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Application of Mind Map and TRIZ to an Advanced Air Mobility System for Post-Disaster Response

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Abstract: In this article, an Advanced Air Mobility (AAM) platform focused on search and rescue applications is discussed and analyzed from a systems thinking perspective. By applying two systems thinking tools, namely Mind Map and TRIZ, the strong interactions within the constituent parts that make up the system's whole are examined with the aim of providing a comprehensive roadmap for a proposed Advanced Air Mobility Post-Disaster Response (AAMPDR) system. Furthermore, two problems are discussed to demonstrate the application of the TRIZ technique. The first is in regards to a clause in the AGL rule that could present operational risks to the AAM's airframe, while the second relates to a potential conflict ensuing from the advent of the 5G C-band and its effect on the AAM altimetry. The resulting solutions to resolve these conflicts using this same technique are also discussed, firstly by taking into account the mean sea/water level as a reference for vertical height within the provisions of the Federal Aviation Regulation requirements, and secondly by applying segmentation of the mission profile as well as a multi-stage frequency designation for each segment depending on a threshold vertical distance. Finally, this study demonstrated that Mind Map and TRIZ can be effective techniques in the early stages of conceptual model development for an AAM system applied to post–disaster response. Furthermore, that the contradictions tool of TRIZ can also be utilized in resolving those potential conflicts identified in relation to the system of interest. To this end, this paper proposes the amendment of the current Part 107 rule to include the term Above Mean Sea (or Water) Level (AMS/WL), a critical yet missing piece of the system requirements that engineers should take into account in future AAM system designs.

Keywords: AAM; SAR; post–disaster response; systems thinking; Mind Map; TRIZ

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1. Introduction

According to Wasson [1], a system may be defined as a set of interoperable components or constituents, each configured and confined in several combinations that enable its behavior and which achieve its mission objectives within an operating environment. Systems thinking, on the other hand, entails a form of conceptual reasoning about a given system as a whole rather than the sum of its constituent parts [2]. Moreover, a systems thinking approach seeks to capture the emergent behavior of the system that may otherwise defy rational explanation following a reductionist approach. It is important to note that a system cannot be reduced into its constituent parts without compromising on key characteristics about the system as it is the interactions between parts that gives rise to the emergent behaviors.

In this paper, the authors focus on an Advanced Air Mobility Post-Disaster Responsesystem, hereafter referred to as an AAMPDR system, which explores Search and Rescue (SAR) use cases as a subset for the broader AAM ecosystem. Generally, the idea of Advanced Air Mobility (AAM) concept vehicles, commonly yet inaccurately referred to as

Urban Air Mobility (UAM), has attracted much debate in recent times among hobbyists, media commentators, academia, researchers, the aviation and aerospace industry, policy makers, and regulators, as well as the general public [3]. Thus, it is instructional to establish its origins as its earliest mention in the literature may be traced back to the work of Patterson et al. [4], albeit under an assumed variant, 'Advanced Air vehicles'. The term 'AAM' also appeared in early market studies, such as that presented by Booz Allen Hamilton [5] to NASA in 2018. However, in the years that followed, the FAA would finally settle on the acronym AAM, with it having been made popular by its counterpart, NASA [6]. To this end, the FAA on its website defines the AAM platform as follows:

> . . . an umbrella term for aircraft that are likely highly automated and electric. These aircraft are often referred to as air taxis or electric Vertical Takeoff and Landing (eVTOL) aircraft [7].

A more formal definition is presented in the AAM Coordination and Leadership Act, as found in a subsequent technical report by the FAA as follows:

> . . . AAM is a transportation system that conveys persons and property by air from one point to another in the United States using aircraft with advanced capability including electric aircraft or electric vertical takeoff and landing (eVTOL) aircraft in both controlled and uncontrolled airspace [8].

The aforementioned report further clarifies:

> For the purpose of this Implementation Plan, however, the scope of AAM is restricted to those relating to passenger-ferrying or cargo shipping operationsalbeit with a pilot on board [8].

Most notable in the foremost quotation, is the key phrase 'umbrella term', signifying that AAM encompasses a wide range of concept vehicle genus that covers several families of Unmanned Aircraft Systems (UASs), Urban Air Mobility (UAM), Regional Air Mobility (RAM), and other classes of Remotely Piloted Aircraft (RPA). To illustrate, Figures 1 and 2 show a graphical and SysML representation of the different classes of vehicle under each family in hierarchical order. At the top level of the tree in Figure 2, for example, is the AAM system denoted by the SysML block labeled 'AAM', connected by the generalization association and symbolized by an open headed arrow symbol, thus signifying that the AAM may be further divided into levels/tiers or specialization levels/tiers. At the second tier is the specialization association showing On-Demand Mobility (ODM) and UAS as types of AAM system. Next is the third tier on the hierarchy, identifying UAM, RAM, and Personal Air Mobility (PAM), otherwise known as Personal Air Vehicles (PAVs), as belonging to the ODM family, while Unmanned Aerial Vehicles (UAVs) (otherwise referred to as RPA in the Defense community) are identified as belonging to the UAS genus [9]. At the bottom-most tier of the hierarchy are classifications based on the flight configuration and orientation of the propulsion system, namely, Vertical Takeoff and Landing (VTOL), Horizontal Takeoff and Landing (HTOL), Short Takeoff and Landing (STOL), and Hybrid configurations [10], each of which may be types of the parent classes and thus may also be derived from the latter, hence the use of the generalization association arrow symbol [11]. In other words, each class of vehicle (UAM, RAM, PAM, UAV, sUAS) can take on any or a combination of the airframe configurations (HTOL, VTOL, STOL, Hybrid), as indicated on the SysML diagram using the 1 . . . * (that is, one–to–many) multiplicity of association, where each type of vehicle on the second level of hierarchy can be designed in one or more configurations on the forth level. By contrast, notice the 'Hybrid' block shares a 1 . . . 1 (that is, one–to–one) multiplicity association with the VTOL and HTOL configurations, thus signifying that it represents some form of combination of both configurations and is hence represented by the composition association, that is, a diamond-shaped arrow [11].

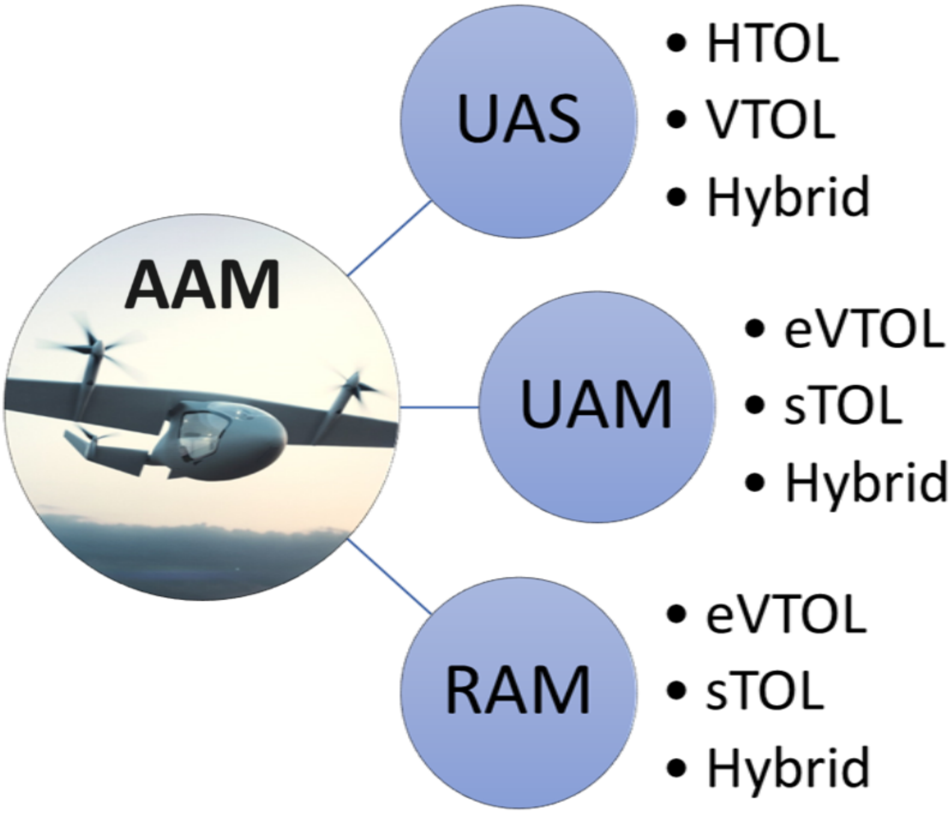

Figure 1. A high-level graphical representation of the taxonomy describing the AAM ecosystem.

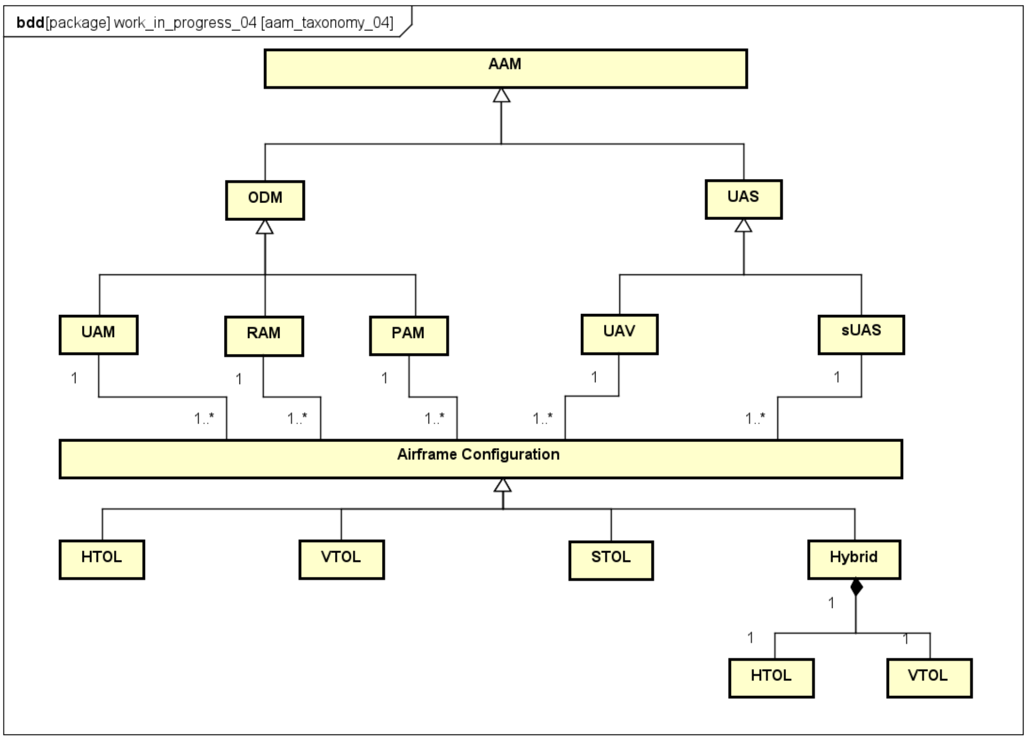

Figure 2. A high-level SysML representation of the taxonomy describing the AAM system family.

As previously mentioned, the system of interest for this study is referred to as an AAMPDR system. The scenario considered is similar to conditions set in the wake of a tropical cyclone, otherwise referred to as hurricane, and flooding disaster around the Mobile Bay area followed by a Gulf of Mexico campaign overseen by the AAM team under the auspices of the National Oceanic and Atmospheric Administration (NOAA) and guidance of the Federal Emergency Management Agency (FEMA) and in conjunction with the Federal Aviation Administration (FAA). Further, their effort is not without assistance from local Air Traffic Control (ATC) and Law Enforcement Agencies (LEAs), among other first responders.

A typical disaster response mission by organizations such as FEMA can be mapped out in five (5) phases, beginning with an assessment of the affected area, evacuation of all surface casualties, search and rescue of casualties from accessible void spaces, selected debris collection in order to facilitate locating and rescuing of casualties, and general debris collection, which is usually followed by the safe evacuation of casualties [12]. One of the earliest examples of disaster response using UAVs was demonstrated in 2005 by the Texas A&M University Center for Robot-Assisted Search and Rescue (CRASAR) situated at the University of South Florida using a fixed-wing vehicle and a helicopter to support rescue workers in flood-ravaged Mississippi during Hurricane Katrina [13,14].

Meteorological events such as these typically snowball into a minor humanitarian crisis, resulting in the displacement of local residents, with some casualties trapped in their homes. Among them may be the elderly as well as persons in immediate need of food, water, and basic medical supplies. In such instances, NOAA and FEMA may promptly dispatch already pre-deployed resources, which include the AAM airframe unit and a Ground Control station located onsite. Under the coordination of FEMA and NOAA, the National Weather Service (NWS) and National Hurricane Center (NHC), as well as Emergency Response (ER) workers, are placed on standby while the Air Traffic Control (ATC) at the Mobile Regional Airport (MOB) would issue a Notice to Airmen (NOTAM), thereby restricting the immediate airspace. According to FEMA, a team consisting of 14 out of 70 members, known as a Type I US&R task force, may be deployed to execute waterway-based rescue operations. This task force is locally mobilized, state administered, and federally supported [15].

The overarching goal of this article is to apply a couple of systems thinking tools to evaluate the relationship between parts of the AAMPDR system, which could potentially lead to emergent system behaviors considering the size and complexity of the system of interest. Furthermore, by applying a systems thinking approach, influences that the organization of system parts have on the emergent behavior of its overall structure may be examined through these tools. As a result, the systems thinker (or designer) can anticipate and identify areas of conflicts regarding the system of interest that could potentially be set in prior to the design stage. In addition, the systems engineer could resolve or manage the impact resulting from unintended consequences early on in the design process and avoid false starts or a faulty design, which often times come at great cost and risk to the stakeholder and/or project management team undertaking the design of said system.

This study intends to demonstrates practical applications of systems thinking to the SoI by examining two (2) main problems. The first being how best to apply the AGL rule as a local reference for measuring the vertical height of an aerial vehicle on an SAR mission considering the current low-cost altimetry technology available on board the airframe units of typical UAV platforms. Thus, in regards to the AAMPDR system, the following research question is proposed:

> How can the AAMPDR system compensate for changes in elevation of the landscape by actively adjusting the airframe unit's flight altitude (or more accurately, vertical height) as the vehicle traverses overhead from a region whose surface is raised above incident flood levels to another that is now completely submerged

by flooding? Moreover, is the airframe unit prone to the risk of being submerged itself?

To illustrate the first problem, further consider two (2) scenarios. Scenario 1 is shown in Figure 3, which describes a situation where the surface within the vicinity of the AAM launch station is surrounded by open air. Scenario 2 is shown in Figure 4 and describes a situation where the destination is fully submerged in flood water. While a team of competent human operators may be able to react in real–time by making instantaneous adjustments to, for instance, a quadcopter's flight altitude in keeping with the airspace regulator BVLOS guidelines, which also implies the operators must be nearby, the outcomes are less clear in regards to what is obtainable for automated UAV flight. This is of particular interest given that the trajectory for AAM technology is ultimately towards full autonomy.

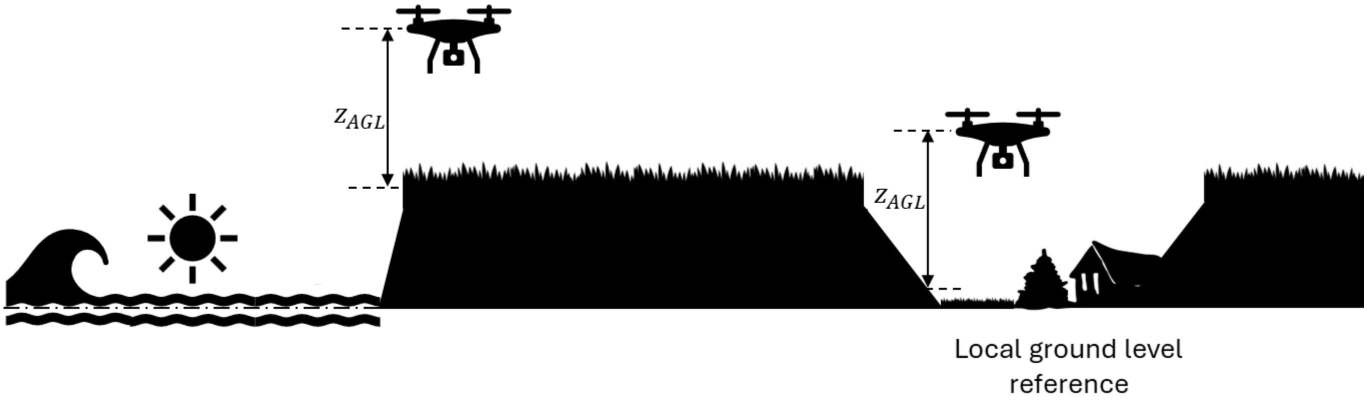

Figure 3. Above Ground Level (AGL) as local reference for AAM on autonomous flight.

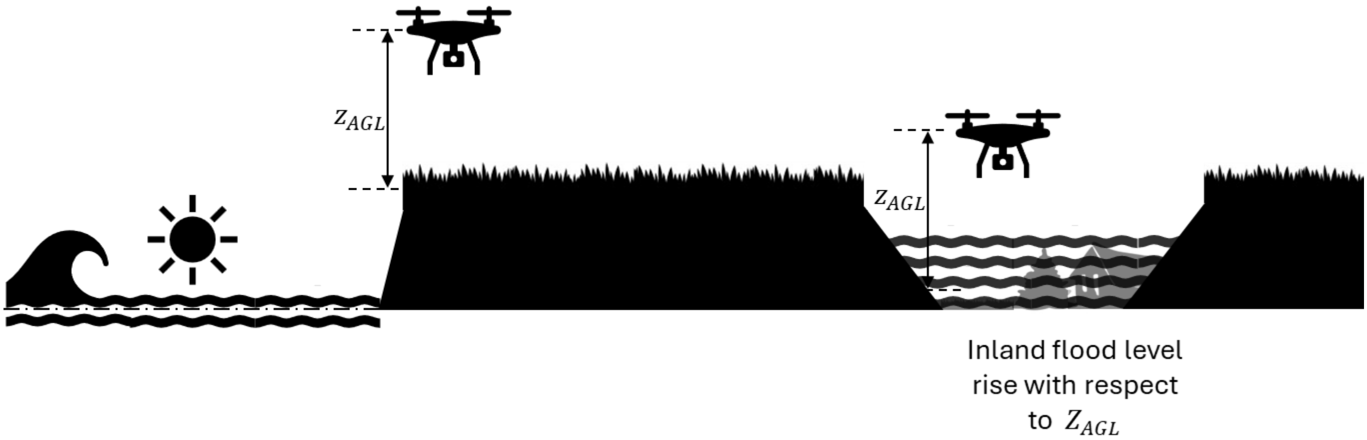

Figure 4. Above Ground Level (AGL) as local reference for AAM SAR flight above inland flooding.

The second problem to be studied relates to the roll out of 5G C-band wireless services, which has been met with growing concerns among stakeholders over its potential impact on aviation, particularly in the US. It ranges between 3.7 and 3.98 GHz, and is part of the mid-band spectrum of Radio Frequency (RF) between 3.3 and 4.2 GHz. In recent years, it has been the subject of much debate due to its potential interference with the Instrument Landing Systems (ILSs), specifically the radio/radar altimeters on board general and commercial aircraft, which provide assistance to pilots in executing the landing phase of the flight, especially during inclement weather and low visibility conditions [16]. Moreover, the events that led up to the introduction of 5G resulted in an inter-agency face off between the Federal Communications Commission (FCC) and the FAA, as reported by [17]. In response, the FAA initiated an Airworthiness Directive (AD) proposal that would enable the coexistence of aircraft and 5G C-band wireless signal operations. With the deadline for its implementation set for 1 July 2023, this initial directive entailed the installation of 5G C-band-tolerant radio altimeters or an approved radio frequency filter [18]. This is because 5G C-band signals share close proximity with Aeronautical Radionavigation Services (ARSs) on the spectrum (refer to Figure 5) and could compromise aircraft safety upon approaching the Decision Height (DH)[1], a parameter that describes the vertical height at which the pilot must decide whether or not to land. On the other hand, the FCC approached this problem by creating what is called a 'guard band', which is a frequency interval of 220 MHz. This serves as a buffer zone permitting only 5G C-band signals between 3.70 and 3.98 GHz [16,17].

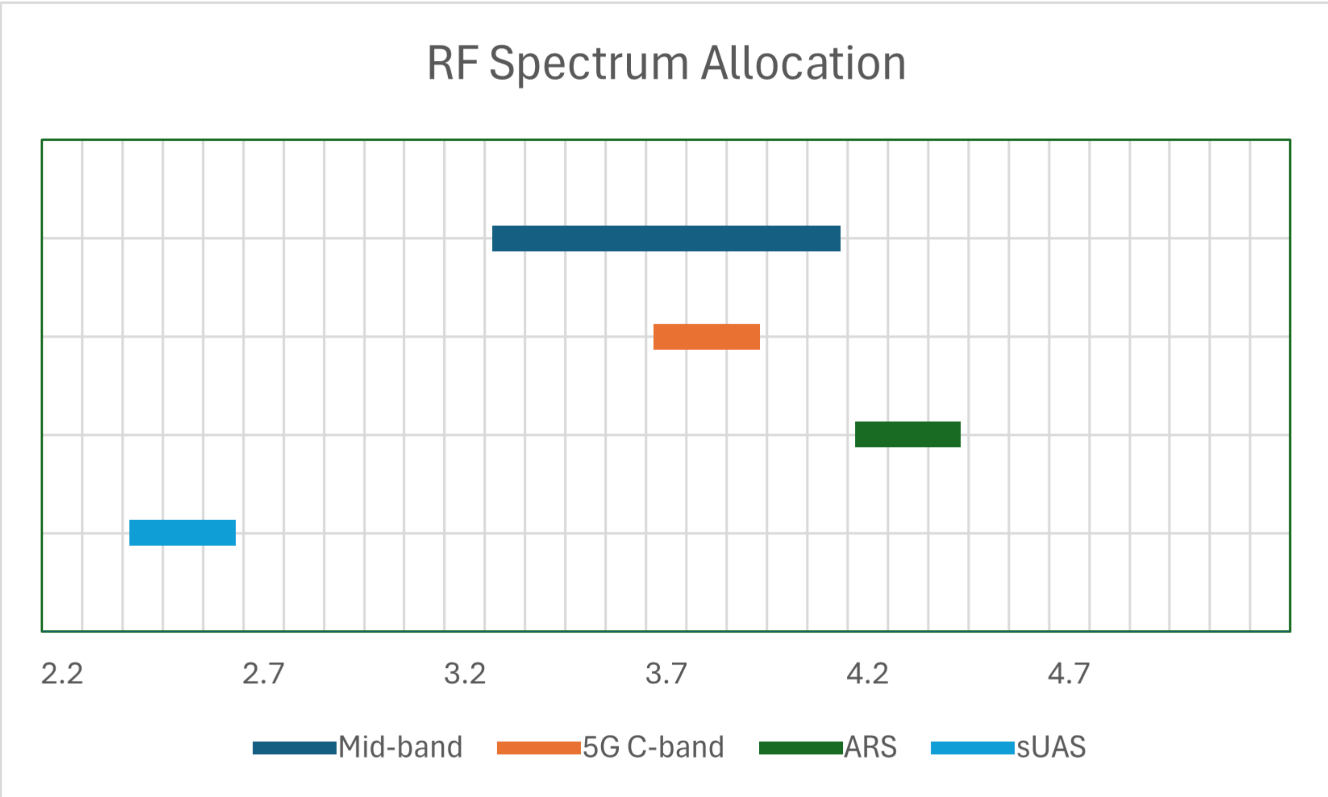

Figure 5. Radio frequency spectrum allocation showing selected bands.

Despite these hurdles facing traditional aviation, a growing number of authors are also proposing to extend the application of 5G and 6G bands to AAM platforms so as to support its chain of Communication, Navigation, and Surveillance (CNS), and especially for digital data link communications. For instance, the practical uses for 5G, such as with the concept of interconnected AAMs, Air-to-Ground (A2G) connectivity, and Internet of Things (IoT)-enabled applications, were discussed by Al-Rubaye et al. [19]. The authors also argued that 5G supports low latency and high throughput connectivity for in-flight passenger utility while identifying four (4) main services, namely, edge cloud, core network, Unmanned Aircraft System Traffic Management (UTM), and data telemetry. Another such application is with AAM swarm technology as treated in the work by Lu et al. [20]. While the potential benefits of 5G abound, it does not appear that much attention is being given to the potential conflict and resulting operational hazards it may pose in deploying safe operations and infrastructure for AAMs.

In the existing literature, authors such as Lyu et al. [21] have explored the use of UAVs in SAR scenarios, outlining the latest developments in UAV technology, different types of UAV, and communication and deployment strategies for UAVs, as well as their limitations. Further discussed were UAV operations in different areas of application, including marine, energy, and artificial-intelligence-related sectors. As part of the examples for SAR applications, Lyu et al. [21] noted the use of rotor wing UAVs in the Lushan earthquake that took place in 2013. These vehicles where deployed in rescuing victims through the aid of on-board HD camera. The authors also noted the use of UAVs for on-site monitoring and live 3*D* modeling of affected areas, whilst the recovery team mapped out its SAR plan using concepts such as Structure from Motion (SfM) in conjunction with tools like Blender© and Pix4D Mapper. According to Lyu et al. [21], the SfM method could also be utilized in flood and tsunami disaster events, such as the case of mapping the waterlogged area in Yuyao city, China, to mention only a few applications cited in their work. However, the authors did not undertake this work from a systems thinking view point.

In the same vein, the Royal National Lifeguards Institute (RNLI), together with the Maritime & Coastguard Agency (MCA), in the UK investigated the potential use cases for Unmanned Aerial Vehicle (UAV) technology, especially in instances where the likelihood of the UAV arriving at the scene faster than manned intervention is significantly higher, so much so as to make a life-saving difference [22]. It is noteworthy that this study was against the backdrop of rescue operations conducted by the RNLI in the previous year, 2021, in which about 3000 swimmers in distress were rescued off the coast of the United Kingdom. However, despite significant SAR efforts there were still over 100 fatalities who could probably have been rescued within the same period according to reports by [23].

In another study, Aljehani and Inoue [24] proposed a new method to construct safe maps covering disaster-stricken zones. Utilizing several scenarios, the researchers tracked pedestrians (otherwise, refugees) through their mobile devices and the image processing applications on board a UAV. The researchers applied an experimental-based approach using gathered aerial imagery data. While the methods applied by Aljehani and Inoue [24] share similarities with those found in the systems engineering discipline, including their depiction of a CONOP-esque schematic of communication architecture between the IoT system and the UAV as shown in their Figures 1 and 2 as well as the Activity diagram for their UAV missions as shown on Figure 15 of the said study, no other systems thinking approach was utilized by them.

Shelekhov et al. [25] investigated the use of UAVs, precisely DJI Phantom 4 Pro and AMK–03 quadcopters, in obtaining low-altitude sensing measurements, such as mean wind velocity, while employing high spatial resolution technologies to overcome atmospheric turbulence. However, while potential concerns to UAV flight operations were addressed, such as fluctuations in wind speed resulting in turbulent vertical displacement, their research followed a mathematically rigorous approach as opposed to the conceptual system modeling approach adopted here. In a similar effort, Awan et al. [26] explored the potential of 77 GHz in automotive radar altimetry.

In regards to systems thinking, Salado and Nilchiani [2] provided a general overview of stakeholder-centric tools as well as contextual- and behavioral-centric methods, which other researchers could explore in order to introduce completeness into the system life-cycle of their designs. Such methods include Soft Systems Methodology (SSM) and Systemigram. However, the methods applied did not extend to those found in this article, namely, the Mind Map and TRIZ techniques. Similarly, Robinson et al. [27] discussed the benefits of conceptual modeling and how it supports the facilitation of mental models for a system development decrease in the likelihood of incomplete, ambiguous, and inconsistent requirements, and the development of credible models that in turn aid computer modeling. The authors also presented two important criteria for creating the artifacts employed in this work, namely, identifying the problem description (otherwise known as problem statement) and projecting desired goals. While useful, the method proposed by Robinson et al. [27] did not cover the systems thinking approaches discussed here.

As early as 2011, Sauser et al. [28] applied Systemigram by characterizing resilience within the Maritime Transportation System program by the Department of Homeland Security. This approach was based on the four R's, namely, robustness, redundancy, resourcefulness, and rapidity, and by utilizing the dramatization and survey tools administered to 25 participants designated into working groups. In a later work, Cloutier et al. [29] noted that systemigrams can be useful in providing insights and identifying important elements of an arbitrary system of interest by extracting graphical models from structured text representing the foundational conceptual thinking. This involves seven steps of the Board Soft Systems Methodology (BSSM), namely, the unstructured problem situation, the expressed problem situation, the structure text, the systemigram design, the dramatization and dialogue, the feasible, the desirable changes, and the action to improve the problem situation. Furthermore, using a generalized approach, Cloutier et al. [29] demonstrated how systemigrams may be transformed into structured SysML models.

Research work by Jafari et al. [30] explored the effectiveness of forty (40) inventive principles of TRIZ, albeit by demonstrating its application to the field of signal processing and medical engineering. In their results, Jafari et al. [30] reported a 71% application of TRIZ among researchers in realizing their innovative products. Using success factors obtained from a combination of literature analysis and Delphi methods, Yan et al. [31] formulated critical problems relating to upgrading the Shaanxi Aviation Industry (SXAI), a subsidiary of the Aviation Industry Corporation of China (AVIC) that deals in both local and international subcontracting, general manufacturing, and supply of military and transport aircraft machinery. This was followed by the development of strategies to settle these problems. Thus, to resolve the two ensuing technical and physical contradictions, the authors promptly applied the theory of inventing problem solving (TRIZ) technique. Their work identified 2 first-level and 16 second-level indicators, with the latter taken as the standard parameter of the matrix contradiction, 10 of which represented the Key Success Factors (KSFs), including mastery of professional knowledge and technology, technological innovation capability, R&D resource security capacity, production organization capacity, technological process innovation, quality and cost control, accurate target market, talent research level, supply-chain management capabilities, and financing capacity. Meanwhile, the remaining 6 external driving forces include government support, market demand conditions, industry competition, development level of supporting industries, industry agglomeration level, and global value chain governance [31]. This resulted in desirable and undesirable parameters as well as their corresponding inventive principles. For instance, considering KSF 2, the authors identified a sought after parameter as #14, which corresponds to Strength, while the unwanted parameter was #22, corresponding to Loss of Energy. Thus, the intersection of these parameters suggested the singular inventive principle 35, corresponding to a 'Parameter Change' which the authors interpreted as 'Strategies'. This result culminated in Yan et al. [31] recommending that SXAI companies focus on initial short-term strategies followed by the incremental introduction of medium- and long-term ones.

Whether in the field of engineering, medicine, business, marketing, or manufacturing, the technique of TRIZ has been applied extensively in exploring contradictions relating to different subject areas of interest, as treated in works undertaken by [32–36]. However, in spite of these developments recorded by the previous works reviewed so far, nothing in the existing body of knowledge suggests that the methods applied in the foregoing section have been directed towards UAVs for SAR and humanitarian purposes in the wake of a meteorological disaster from a systems thinking perspective. Thus, this presents a gap in literature that the authors seek to fill with this work.

2. Systems Thinking Methods

2.1. Mind Map

The Mind Map is a simple tree-like structure used to represent and lay out the author's thought process regarding a particular subject, in this case for the AAMPDR system. Mind

Maps visualize the rationale behind the designer's adoption of important design choices. Buzan and Buzan [37] defined Mind Map as a comprehensive systems thinking tool that facilitates self-analysis, problem-solving, and memory retention covering a broad range of topics regarding a particular subject of interest. Moreover, Sun et al. [38] reported on learners who utilized the Mind Map tool. Executing a Mind Map involves three (3) simple steps, starting with identifying the central theme around the subject matter and then drawing a node representing the theme. This is followed by an iterative step of considering each problem associated with the system of interest, labeling the nodes according to each of those problems identified and connecting these nodes to the root node, which contains the central theme. Finally, each branch is explored along the related sub-themes or sub-branches until a reasonable conclusion is arrived at. In the preparation of this work, the Mind Map tool Xmind.works was employed [39].

2.2. TRIZ

TRIZ, which in Russian stands for теория решения изобретательских задач, may also appear as Teorija Rezbenija Izobretatelskib Zadach, and further transliterated in English language lexicon as the Theory of Inventive Problem Solving, hence the pseudonym TIPS, is a problem solving and inventing tool developed by Genrich Altshuller, a former USSR inventor, in 1946. Oxford Creativity [40] defines TRIZ as

> . . . a systematic approach for understanding and solving any problem, boosting brain power and creativity in addition to ensuring innovation.

TRIZ is a highly organized methodology that involves contemplating, conceptualizing, and brainstorming a solution to any given problem by stimulating creative thinking with the end goal of facilitating unique innovation. It utilizes a step-by-step process of identifying conflicts within the system of interest while attempting to minimize compromise. Thus, the TRIZ approach is particularly useful when confronting trivial problems that are intractable in nature [40,41]. To this end, TRIZ has been identified as a tool that helps inventors overcome barriers they may encounter during brainstorming sessions by guiding them through a systematic innovating process. In particular, the contradictions tool of the TRIZ methodology is utilized in this study [42]. There are at least five (5) key components that make up TRIZ contradictions [41], which include four (4) fundamental navigators, nine (9) laws of system evolution, forty (40) principles of innovative thinking[2], thirty-nine (39) characteristics of technical systems or engineered parameters, and a table of the contradiction matrix[3] [43].

A summary of the TRIZ flow process is presented in the following list and is illustrated in Figure 6:

1. Define the need as it relates to the system of interest
2. Understand the problem at hand by observing the system's operation
3. Identify the contradiction within its operation or structure and formulate a problem statement
4. Envision an ideal solution for the system of interest
5. Determine which of the 39 technical parameters are in conflict
6. Resolve the conflict using the indicated subset of forty (40) innovative principles as found in the contradiction matrix. Represented across the topmost column as well as along the leftmost row are the thirty-nine (39) technical parameters to be considered. Thus, apply the set of suggested innovative principles that lie at the cross intersection where the pair of row and column parameter coordinates indicate.

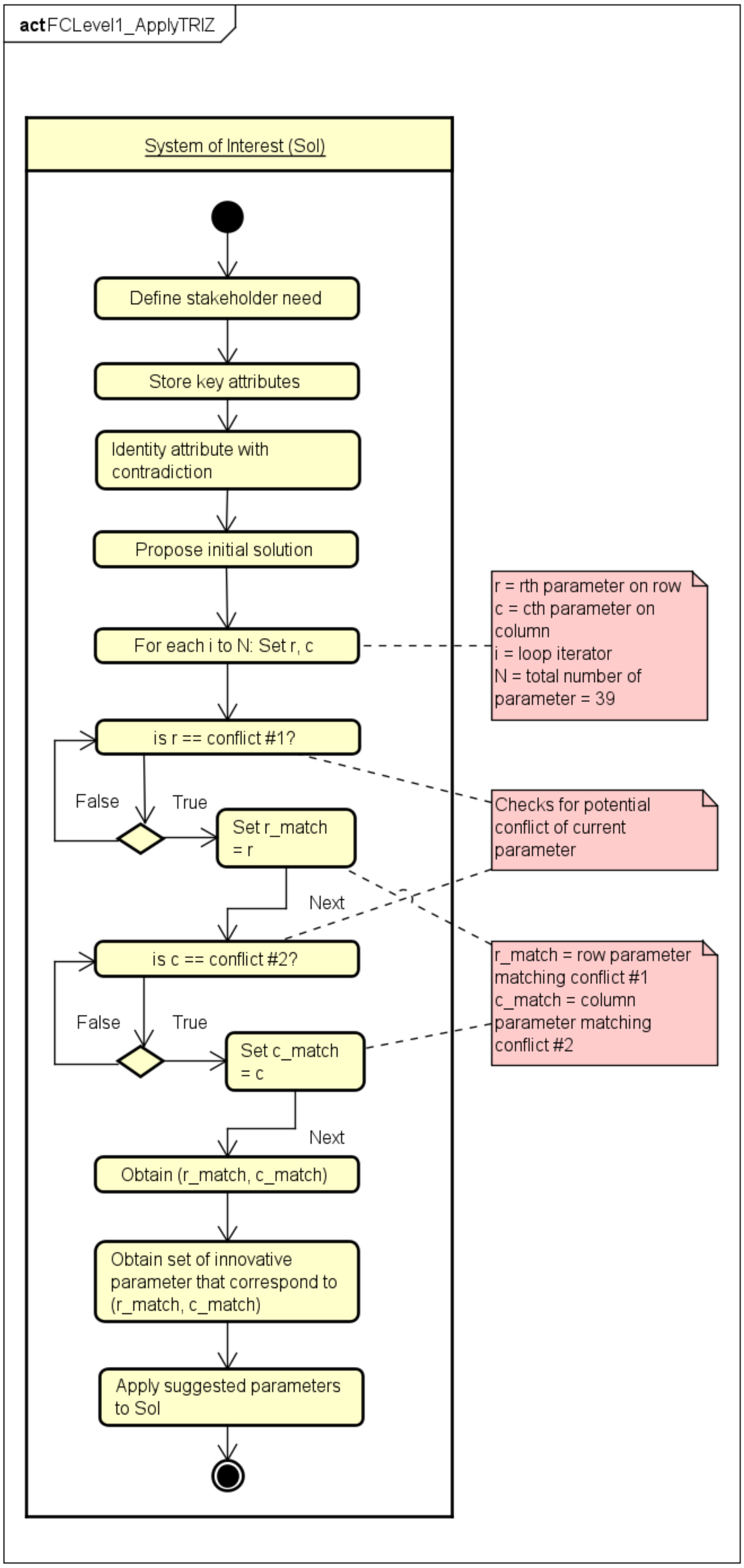

Figure 6. A flow chart showing the steps of applying TRIZ to a given system of interest.

3. Results and Discussion

A discussion of salient points describing the rationale behind the adoption and formulation of conceptual models for the AAMPDR system is presented as follows using the systems thinking tools identified in Section 2.

3.1. The AAMPDR System—Mind Map

As previously mentioned in Section 2.1, the purpose of Mind Maps is for the system thinker to develop a versed knowledge base regarding the model in addition to a broad understanding of the core concepts that are critical to actualizing the product, in this case, the AAMPDR system [44]. The Mind Map illustrated in Figure 7 was designed using the Xmind© program [39], which captures the root (or center) of the AAMPDR system, as well as the nodes that form the core subject matters critical to the successful realization of the AAMPDR system end product, categorized into Requirements, Model & Simulation, Safety & Risk, Environment, Operation & Management, and so on. In addition, the Mind Map shows the branches that stem from the nodes, including (in no particular order) Systems Modeling, Digital Twin, System "V" Life-cycle, and so forth. The salient points illustrated in Figure 7 as relating to the nine main nodes are presented as follows:

Figure 7. Mind Map showing the system of interest, AAM Post-Disaster Response (AAMPDR) System.

1. Operations and Management: These take into cognizance the mode of service that supports successful execution of missions when the AAMPDR system finally enters into full operation. As Cohen et al. [3] noted, there are several operation characteristics for AAM, which range from private service, air taxis, air pooling, semi-scheduled commuter, and scheduled commuter. In this case, the AAMPDR system is purposed for humanitarian assistance; thus, a scheduled flight operational model could appropriately describe its service. Also included within the Mind Map branches are the maintenance policy, servicing, and logistics that ensure its smooth operation (Refer to Figure 8).

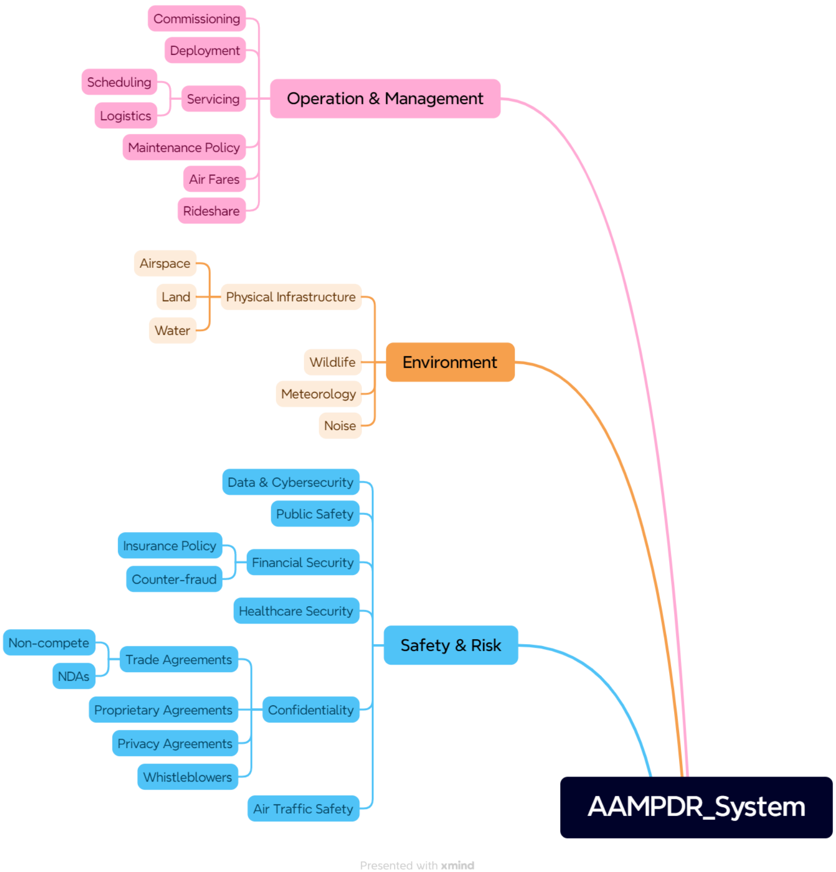

Figure 8. Section 1 of 4 of the Mind Map for the AAM Post-Disaster Response (AAMPDR) System.

2. Environment: Martin [45] defined environment as the circumstances, objects, or conditions by which an entity is surrounded. Furthermore, Holt [46] noted that all systems need to exist and be defined within a natural environment accompanied by constraints. In the case of the AAMPDR system, these constraints are those parameters imposed on the system by the environment, such as changing weather conditions, by governmental authorities through airspace regulation or by other systems, including the encroachment of wildlife, which may be categorized as a bio-life system in itself. Reports, such as those by Lyons et al. [47] that discusses the constraints imposed by wildlife systems due to interactions between raptors and UAVs, are starting to receive attention among government airspace regulators and UAV manufacturers alike. For instance, in 2020 there was a report of an attack on a DJI Phantom quadcopter owned by the Department of Environment, Great Lakes, and Energy [48]. While embarking upon shoreline aerial mapping activity along Lake Michigan, an irate bald eagle ripped off a propeller, causing the aerial vehicle to plunge into the lake below. Thus, it is important that the systems designer take this into account. Further, these factors may influence the drafting of design requirements that should have the properties of being non-rigid and adaptable. For example, this could mean the inclusion of some clause within the design requirement documentation advising AAMPDR system administrators on alternatives to explore when choosing a mode of deployment for the AAM airframe unit. Further, this might entail deploying fixed-wing UAVs for missions that are conducted within close proximity to a natural habitat for wildlife, as UAVs of this configuration type tend to support low noise propagation during flight compared to rotor-wing UAVs.
3. Safety and Risk: Risk may be defined as the likelihood for the occurrence of undesirable events, which may be followed by either positive or negative outcomes [49].

In order to avoid the risks associated with the AAMPDR system, it is important for the system designer to anticipate various aspects within the system that are likely susceptible to being compromised [50] and could lead to public safety concerns [3]. Aspects of the Safety & Risk node have also been identified in Figure 8 as lower level leaf nodes, including breaches in Data & Cybersecurity, Healthcare Security, Financial Security, and so forth.

4. Socio-Technical System (STS): SEBoK [51] defines STS as the study that accounts for both social (human-related) and technical (machine-related) factors that impact on the utility and functionality of computer-based systems. One of the socio-technical aspects as it relates to the AAMPDR system may include studying the rate of service and wait times between when an AAM aerial platform is deployed from a vertiport and when it arrives at a designated location to deliver aid. This also highlights the Human–Machine Interfacing (HMI) that is involved in delivering intervention to casualties and victims who may be trapped by the flood, as previously described in Section 1 [52]. Another socio-technical factor includes emergent behavior, as identified in Figure 9. Boardman and Sauser [53] define emergence as the occurrence of new phenomena during the course of the development or evolution of a system. In other words, emergent behavior describes macro phenomena that are observable between human and machine interfaces.

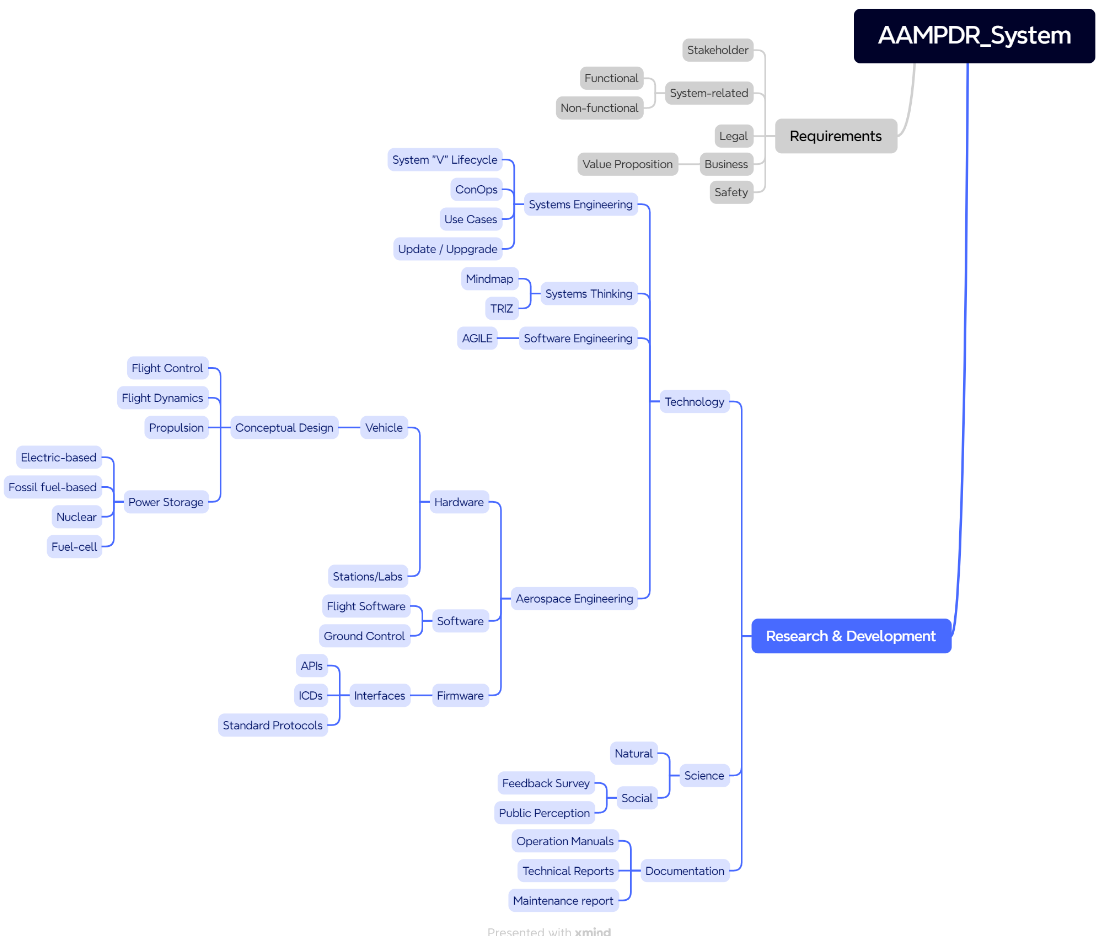

Figure 9. Section 2 of 4 of the Mind Map for the AAM Post-Disaster Response (AAMPDR) System.

5. Requirements: Refers to the set of clear and concise statements highlighting the desired functionality the system is expected to execute [46]. Included in this statement is the legal term "shall", signifying the strict conditions under which these requirements

must be met and satisfied by the system developer. These may include statements such as:

> The AAMPDR system shall have a takeoff weight that is less than 55 lbs in accordance with 14 CFR, Part 107 regulation.

The aforementioned is an example of a system requirement for the AAMPDR system. Others may be related to the stakeholder, legal, business requirements, or otherwise, as illustrated in Figure 9.

6. Model and Simulation: This is a mathematical, computer, or analytical representation of a real-world object or entity [54]. As famously quoted by Box [55] that all models are wrong; however, some are useful [paraphrased], the same may be applied to the AAMPDR system model. For this reason, the following components have been included into the lower level leaf nodes for this branch of the Mind Map, as indicated in Figure 10. This includes the digital twin model, which is particularly useful for the testing and integration of prototypes before they are integrated into service.

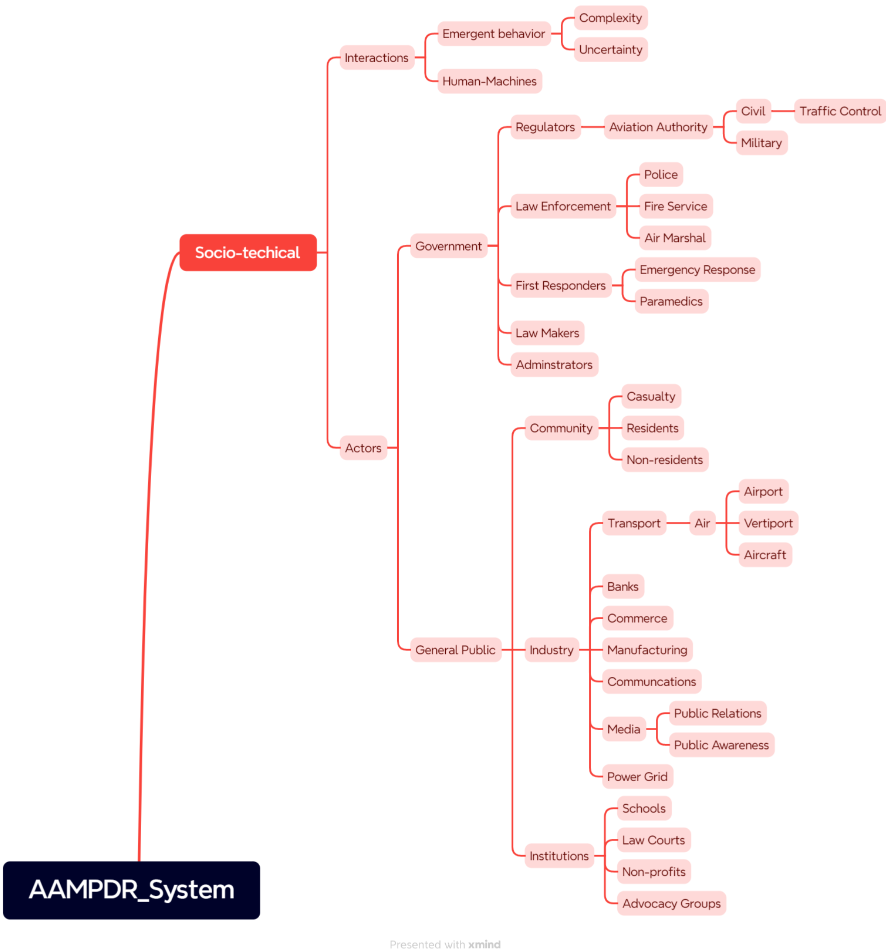

Figure 10. Section 4 of 4 of the Mind Map for the AAM Post-Disaster Response (AAMPDR) System.

7. Design and Architecture: Systems architecting may be described simply as the creation and construction of a system from its inception to termination [56]. It is important to note that system architecting is both a science and an art form, as Maier and Rechtin [56] noted. Furthermore, the ANSI/IEEE Standard 1471-2000 defines systems architecture as

> . . . the fundamental organization of a system embodied in its components, their relationships to each other and to the environment and the principles guiding its design and evolution [57].

Another simple and succinct definition that is instructive was given by Hilliard et al. [58] as

> . . . the highest level conception of a system in its environment [58].

In relation to the Mind Map depicted in Figure 10, the system design process may involve several approaches, such as the Waterfall model, or, as in this case, the system 'V' life-cycle process, which may entail both physical and logical architecture. The stakeholder requirements are first elicited through a stakeholder expectation discovery process, which is then followed by the development of formal system requirements towards ensuring that the stakeholder needs are met [59]. The stakeholder discovery information feeds into the Concepts of Operation (ConOps) and activity diagrams, which inspire the logical and physical system architectures. These diagrams or models are conceptualized through a Model-Based System Engineering (MBSE) framework and implemented using the System Modeling Language (SysML), as represented in Figure 10.

8. Research and Development (R&D): Creswell and Creswell [60] defined research as the process of making claims and then improving or discarding the same for others that are more firmly grounded. The ideas gathered from research may further be applied to developing other ideas, products, or services for the advancement of mankind. At the core of its research and development are two (2) primary drivers identified for the AAMPDR system, namely, science and technology, as indicated in Figure 11. Other branches that are relevant to the SoI are also noted, including aerospace, systems, and software engineering, as well as the natural and social sciences where key factors are researched and taken into account, including public perception and acceptance, which may easily be overlooked by the design team. For instance, in effectively facilitating its research objectives on the AAMPDR system, an R&D team that prioritizes public safety as part of its research objectives may also be interested in assessing and analyzing public safety factors by conducting a survey of public perception, a component that is already identified on the Mind Map, as shown in Figure 8, thus showing the invaluable benefits of the Mind Map as a tool that helps the systems thinker connect the dots.
9. Integration and Testing: According to Engel [61], integration is the highlight of the system life-cycle phases that entails the implementation of subsystems being synchronized into a realized system that meets the system requirements. For this purpose, integration is heavily dependent on interfaces, while whatever is being integrated is considered as a black box [62]. Points of interfacing for the AAMPDR system may include the data communication interface, which can range from the transmission of flight data between the ground control station to the airframe units, to data gathering and analysis of casualty medical records as a way of determining which appropriate medication should be administered to each casualty that requests medical intervention to be executed in a way that will not violate privacy protection laws, such as the Health Insurance Portability and Accountability Act (HIPAA) in the United States [63]. In terms of modeling and simulation, testing is determining whether or not inaccuracies or errors exist in the model while it is subjected to training datasets, use cases, or user story testing. A number of testing techniques may be applied during the V&V process for the AAMPDR system, including walkthroughs, consistency checks, scenario-based testing, interface validation, and so on, some of which are shown in Figure 10 [62].

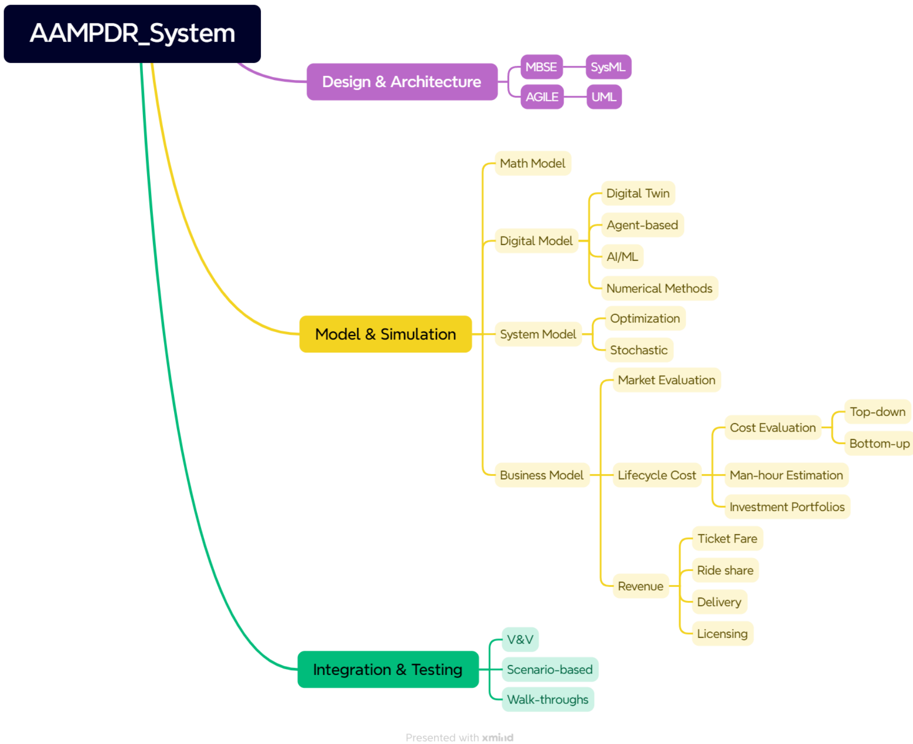

Figure 11. Section 3 of 4 of the Mind Map for the AAM Post-Disaster Response (AAMPDR) System

3.2. The AAMPDR System—TRIZ

Above Ground Level (AGL) Rule

Based on the four fundamental navigators of TRIZ briefly mentioned in Section 2.2, the first of the problem statements discussed in Section 1 may be conceptualized as a separation between the conflicting properties of space and the measurement in accuracy of the pressure parameter. Those are the key binary contradictions, where space refers to the environment in which the AAM airframe unit traverses from its station of origin (that is, home) to the location affected by the natural disaster before making a return flight home. Meanwhile, the latter relates to the effectiveness of on-board sensors in accurately measuring barometric pressure, thereby determining the vertical height, Z_{AGL}, of the AAM airframe unit from a reference position while in flight, as illustrated in Figure 3.

By further localizing the scenario to the Gulf of Mexico, USA, the TRIZ technique may be applied to identifying and resolving potential conflicts encountered during the deployment of the AAMPDR system for SAR operations following the event of a hurricane disaster around the Mobile bay area. Recall that the 14 CFR Part 107 rule strictly specifies that the flight altitude for a sUAS with a takeoff weight of less than 55 lbs has to be under 400 AGL [64]. However, what happens when atmospheric pressure drops below the standard conditions of 29.92 inHg (or 1013.2 hPa), taking the barometric pressure reference at mean sea level? An event such as this may typically be associated with atmospheric conditions following meteorological disasters, including a tropical cyclone [65,66]. Moreover, this could potentially trigger erroneous isobar readings from the digital altimeter or pressure sensor, leading to loss in flight level, a scenario that could further subject the sUAS/UAV to the risk of being submerged as it approaches rising flood water levels around its direction of travel, as illustrated with the aid of a diagram in Figure 4. Erroneous barometric readings are by no means the only potential problem that could arise when AAM airframe units traverse turbulent water bodies. The following contribute to the increased risks caused by over-water navigation of AAMs: signal loss owing to wave frequency interference within the first Fresnel zone, attenuation of infrared signal reception due to refraction, and reflection and absorption phenomena as transmitted signals propagate and fluctuate over water. The latter could depend on the degree of changes in texture and translucency of the water surface below and unreliability associated with GPS signal reception. Similarly, this could also occur with the use of ultrasonic sensors partly owing to the Earth's curvature, which limits the horizon range. Others include challenges relating to the affordability and suitability of deploying alternative or enhanced GPS receiver solutions such as the Wide Area Augmentation System (WAAS), inconsistencies in altimeter readings with regards to the ground level at point as reference, and much more [67–70].

For proper context, a contradiction such as the one described here is regarded in TRIZ as a model of conflicts within the system that places incompatible requirements on the functional properties of components, which give rise to such conflicts [41]. Thus, could TRIZ be applied to address this resulting conflict or technical flaw that appears to originate from an ambiguity in the 400 AGL requirement?

A mock-up scenario is depicted in the work by Williams and the RNLI [22], with visual images showing where a UAV platform is used to provide aerial support in an SAR exercise by crew members of the Royal National Lifeboat Institution (RNLI), some of whom were depicted as administering care to a fictitious casualty.

Applying the Contradiction Matrix

For illustration, consider a design decision to improve the UAV reaction to changes in barometric pressure and thus make self-adjustments to its flight level depending on the reference level at any given point in time, yet without compromising the accuracy and efficiency of its measurement reading on the digital altimeter or pressure sensor onboard. In other words, an ideal solution here would be one that ultimately results in a more dynamic or flexible design requirement.

Using the contradiction matrix and based on the criteria outlined above, the following pair of technical parameters may be selected for improvement:

- Parameter #11: Pressure
- Parameter #28: Measurement accuracy

At the intersection of these two selections are the following sets of suggestions derived from the forty (40) innovative principles (6, 28, 25), which may be further expiated as follows:

- Principle #6, which corresponds to Universality, may be interpreted as specifying a more consistent reference or datum, one that is invariant regardless of varying conditions that the aerial vehicle might encounter while in service. A fitting recommendation may also be to adopt a universal terminology that would more appropriately describe this barometric reference within the FAR rules, such as:

    1. "mean sea level" as opposed to "above ground level",
    2. "vertical height" or "flight level" as opposed to "flight altitude".

    This may help to reduce ambiguity for the systems engineer and domain expert when developing parts of the system of interest. For instance, measuring altitude from ground level is subject to variation due to differences in its elevation or gradient with respect to the mean sea level. However, the term "vertical height" is less subjective in meaning once the barometric reference is set to mean sea level. Hence, in addition to the AGL term, a case for the inclusion of an Above Mean Sea/Water Level (AMS/WL) clause within the 14 CFR Part 107 rule that caters to special SAR scenarios such as this may be justified.
- Principle #28, which correspond to "Replace mechanical system", which may be adapted or interpreted as a replacement of the appropriate electrical system. Thus, in this case, the altimeter may be replaced by a more efficient device that will improve its ability to measure vertical height or flight level more accurately. Examples of such recommendations may be for the system developers to implement Global Navigation Satellite System (GNSS)-enabled altimetry. Other alternatives involve using high spatial resolution technologies, including Lidar, Sonar, and Radar, such as described

by [25,26], or Ground Penetrating Radar (GPR) that could detect waterbed depth or elevation above the water surface, as discussed by Bandini et al. [71].

- Principle #25, which corresponds to "Self service". A parallel for this would be synonymous to incorporating some level of automation or autonomy and situation awareness into the architecture of the AAMPDR system. In other words, an implementation of a flight controller with autopilot software that is capable of self-calibrating the static pressure on the digital altimeter to match with the reference pressure of its immediate environment, similar to the way a human pilot would assist in updating flight instruments onboard a general aviation aircraft. This may be executed in combination with the other two actions to achieve the desired results.

Thus, using the contradiction matrix, it is possible to envision a solution to the parameter-measurement accuracy conflict/problem earlier defined by devising a technology that maintains a uniform altitude above the ground with reference to an AMS/WL clause and potentially prevent the loss of AAM airframe equipment by submerging in water during its course of operation. Therefore, the solution to this problem is graphically illustrated in Figure 12 as a vertical height, Z_{AMSL}. Thus, with the global mean sea level as a reference, the likelihood of the AAM being submerged as inland flooding rises is significantly minimized.

Figure 12. Above Ground Level (AGL) as local reference for AAM SAR flight above inland flood.

Fifth-Generation (5G) Infrastructure

The remedies proffered by the FAA and FCC as described for the second problem introduced in Section 1 are not without their limitations and challenges. Firstly, the airworthiness directive appears to be limited to transport category airplanes, that is, traditional aviation, not emerging AAM concept vehicles. Also, the resources required to satisfy these requirements could come at some cost to the aircraft operators and manufacturers. More importantly, while this intervention is noteworthy, the future remains unclear as to whether or not this is a temporal or lasting solution. The latter seem unlikely given the expectation of evolving technological innovations. Moreover, UAVs and sUASs are subsets of the AAM class, which already have digital links for analog communication in situ through the RC transmitters and receivers that broadcast signals on either 72 MHz or 2.4 GHz [72]. Their respective transmitters also have drawbacks, with the former being prone to co-channel interference. Although the latter supports frequency hopping as a counter measure to co-channel interference, it is, however, susceptible to disruptions by obstacles along its paths and requires that Line of Sight (LOS) is maintained [72].

Furthermore, what happens following the advent of a newer broadband communication technology, an eventuality that a systems thinker must grapple with? Would that require another upgrade of on-board instruments? Could a simpler solution be proposed using the TRIZ methodology, one that is cost effective and possibly invariant to ever-changing technology?

The problem is evident. For illustration, a sample of the mission profile is presented in Figure 13. It depicts the use case of an outbound airframe unit that takes off at a designated station, climbs to some predetermined flight level, proceeds at cruise speed to the affected location, loiters before making a routine drop–off of relief aid to the casualty at a pre-designated location, embarks on a return flight, and completes the mission by making a schedule descent and landing. It is important to note that there is a 200 ft baseline for the ceiling where the decision has to be made and corresponds to the Decision Height (DH), as previously described. Here, it is denoted as 'red zone' where there is a possibility of frequency interference at different stages of the flight mission when the airframe unit of a proposed AAMPDR system comes within the vicinity of 5G towers, as determined by the parameter DH indicated in Figure 14.

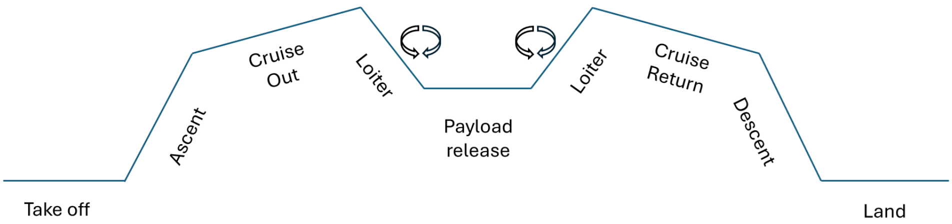

Figure 13. Sample mission profile of the AAMPDR system on SAR.

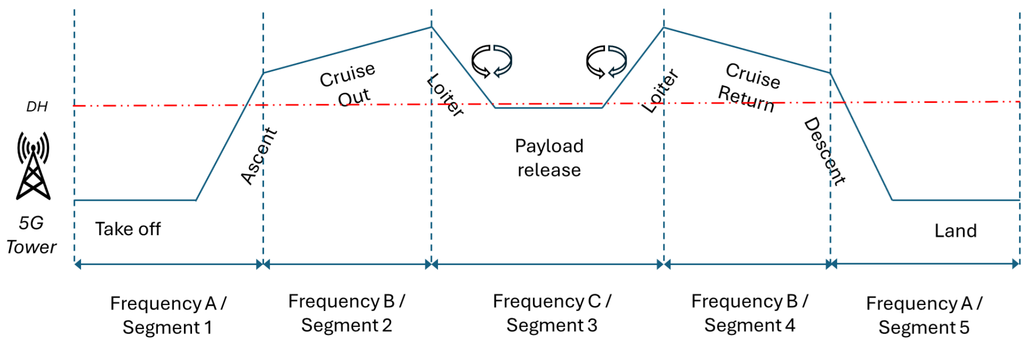

Figure 14. Segmented mission profile of the AAMPDR system on an SAR mission.

5G—Applying the Contradiction Matrix

In applying TRIZ to the problem described, consider two (2) competing objectives. Firstly, the potential frequency interference, which requires improvement. Secondly, the objective crucial to the success of the mission, which is the collection of different stages/segments that make up the mission profile and include a critical sequence to be executed autonomously[4] in Segment 3. On the contradiction matrix, each objective corresponds to the following technical parameters, respectively:

- Parameter #37: Difficulty of detecting and measuring
- Parameter #35: Adaptability or Versatility

At the intersection of these technical parameters are the following pair of suggested innovative principles, (1, 15), which correspond to the principles of Segmentation and Dynamics. Owing to scope, the following discussion has been limited to the former only[5]:

- Principle #1, which corresponds to Segmentation. One way to achieve this may be to divide the mission profile into multiple stages and for each stage to transmit a unique frequency. To make this possible, this multi-stage frequency transmission would need to be able to switch seamlessly between two bands. The objective is to maximize efficiency with which frequencies are transmitted and minimize attenuation in signal transmission with respect to space, or otherwise vertical height. While its application might be new in terms of enabling digital link communication in AAMs, the overarching concept is not, as a similar approach has been applied towards multi-stage gear transmission [73]. Using the mission profile, it is possible to present a generalized example illustrating how its segmentation could be implemented, as shown in Figure 14. Further, a specific use case may also be demonstrated that shows the segmentation of the mission profile for a UAV operating at 400 ft. The proposed bands for AGL are shown in Figure 15, and the proposed RF spectrum allocation to support the same is shown in Figure 16. Reading from left to right, Figure 15 indicates a 200 ft threshold below which transmission takes place at 4.7 GHz and above which the on-board navigation instrument will broadcast at 2.4 GHz. While a relatively higher frequency is suitable for short range and high data rate demands, it is also susceptible to attenuation. Furthermore, with the increase in distance there is the likelihood of a corresponding increase in interference. This is the rationale behind designating 4.7 GHz to flight regimes at an altitude within 0–199 ft. Conversely, 2.4 GHz is designated to flight regimes at an altitude within 200–399 ft since relatively lower frequencies correspond to lower signal attenuation, which is also suitable for long distance communication. Bear in mind that the choice of 4.7 GHz was arbitrary for the purposes of demonstrating this specific example as a potential use case. This decision was partly informed by a gap in interval between the upper limit for the ARS band (3) and the transmission frequency (5 GHz) for wireless IEEE 802.11 radio networks, colloquially referred to as Wi-Fi [50]. Thus, Figure 16 shows a proposed band spectrum for AAM consisting of three separate frequencies which could be implemented depending on the designation of choice, that is, 2.3–2.6 GHz, 3.6–3.9 GHz and 4.6–4.7 GHz.

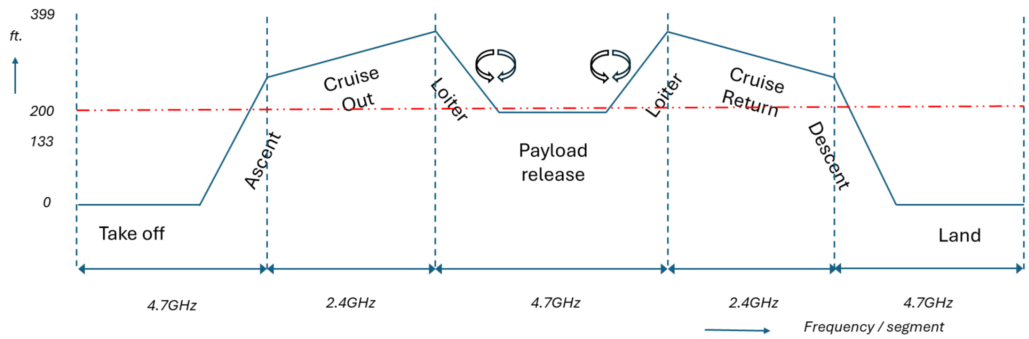

Figure 15. Radio frequency spectrum allocation showing a proposed band for AAMs.

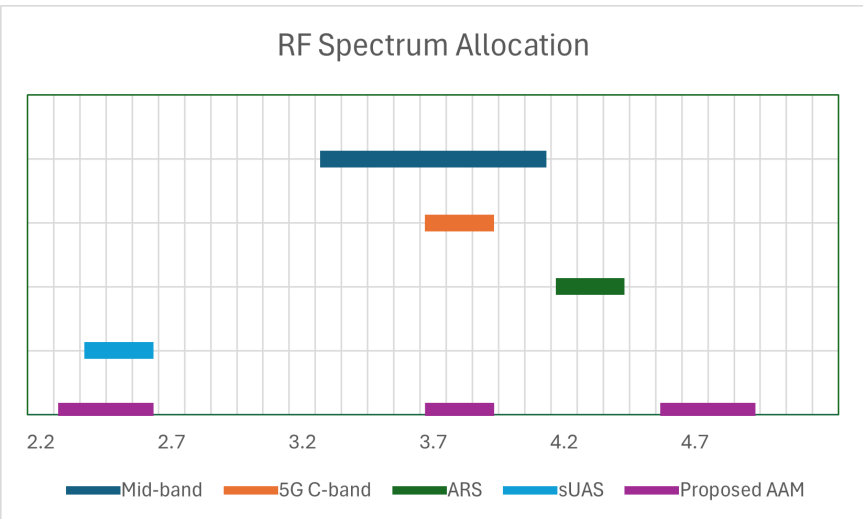

Figure 16. Radio frequency spectrum allocation showing a proposed band for AAMs.

4. Conclusions and Future Work

In this work, two (2) systems thinking tools, namely Mind Map and TRIZ, were applied, resulting in a comprehensive analysis covering wide ranging aspects of the system of interest, an AAM Post-Hurricane Disaster Response AAMPDR system. The key topics addressed and discussed at length include (but are not limited to) customer realization, such as a resident and casualty of the immediate surroundings affected by the hurricane disaster, and the identification of potential conflicts, such as the 14 CFR Part 107 rule, which does not explicitly cater for scenarios where the AAM airframe traverses above water.

A Mind Map depicting the granularity of organizational divisions entailed in envisioning the AAMPDR system was conceptualized. In addition to the main root, which is the AAMPDR system itself, nine (9) core concepts, including operations and management, environment, safety and risk, requirements, research and development, socio-technical systems, design and architecture, model and simulation, and lastly, integration and testing, were identified. Each of these concepts was further sub-divided into branches, highlighting the contributions of each leaf to the whole system. Furthermore, the Mind Map of Figure 7 may be applied and developed by other researchers as a template for other AAM concept vehicles since the factors identified are as generalized as possible.

Furthermore, the Mind Map was utilized to stimulate new efforts into investigating the interconnections between these nine core concepts as they pertain to the AAMPDR system in a way that would otherwise not have been possible. For context, the reader's attention is drawn to the interconnection between the Environment and Safety & Risk nodes. It may be recalled that, through the application of the Mind Map, insights into the behavior of raptors as system actors, and the potential risks posed through their interactions with the SoI, could result in mission failure. Interestingly, further investigation to test this hypothesis led to the discovery that the Mobile bay area, earlier identified for this specific use case as a place of interest for future SAR intervention following a natural disaster, indeed hosts a thriving avian habitat, as documented by [74]. Thus, this realization lends credence to the anticipated risks inherent within the system's operation, which otherwise may not have been foreseeable without the application of a Mind Map. In retrospect, this risk factor can now be taken into account, thereby improving the system design process.

The TRIZ process was also discussed, and the steps involved were also illustrated in the form of an algorithm and flow chart. Furthermore, by applying the contradiction matrix, solutions to two problems were suggested, with the first being in regards to a contradiction with the AGL rule. Here, the parameters of Pressure (which corresponds to #11 on the left-hand-side row field) and Measurement accuracy (which corresponds to #28 on the topmost column field) were identified using the TRIZ approach. The next steps involved obtaining the corresponding set of principles at the intersection taken from the overall forty (40) innovative principles. Thus, the recommended principles were 6, 28, and 25, which correspond to Universality, Replace mechanical system, and Self service. Finally, these recommendations were applied to proposing a modification to the in situ 14 CFR Part 107 rule by the inclusion of an "Above Mean Sea/Water Level" (AMS/WL) specifier to the already existing "Above Ground Level" (AGL) terminology, which will help clarify, specify, and verify the barometric pressure reading of 29.92 inHg as the static reference.

The next demonstration of the TRIZ technique was with regards to the second problem involving the advent of the 5G C-band network and the possibility of its unanticipated interference with broadcast frequencies for altimetry on board the airframe unit of the AAMPDR system. Applying the contradiction matrix resulted in the identification of the principle of Segmentation as a proposed solution to this problem. This principle was applied accordingly by dividing the mission profile for a typical SAR mission. This effort was further complemented by the designation of lower 2.4 GHz and higher 4.7 GHz frequency bands to vertical heights below and above the threshold of 200 ft in an attempt to minimize the possibility of interference of signals for the altimeter from a nearby 5G C-band tower.

In a subsequent work, the authors plan to expand on these ideas by analyzing the AAMPDR system using other systems thinking tools, including CATWOE, Conceptagon, and Systemigram. This effort will be followed by a demonstration of how the AAMPDR system may be implemented from a systems engineering perspective through an MBSE approach. This would include producing SysML artifacts of the AAMPDR system architecture, including Activity diagrams that incorporate the key elements discussed here, such as the inclusion of a checklist of pre-deployment activities that the ER ground support and UAV air support teams shall follow in coordinating and executing a safe SAR intervention in areas prone to tropical cyclone disasters.

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Data Availability Statement: The original data used to generate the Mid band, 5G, ARS and sUAS frequencies in the RF Spectrum chart of Figures 5 and 16 were referenced from works by Sobieralski [16], Leslie [17] and Quan [72].

Conflicts of Interest: Author John T. Wade was employed by the company Gulf States Engineering. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Acronym	**Definition**
AAM	Advanced Air Mobility
AAMPDR	Advanced Air Mobility Post-Disaster Response
AGL	Above Ground Level
AMSL	Above Mean Sea Level
BVLOS	Beyond Visual Line of Sight
CFR	Code of Federal Regulations
EMS	Emergency Medical Services
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FEMA	Federal Emergency Management Agency
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HIPAA	Health Insurance Portability and Accountability Act
LAANC	Low-Altitude Authorization and Notification Capability
LEO	Law Enforcement Officer
NAS	National Airspace System
NASA	National Aeronautic and Space Administration
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
SAR	Search and Rescue
SoI	System of Interest
SysML	System Modeling Language
TRIZ	Teorija Rezbenija Izobretatelskib Zadach
UAM	Urban Air Mobility
UAV	Unmanned Aerial Vehicle

Notes

1 DH parameter is denoted on Figure 15.

2 Refer to [43] for complete list of the 40 principles.

[3] Refer to [40,43] for comprehensive table on the contradiction matrix.
[4] The reader should note that the underlying assumption here is that the flight is fully autonomous, thus requiring some level of situation awareness and agility.
[5] It is noteworthy to mention that while the TRIZ technique offers several pathways to exploring a problem, it is not compulsory for all of these suggestions to be explored before arriving at a feasible solution that is useful and satisfactory.

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