration among all these agencies, along with the participation of other members of the public and private administration. It is also essential that the involved actors be capable of handling the system variabilities that will inevitably arise.

4.1. Recommendations

Based on the analysis conducted, recommendations and potential issues that require further research are presented at Table 2.

Table 2 Recommendations and potencial issues related to multiple aspects.

Aspect	*Recommendations*	*Potencial Issues*
Government (local, regional and federal)	Creating and/or modifying laws, regulations, and standards are essential to define responsibilities for standardization, oversight, control, and accident investigation. Additionally, it is necessary to consider cost estimates and the burden on public authorities.	Undefined actors and responsibilities may overload the system, resulting in irreparable disturbances that compromise the full functioning of the model.
Urban infrastructure	It requires well-planned vertiports, considering adequate dimensions, criteria for installation such as electrical demand, isolation, access restrictions, and efficient integration with other modes of transportation. Clear regulations for their construction are essential, including impact studies on the neighborhood and system operation, such as passenger boarding and disembarking, as well as aircraft takeoff and landing. Site selection should be guided by operational feasibility, ensuring adequate access to electrical power for aircraft battery recharging and maintaining safe distances from other infrastructures, such as high-voltage towers and buildings. Effective integration with existing road networks is also crucial.	Limited availability of vertiports in specific areas may restrict the usability of the mode and affect the cost-effectiveness of its implementation. Moreover, in emergency scenarios, contingency measures may require traffic and law enforcement agencies to facilitate landings in congested urban areas.

Aspect	*Recommendations*	*Potencial Issues*
Environment	Resolutions and regulations are necessary for vertiport implementation and air route establishment. This includes coordination among licensing agencies to define safe routes aiming to protect wildlife, especially avifauna (Cardoso et al., 2022), and the construction of radars for operational use and assessment of noise-related impacts (Paul et al., 2020). Certain parameters are directly linked to flight safety aspects	Environmental restrictions may reduce existing routes, negatively impacting the feasibility of system implementation.
Air traffic management and control	Defining responsibilities for air traffic management and control is very important, with specific regulations for training professionals capable of performing these functions. With an increasing number of personal flights and, consequently, aircraft in the air, concerns arise about requirements to manage intense air traffic. This encompasses standardization, establishment of predefined routes, control of takeoffs and landings, guidance for emergency diversions, and integration with other sectors to synchronize operations. Deniz et al. (2024) address traffic management issues and cite artificial intelligence as an alternative to reduce human workload and the risk of collisions among eVTOL-like aircraft.	Limitations in the number of air traffic controllers may require greater system autonomy and, consequently, higher technological levels. These changes introduce new technological risks, necessitating new mitigation measures. Additionally, regulatory uncertainties point to the need to delineate pilot and operator workload and ongoing training, ensuring flight safety and protection against malicious individuals.
Users	Defining security procedures for aircraft access is fundamental. The increase in the number of operating aircraft raises concerns related to preventing terrorist attacks and limiting interaction between pilots and passengers.	Security inspection failures can lead to serious operational safety problems. It is also important for aircraft design evaluations to consider restricting interaction between pilot and passenger to mitigate risks.
Product risk assessment	Quantitative risk analysis is essential in product development to ensure safe design against undesired outcomes and critical results. Quantitative risk analysis relies primarily on statistics, historical data, and product component design and architecture. Understanding the operational scenario (CONOPS), stakeholder interactions, and all involved variables is extremely valuable for risk analysis to reduce uncertainties in the process as much as possible.	Lack of statistics and historical data on accidents and incidents involving the studied vehicle type (eVTOL) results in higher uncertainty levels. Using statistical data from other vehicle types, such as helicopters, drones, or even aircraft, may obscure risk analysis outcomes. Moreover, lack of knowledge about eVTOL operation, potential issues that may arise, and interaction with stakeholders involved in the process also generates high levels of uncertainties.

5. CONCLUSIONS

The Functional Resonance Analysis Method (FRAM), developed by Hollnagel (2004; 2012), emerges as an effective tool for understanding interdependencies and relationships within highly complex and integrated systems. The method provides a clear view of how each variable acts within a function (whether as input, prerequisite, control, resource, or temporal parameter) and how variability in each can impact the function in question.

In contrast to Fault Tree Analysis (FTA), which adopts a quantitative and deductive approach focused on specific failure events, FRAM takes a more holistic and systemic approach. It considers how functions adapt and dynamically interact within the operational context. The attempt to unite quantitative aspects with FRAM should be the focus of research to improve this method, although its current form is useful for illustrating the unpredictability of human functions, while FTA solidly addresses failure patterns and the reliability of technological components.

Regarding the integration of methodologies, there are strengths related to illustrating temporal factors and hierarchical levels. However, in general models, technical difficulties may arise due to high complexity, making precise mapping challenging, which becomes clearer during instantiation.

Regarding the generated model, within an organizational analysis, the implementation of eVTOL requires concerted actions from various sectors of society. Aspects and factors related to urban infrastructure and intelligence actions for system security control require detailed studies and analyses because they are tied to significant impacts on society.

There is also a strong influence of timeless functions, which are predefined functions related to procedures, norms, standards, regulations, among others, derived from higher organizational hierarchical levels. These functions regulate the entire vehicle operation across various layers of the sociotechnical system, directly affecting the safe operation of eVTOL within the aerial and urban context.

In summary, at a generalized level, it is evident how political, governmental, regulatory decisions, among others, can indirectly affect daily operations. For the implementation of a new air transport mode, it is crucial to involve all stakeholders at all layers of the sociotechnical system in project decisions, as corroborated by Guan et al. (2024), especially concerning the risk analysis of an entire system.

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