MRO FOR VTOLS IN A FUNCTIONAL SEQUENCES SOLUTION SPACE

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Abstract

A crucial aspect of emission reduction in urban environments is the development of electrically (or hydrogen) powered vertical take-off and landing vehicles (eVTOLs) and the corresponding infrastructure planning. To ensure the continuous use of these vehicles for urban passenger transport, proactive maintenance methods, plans, and intervals must be established for so-called Vertistops, Ports, and Hubs. In addition to the maintenance schedule, safety restrictions, risk levels, failure modes, and failure hazard analyses must be conducted for taxiing, the maintenance process, and energy management to assess potential safety risks and ensure accident-free operation. This paper provides a literary overview of the current research on maintenance measures and methods. It addresses the maintenance schedule via checklists and presents a revised functional overview for maintaining eVTOLs. Our approach transfers the conventional maintenance planning of airplanes and helicopters using checklists into Business Process Model and Notation (BPMN) diagrams, extended with attributes for the temporal and spatial design of Vertiports. The expansion of the solution space also includes the classification and generation of synthetic damage data for eVTOLs, which is intended to serve as a suggestion for further work in this area. Finally, we conducted a comprehensive safety analysis for the scenario of pre-flight maintenance using an inspection drone, which, in addition to purely visual inspection (e.g., through Smart-Hangar approaches), constitutes part of our solution space."

Keywords: MRO, Maintenance-Checks, UAV, AAM, Vertiport-Processes, BPMN, Swimmlanes

1. Introduction

Following Uber's whitepaper [1], it is assumed that the maintenance costs per flight hour for electric VTOLs are considerably lower compared to those for a light helicopter, approximating a reduction of about 50% in total maintenance costs. The hypothesis of lower maintenance costs is based on the elimination of all cyclic rotor components replaces by electric motors which only have one single moving part (bearing). Friction, which is the primary cause of maintaining certain components, does not pose a significant issue [2]. On the other hand, the strong magnetic field generated by the rotor's permanent magnets has an aging effect on the bearings. The magnetic field emanating from the electric motors can induce currents in the bearings, which can lead to electrical erosion, so-called electrical discharge machining (EDM) [3]. In addition to the effect of EDM, the induced currents can also cause the bearings to heat up. This heating leads to an accelerated degradation of the lubricant, resulting in increased wear and premature maintenance of the bearings [4]. Abdalmagid [5] analyzes and simulates an overview of the influences of parasitic effects on the electric motors in an eVTOL, assuming a permanent magnet synchronous motor in which the longevity of the motors is due to the inverters.

According to Hein [2] the bearings, including those effects, have a long lifespan and ensure durability. The lifespan of solely the electric motors can reach up to 10,000 hours of operation which is in comparison to the 5000 hours of most helicopter gearboxes and swash plates a significant improvement. Maintenance efforts are assumed to be similar to existing helicopters (e.g. R22 and R44, see [6]), involving daily visual checks and minor maintenance every 100 hours. Major maintenance would be conducted annually to bring the vehicle back to its original specifications.

One of the primary challenges in Maintenance, Repair, and Overhaul (MRO) for Urban Air Mobility (UAM) is dealing with regulatory tasks specific to individual vehicles, as highlighted in Schoppmann's research [7]. By now there are a lot of different types of eVTOLs in different sizes, with different PAX numbers, ranges, symmetries, freight compatibility, hydrogen alternatives, etc.. Due to these different types of vehicles it is not possible to create standardised maintenance concepts [8]. Our solution therefore presents a tool that is modularly expandable. If we were to proceed according to the classic concepts of aviation, which are presented in section 1.2- 1.5, we would need a different checklist for each vehicle type, requirements for ground personnel and different charging options, as some vehicles such as the *Lilium* Jet can only be charged [9] and the *Volocopter* Volocity can only be battery swapped [10].
Establishing UAM infrastructure dedicated to maintenance after flights is crucial for ensuring the success and safety of operations [11]. Additionally, a significant challenge lies in securing an adequate energy supply to recharge drones between flights. In the realm of MRO services for UAM, various institutions, including independent companies, vehicle manufacturers, vehicle owners, or service providers, may offer these services [12]. However, due to the stringent safety and security standards inherent in aerial transport, any MRO company operating in this domain will face strong certification criteria and must ensure consistently high levels of quality [13, 14]. This includes the establishment of maintenance regulations governing both the operation and related personnel involved in UAM maintenance activities.
Our most important contributions are the following:

- We explain the classification of MRO methods in aviation. We divide the strategies into planned, unplanned and predictive maintenance concepts. We explain the advantages and disadvantages of the respective methods and give a statement as to which of these concepts is suitable for the field of electric aviation.
- We give a literary overview of how eVTOL related MRO topics are distributed to illustrate the relevance of this topic.
- We transfer the check-up tables of conventional aircrafts to eVTOLs and approximate the content of the maintenance, the time required and the location the .
- We provide the extension of our tool, which displays classic check-up tables as swimlanes in order to extend them modularly with the approximated times, generated damage data and security checks.

1.1 Maintenance Approaches

Current MRO (Maintenance, Repair, and Overhaul) methods in aviation are divided into scheduled and unscheduled maintenance. Another method currently gaining industry focus is predictive maintenance [15], which involves continuously monitoring the condition of active and passive components to determine the optimal time for maintenance to minimize costs. This paper addresses scheduled and unscheduled maintenance for eVTOLs due to the lack of data necessary to train predictive algorithms, although the future potential of predictive maintenance is also highlighted.
Unscheduled maintenance occurs if an issue or finding is identified during scheduled maintenance checks, potentially delaying the maintenance process. Concerns exist regarding type certification, particularly with the challenges of implementing predictive maintenance practices before the safe operation of the aircraft is demonstrated. Machine learning models for maintenance and inspection require substantial data, which can be challenging without existing data. An alternative is synthetic data generation from eVTOL simulators.
Daily or weekly checks are feasible and supported by EASA regulations [16]. Predictive maintenance becomes more practical once adequate data is collected. Operating smaller eVTOLs, particularly in the open environment of a vertiport, presents challenges. Initial flights are expected to be conducted by wealthy individuals using existing heliports for eVTOL operations.
An expert interview with an eVTOL maintenance engineer revealed that maintenance procedures, similar to those at Lilium, focus on consistent checks, including unplanned maintenance triggered

by events or routine inspections. Components such as fans or bearings require regular inspection as motor repairs might not be feasible in the field. Charging the vehicles to 20-80% takes about 30 minutes. Daily checks take approximately 30 minutes, with a flight-to-ground time ratio of 0.5 (30 minutes flying followed by landing). Normal transport aircraft operate 1,800 hours per year, with weekly checks requiring about 5 hours of ground time. Monthly or quarterly longer maintenance sessions of 24 hours, and annual 48-hour sessions, are necessary.

Pre- and Post-Flight Checks

Pre- and post-flight checks, ideally completed within 10-15 minutes, can be conducted by pilots if maintenance personnel are unavailable. In case of discrepancies, team intervention or a "minimum equipment list" is necessary. Comparatively, maintenance hours for eVTOLs are fewer than for larger aircraft, but specialized VTOL mechanics may incur higher costs. Engine replacement should occur within 60 minutes, and charging to a 20-80% capacity takes roughly 30 minutes. Initially, maintenance is nominal, with approximately 1,000 charging cycles. A flight cycle lasts around 0.5 hours, covering roughly 175km. Development has recently commenced on constructing an entire battery pack [17]. For the pre-flight and overnight check, the condition of the monitored components such as the high-speed bearings in the motor core should be checked. These bearings are crucial for the smooth operation of the electric motor and must be inspected regularly and replaced if necessary. Electric motor windings must also be checked for possible short circuits, as these can be caused by contamination, abrasion, vibrations or voltage peaks. Another critical point is to check the insulation components for thermal damage. Overheated insulation materials can lead to power losses and impair the efficiency of the motor. Therefore, all insulating parts should be carefully inspected for signs of overheating or damage. For aircraft with permanent magnet motors, it is also necessary to inspect the magnets for safety and condition. Loose or damaged magnets can significantly affect the performance of the motor and must therefore be closely monitored. Special attention should also be paid to the high-performance batteries. These require special inspection and repair protocols. The connectors of the removable, rack-mounted batteries should be checked for damage, as such damage could affect the electrical connection. In addition, it is important to identify any potential impact damage that could occur when removing or installing the batteries. Individual battery cells may need to be inspected and replaced, which requires careful disassembly of the battery pack. For vehicles with distributed electric drive technology, all propulsion components must be fully functional both individually and in the integrated system. Therefore, all drive elements should be checked for operational readiness [18].

1.2 Scheduled Maintenance Approaches

The maintenance frequency for eVTOLs is currently not uniformly established, given that this aircraft category is still in the developmental and certification phases. However, the European Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA) have subjected eVTOLs to the most stringent safety requirements, indicating the necessity for an exceptionally comprehensive safety approach for these aircraft. According to Sieb [19] MRO requirements for a new aircraft type are determined by a maintenance review board consisting of experts from the manufacturer, authorities and operators. The resulting time between overhauls can be divided into Flight Hours, Cycles (FCs) and calendar days [16]. As eVTOLs are expected to operate in various modes, such as passenger or cargo transport, the maintenance frequency is likely to depend on specific operational demands and regulatory mandates. At present, it remains to be seen how the maintenance intervals for eVTOLs will evolve when these aircraft are commercially deployed in the future.

In Figure 1, the traditional inspection intervals for most aircraft are summarized. The maintenance checks have different frequencies and durations depending on their type. A type A check is repeated every 250 hours of flying or every week and involves visual inspection of major systems for about eight hours. A type B check is repeated every 300–600 hours of flying and lasts around 1–3 days. Type C and type D checks are repeated once every one to four years and can only be completed at specialized hangars in about one month.

In comparison eVTOLs are generally "small" flying vehicles, for which the traditional maintenance strategies mentioned in the literature are sufficient. Original Equipment manufacturers (OEMs) usually assume taxiing or towing of the vehicle, as illustrated in our previous paper [20] with an automated guided vehicle (AGV). Some eVTOL manufacturers do not differentiate between the various checks and only perform maintenance when a defect occurs (unscheduled maintenance). In most cases, the fans/propellers or bearings are maintained, which represent the most significant challenges for these vehicles. If a motor is defect, it cannot be repaired at the vertistop or vertiport; instead, it must be replaced at a maintenance port or by maintenance personnel. The research gap in the maintenance of eVTOLs [21, 22] involves the significant monetary effort required for training maintenance personnel [23]. Ideally, OEMs want pilots to perform most basic maintenance tasks themselves, as it is not feasible to have maintenance personnel at vertistops. Therefore, pilots must also be trained in maintenance and defect identification. To expedite this training and reduce costs, a virtual training environment as well established as the Computer Based Training (CBT) of *Airbus Helicopters* for pilots could be beneficial. If everything is in good condition, the system works well, but if not, a team must be dispatched, or a "minimum equipment list" must be used. Maintenance hours are fewer compared to larger aircraft, but mechanics specialized solely in VTOLs can be very expensive if they do not perform other tasks as well. A pre-flight check should not take longer than 10–15 minutes, and within 60 minutes, for example, one of the 30 engines should be replaceable.

Event	Interval	Scope	Ground Time	Man-Hours
Trip-Check	Before every flight	Tour around aircraft Cabin and cockpit check Checking the amount of fuel Cleaning of the cabin	35 min	0,5
Service-Check	Weekly	Filling of all operating materials Advanced cabin cleaning	4 h	20
A-Check	After every 250 flying hours	Service-Check Additional booth and system control	6 h	40
C-Check	Every 13 Months	A-Check Detailed structural check and extensive system tests Partial removal of the cladding	30 h	700
R-Check	Every 15 Months	Cabin overhaul	Parallel to other checks	10
IL-Check (Intermediate Layover)	Every 4 Years	Thorough overhaul of the cabin and structure Polishing and touching up the exterior paintwork	2 Weeks	12000
D-Check	Every 8 Years	Overhaul of the cell (all systems) Replacement of large components Repainting Intensive cabin overhaul Includes all other checks	4 Weeks	30000

Figure 1 – Example for a traditional Maintenance checks for commercial aircrafts Vorlesung

1.3 Unscheduled Maintenance

Unexpected maintenance refers to events triggered by incidents that can lead to the failure of components or entire structures of the vehicle. A classic example of such an event in traditional aviation is a bird strike. Only in the US there are over 13,000 bird strikes in the US alone [24]. Events like these are impossible to predict, which is why guidelines from the FAA or EASA exist, outlining the procedures to be followed in such cases. It is expected that eVTOLs operating in urban airspace will utilize distributed landing sites across the city. Given the anticipated high utilization of eVTOL fleets, it is likely that a vehicle will occasionally be grounded at one of the vertiports for unscheduled maintenance. In this relation the questions arises of how vertistops or vertiports be designed to enable maintenance work and what kind of events can lead to unplanned MRO? For eVTOLs or electrical aircrafts which are designed to have a nose propeller or like the *Rolls-Royce* ACCEL or the *Beta Technologies* Alia-250, propeller strikes are one example of unplanned events, often caused by the propeller contacting the ground due to landing gear collapse, failure to extend the landing gear, or nose-over incidents. In the event of a propeller strike, the engine usually needs to be completely overhauled or replaced, which can be very costly for the owner. Additionally, aircraft affected by a propeller strike are typically out of service for several weeks or months [23]. For aircraft with rear-mounted propellers, the greatest risk of a strike occurs when there is insufficient clearance of the hangar doors above the ground. It is important to consider hangar clearance to ensure that the availability of hangars for general aviation at small airfields does not limit the demand for these

aircraft. According to the study conducted by Naru [23], vibrations are the main reason leading to unscheduled maintenance tasks, at least in combustion engines. The study suggests that 70% of unplanned maintenance can be attributed to damage caused by vibrations. Vibrations in helicopters with combustion engines are primarily caused by rotor blade imbalances, natural engine vibrations, the complex gearbox system, and turbulent airflows. These factors lead to significant oscillations, which can be exacerbated by wear, damage, or uneven wear of the rotor blades [25].
In contrast, eVTOLs with electric motors have different causes of vibrations. Major sources include electrical discharges, particularly in motors with permanent magnets, which can occur due to insulation faults or unwanted electrical paths. Propeller imbalances, caused by manufacturing defects, wear, or damage, also contribute significantly. Additionally, electric motors can produce resonances in certain frequency ranges, exacerbated by mechanical or electromagnetic influences. Structural vibrations arise from the operating frequencies of the motors and can be worsened by poor material choices or insufficient damping. Finally, electronic disturbances from motor control, such as unstable power supply or interference, can also lead to vibrations [26]. To reduce this risk, companies like the lift-and-cruise manufacturer *Beta Technologies* hire service providers like *GPMS* to create Health and Monitoring Systems (HUMS) to continuously record vibration data. Researchers like Meletis [27] have also addressed this knowledge gap and presented proposals on how such a system can be implemented for the Airbus A^3 Vahana.
To respond to unplanned maintenance in eVTOLs, monitoring and data-based prediction present viable solutions. Another possibility is the development of suitable ground infrastructure, as presented by Eltgen [28]. In combination with a minimum equipment list, which offers the necessary repairs to bring the vehicle to a maintenance site, the risk of unplanned maintenance can be minimized. Additionally, the vehicle type, materials used, and types of electric motors are of great relevance since the geometry of the vehicle can result in different types of damage.
In our advanced functional space in Section 2.1, we have implemented unplanned maintenance as event-based occurrences. In this context, we have included lightning strikes as unplanned events in our functional chain.

1.4 Research Gap

As shown in Table 1 maintenance in research for eVTOLs (Urban Air Mobility Vehicles) is divided into scheduling, ground architecture, relevance, methologies/implications and energy management and is dealt with in a rudimentary way. This tabular summary clearly shows that there is an industrial as well as a research gap in the MRO sector for electric vertical takeoff and landing (eVTOL) aircraft. According to Grandl [29], the projected market volume for UAM services, including insurance, MRO, and certifications, is 5 billion USD. It is alarming that, as of 2023, there is only one active publication [23] documenting MRO challenges. This publication calls for a training process for repair and maintenance personnel, including for electrical power plant mechanics. Additionally, it criticizes the battery handling (charging/swapping), the location of the installed battery, and the modularity for easy repair and maintenance. There are papers such as [28], [30] and [19] that cover the maintenance ground structure (MROPorts) and automated maintenance options, but the maintenance implications for these vehicles have not yet been covered in detail.
To close this knowledge gap, we focus in section 1.5 on the revised look-up table for eVTOLs, which we created using helicopter maintenance and our exchange with eVTOL OEMs. We derived a maintenance schedule from the intervals, as there are hardly any estimates of what maintenance intervals for UAMVs might look like. We published the solution to the maintenance scheduling problem in a separate publication at the ICAS conference [31].

Subfield	Keywords	Comments	References	Year
Scheduling				
	Airline maintenance scheduling	Maintenance regulation compliance, efficient resource allocation, competitor cooperation, workshop resource sharing	[32]	2020
	-	Tool for Maintenance Schedules, Downtimes, and Intervals	[28]	2023
	ATS, eVTOL, Current Developments, Challenges, Opportunities, Review	A-Checks: Once per week, Inspection of landing gear, engines, and control surfaces. B-Check: visual inspection and lubrication of parts. Preventive Check: 100h	[30]	2020
	UAM, Agent-based transport simulation, Maintenance Planning, On-demand operation	Identifying challenges in MRO planning for on-demand UAM fleets using agent based simulations	[19]	2023
Ground Architecture				
	Ground-based infrastructure, systematic literature review, Vertiport, air taxi	Automated Ground-Based MRO for UAM	[33]	2022
Relevance				
	-	Relevancy of maintenance hubs and to what monetary percentage could be saved	[1]	2016
MRO Methodologies				
	MRO, Ground-Based Infrastructure, Skyport, UAVs	Technical concepts for inspecting UAVs for damage	[34]	2022
	Maintenance Challenges, Electric Propulsion Concept, Review	Maintenance considerations for electric aircraft and feedback from aircraft maintenance technicians	[23]	2018
Energy Management				
	Aircraft; MRO; Battery, Fuel cell; Life cycle sustainability assessment	Estimation of maximum operating lifetime of batteries, fuel cells, and electric motors for more frequent replacements.	[35]	2023
	Electric Aircraft, Battery, Flight Dynamics, Simulation, Optimization	For the Batteries 7,000 charging cycles can be achieved with UAVs	[36]	2020
	UAM, eVTOL, HUMS, energy harvesting, battery heat monitoring, Data Acquisition Unit	Creation of a health monitoring system (HUMS) for eVTOLs on the example of the Airbus A3 Vahana	[27]	2021

Table 1 – Subdivision and summary of the scientific literature on the subfields of MRO for eVTOLs

1.5 Look-Up-Table

Derived from the traditional maintenance plan of aircraft [37] (using the example of the *Airbus* A310) and the Robinson R44 with which we legitimized and justified a comparison in the previous paper, we have created a revised table 2. The nominal values in this table are derived from the sum of the maintenance times required to maintain the various parts of the VTOL.
In terms of motor size, we differentiate between large electric PMSM motors such as the *Airbus* Citybus, which have high efficiency, high power density and low maintenance requirements. The size of this motor is approx. 1.20 meters (4 feet) per motor. For a scheduled and well thought-out maintenance scenario, replacing an electric motor in an eVTOL such as the CityAirbus takes 1-2 hours for preparation and diagnostics, 2-3 hours for removal of the old motor, 3-4 hours for installation of the new motor and approximately 1-2 hours for testing and calibration.

Event	Intervall	Scope	Ground Time	Location
Trip-Check	Before Every Flight	Tour around aircraft Cabin and cockpit check Checking the amount of fuel Cleaning of the cabin	max. 10 min	Vertistop,-port,-hub
Over-Night-Check	Daily	Repair of Findings Inspection of the Batteries SoC/SoH Inspection of all major systems such as landing gear, engines and control surfaces	0.5-2 h	Vertistop,-port,-hub
Weekly-Check	Weekly	Airframe visual inspection, battery (SoC/SoH) inspection (e.g. swelling etc.), test motor functionality, check control linkages, landing gear	4-6 h	Vertiport,-hub
A-Check	Monthly	Complete overhaul including paint, interior, and all systems, External visual inspection, filter replacement, lubrication etc.	8-30 h	Vertiport,-hub
Half-Yearly-Check	6 Months	Verify the proper functioning of all sensors (e.g., gyros, accelerometers) and actuators. Calibrate as needed, Test and service shock absorbers, Clean the entire aircraft, including the interior and exterior	1 Week	Vertiport,-hub
Yearly-(B)-Check	12 Months	Overhaul of parts that are approaching their lifespan, **BLDC/PMSM motors**, fans, batteries, Thorough inspection of the individual systems and components (if permanently installed)	2 Weeks	Maintenance Hub (also MROPort [28])

Table 2 – Checklist for the frequent scheduled checks for (e)VTOLs

Under ideal conditions, the entire engine replacement process could take between 7 and 11 hours. This estimate assumes that all the necessary tools and spare parts are available and that the maintenance personnel are well trained and experienced. All these time estimates are made under the assumption that no findings occur in the motor. For example, if a positional error is detected, which is one of the major maintenance targets in a permanent magnet synchronous motor (PMSM) due to its operation in hostile environments, the time required and the aircraft on ground (AOG) time increase rapidly [38]. In summary, a distinction must be made between the vehicle type (multicopter, ...), the motor type (BLDC, PMSM, ...) and the model (*Volocopter*, ...) when estimating the time required for a check (and the replacement of the motor is only part of the check) [39].
In our table 2 we have divided the maintenance processes into their chronological order analogous

to Figure 1 and estimated them using a time window. We have approximated a subdivision into trip, overnight, weekly, A, half-yearly and yearly checks. During the trip check, which is also known as the pre-/post-flight check, the cabins, cockpit, outer casing, etc. are checked for slight defects on the surface (e.g. dents and scratches). OEMs set a maximum limit of 10 minutes as a hard constraint. One problem formulation related to a thorough pre-flight inspection, according to [23], includes, that the motor and propeller located high above the ground can difficultly be maintained due to the potential lack of a scaffold or platform. Anoother difficulty occurs when the propeller was imbalanced for any reason, the tail structures might experience dangerous vibrational loads and require additional unscheduled inspection. During the overnight check, the vehicle is checked for damage and anomalies that were monitored during the day (e.g. vibration data from the HUMS). The vehicle's fault memory is read out during this process and more complex repairs can be carried out. The overnight check can be parallelized with the weekly and monthly checks, because the complexity of these checks can also be carried out overnight.

The limits of this method are the complexity and quantity of the checklists. In the "worst case scenario", one or more checklists must be created manually for each vehicle, which represents a considerable loss of time and consequently an economic hurdle. In preparing the maintenance plan, we analysed the overhauls of the robinson r44 and robinson r22 light helicopters in our last paper [20], modified them for eVTOLs in the multicopter class and evaluated them on the basis of sources and interviews with OEMs. Our approach avoids this hurdle by using BPMN diagrams to create a modular tool that can be applied to the solution space of all vehicles and vehicle types.

2. Methodology

2.1 Extended Swimmlane Diagramms

The paper aims to address the functional design aspects of vertiports, so different configurations can be carried out by a function-oriented description of a vertiport [40]. This paper introduce a solution space that includes possible functions and sequences (which was also presented in [20]) and outlines exemplary sequences. To build up the solution space it focuses on establishing a module-based design foundation considering various scenarios, offering a comprehensive range of functions. By utilizing Business Process Modeling Notation (BPMN) in swim lane diagrams, the study defines main functions and interfaces, offering insights into vehicle handling, passenger services, energy supply, and Maintenance, Repair, and Overhaul (MRO) processes.

Emphasis is placed on detailing various vertiport functions, their interconnections, and sequences. For instance, vehicle handling encompasses procedures from registration to landing, taxiing, and turnaround, varying based on vertiport types and operational contexts. The paper particularly highlights the MRO process, depicted in figures and detailed in the dedicated section.

Moreover, it introduces an automated taxiing concept for EVTOLs, conducting safety analyses to ensure passenger safety during these operations. The analysis evaluates potential risks, deriving qualitative and quantitative measures to mitigate dangers, considering scenario occurrence, passenger injury severity, and situational avoidability.

In the underlying approach of the paper the BPMN is used to create a database that, in addition to configuring, adapting and analyzing the vertiport functions, also enables the maintenance processes and documentation of vehicles directly and adaptably (to other vehicle models and types). This is a significant advantage over traditional maintenance procedures, which were presented as a checklist in section 1.2.

The developed research's database provides a foundation for ongoing analyses, potential automated configurations, further studies and maintenance procedures and documentation. Although not every process is extensively covered, this work illustrates a fundamental understanding of vertiport functionalities and their interconnectedness, aiming to serve as a valuable resource for future design considerations, process planning and safety analyses.

The Swimlane diagrams delineate a functional space similar to traditional maintenance methods and intervals listed in figure 1, focusing on modularity (easy expansion of functions/image-datasets/safety and security details) and intuitiveness. In our previous paper [20], we conducted an extensive safety analysis using the outlined procedures for an AGV example transporting the eVTOL to its mainte-

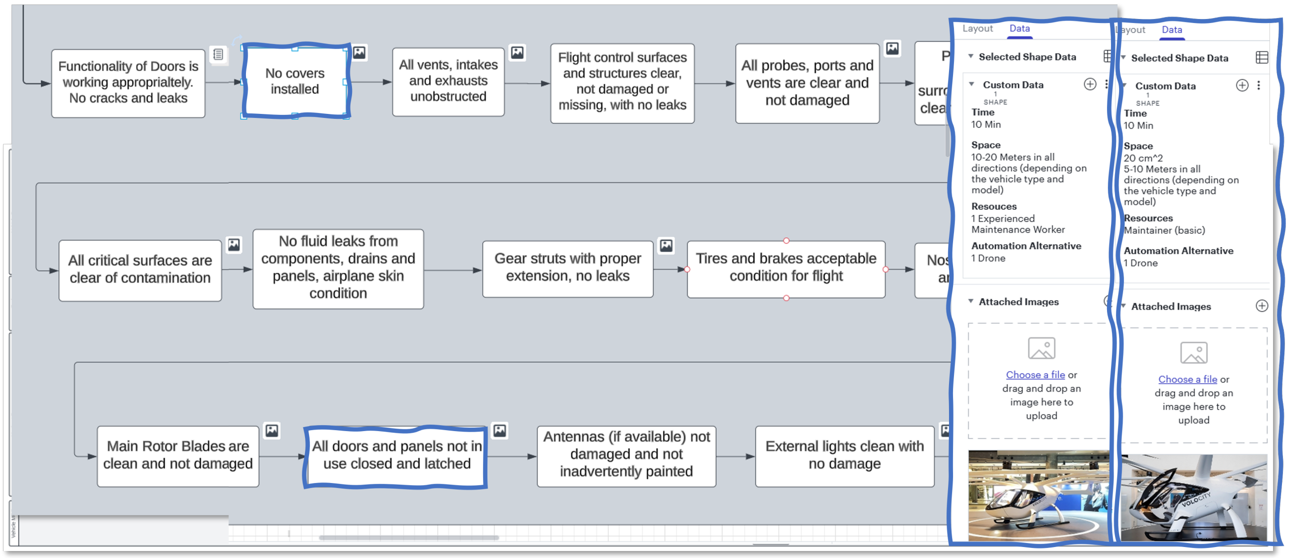

Figure 2 – Extension of the Functional MRO Sequences for time estimation, space estimation, necessary resources, automation alternative and image datasets

nance position during more elaborate checks (A, B-Check), addressing relevant risks. This paper's scope refines the findings, implying a security analysis for more frequent maintenance routines, which include purely visual, drone-assisted, or Smart Hangar-based checks (Pre, Post-Flight Check). This analysis presents the systematic risks involved in drone-assisted maintenance, as an example.

2.2 Why to use BPMN, is it better or worse than traditional approached?

The extended swimlane diagram approach, which is illustrated in figure 2, maps all potentially possible functions of the vertiport and enriches them with further information and parameters and creates a comprehensive database and a system solution space. In addition to the functions themselves, this database also contains information about the space requirements resulting from the functions, what materials and equipment are required to implement the functions, what human resources (which technicians with which qualification level), what time resources (duration of the function sequence) and potential automation variants. This information can be used to configure the processes (functional sequences) at the vertiport based on the given boundary conditions and requirements for the individual vertiport. Furthermore, the technical requirements and specifications of the Vertiport and its equipment can also be derived (configuration of products and hardware). Furthermore, this approach has the additional advantage that not only the process flows and products are configured, but also the resources of the services, such as the required technicians and qualification levels. These resources, as well as the time and space required, can be seen in Figure 2, which shows an example of the extended data for two functions of the function sequence.

The approach of the extended Swimmlane diagrams creates a database that spans a solution space that enables the configuration of vertiports from a product perspective (specification of buildings and technical equipment) as well as the configuration from a process and service perspective. This creates a basis that provides significant advantages in the various development domains that are necessary when adapting a vertiport to its specific use case and environment.

In addition, the solution space represents a database that provides fundamental information for further work and analyses. An example is shown in the following security analysis, which uses a system model that implements automated maintenance using a drone. This maintenance is already part of the database and has been documented in the Extended Swimmlane Diagrams.

3. Security Analysis

Safety standards are an important step for the certification of vehicles in aviation that are new to the market. In addition to the safety analysis (according to ISO 6966-2:2014), which evaluated the various performance levels in the last paper [20] using the example of the rolling function of an electrically powered automated guided vehicle (AGV) with lifting function, the security analysis is the next step in the safety assessment of the vertiport processes.

3.1 Technical Standard EUROCAE

Within the scope of this paper and the related project a security analysis was performed on drones used for maintenance tasks on the vertiports in order to determine which security measures would be required.

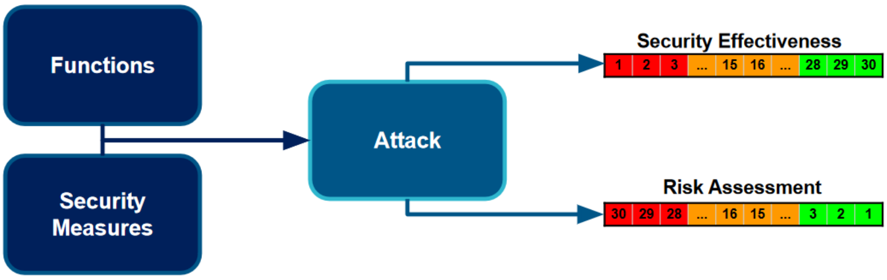

Figure 3 – Security Effectiveness Method

The method used for this analysis is a customized version of the approach by *Airbus* described in EUROCAE ED-203A Appendix E which involves systematically evaluating aviation systems and their intended functionalities to ensure they meet security requirements. It follows a structured approach, identifying potential threats, vulnerabilities, and impacts to the functions of aircraft systems. By analyzing security controls and countermeasures, it determines if they align with established criteria. This method emphasizes cost-effectiveness by guiding implementation to match security needs. The process aims to verify that aviation systems have robust security measures in place and address potential risks adequately. Ultimately, it ensures a comprehensive security posture that aligns with industry standards and regulatory requirements, safeguarding against threats in aviation environments.

3.2 Threat Modeling

In order to conduct the analysis the threats to the systems are modeled using specific building blocks. First the general "Assests" within the Security Scope are identified. In the case of this methodology, these assets are functions implementing the requirements the Aircraft or the eVTOL has to fulfill. This might, for example, be the ability of a drone to communicate with a central control system.
Afterwards the interfaces of the actual system hosting the functions are identified. This includes all physical access points which might be used to communicate with the system (harmfull and non-harmfull); Human-Machine interfaces such as keyboards or touchscreens, wired ports like RJ45, USB or UART pins and wireless interfaces including WiFi, Bluetooth or SATCOM. It is to note that this includes all available interfaces, even those which are not actually in use by any function.
Combining the functions and interfaces, one is able to determine the possible paths of communication one could take to reach a specific function. This then translates into so called "Entry Points" and "Threat Vectors" which describe all potentially possible ways for an attack to propagate from an entry point, through the system and towards a target function.

System Model

While gathering all this information it is helpful to create a model of the system in order to visualize all hardware-components, interfaces, communication paths/protocols and functions.
Using this one could, for example, model a potential attack with the Transmitter on the Drone as en entry point and the Jetson Board as a target. In this case the Beagle Board would only be used to propagate the attack.
An attacker could then manipulate the integrity of the "Send Waypoints to BB" function. The actual impact would then propagate further through legitimate means via the Beagle Board to the Motors. Since the Motors now receive false Waypoint-Data, they can no longer correctly fulfill their function "Steer / Lift Drone", which might lead to an impact e.g. a collision.

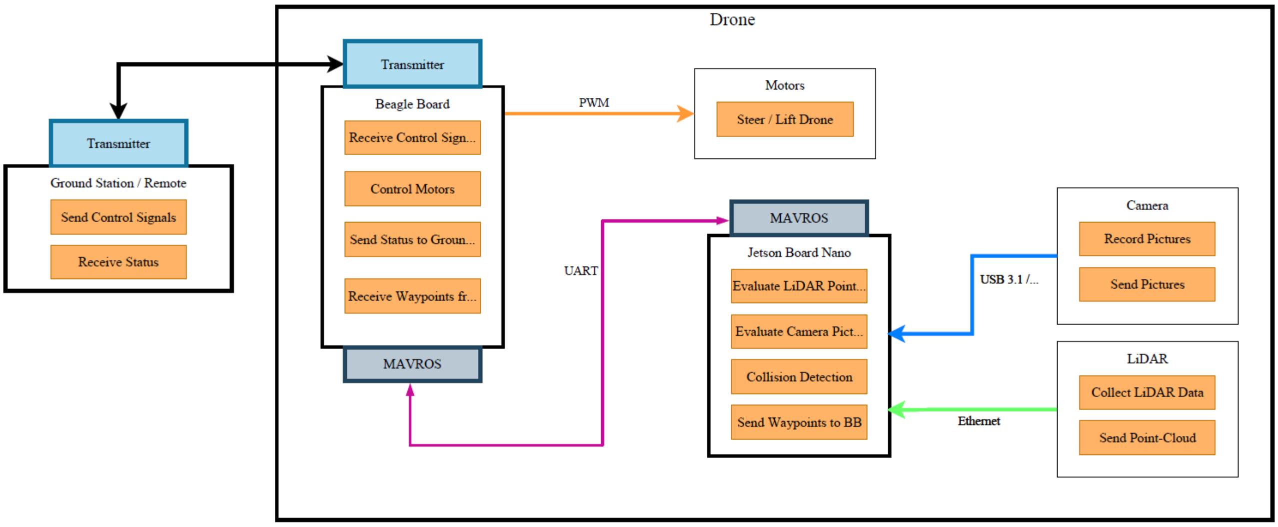

Figure 4 – System Model - Drone

Risk
In order to prevent functions from attacks, it is also important to define which risk is given to a. A risk itself is hereby a combination of:

- Impact, defining the severity of a given risk.
- Likelihood, defining the chance of a Risk occurring.

Impacts are based on the CIA Triad which is a fundamental concept in information security and stands for Confidentiality, Integrity, and Availability. These principles aim to ensure that data is kept private, accurate, and accessible when needed. The resulting risk can then be classified using a risk-matrix which combines the Impact and likelihood into a risk with a classification ranging from low over medium to high.

Risk		Impact				
		No Impact	Low	Medium	Strong	Very Strong
Likelihood	5	Low	Medium	Medium	High	High
	4	Low	Low	Medium	Medium	High
	3	Low	Low	Low	Medium	Medium
	2	Low	Low	Low	Low	Medium
	1	Low	Low	Low	Low	Low

Figure 5 – Risk-Matrix

The lower the likelihood and impact, the less severe the resulting risk and vice versa. The overall goal of the security Analysis is to identify the risks posed to all functions and reduce them to an acceptable level, generally "Low".
In order to make the resulting risk usable for the following steps of the analysis, it needs to be transformed into a numerical value. In order to achieve this, the impact-column is expanded into six "pieces" per likelihood which results in a risk-scale. For the "Strong" impact this would look as follows:

High						Medium						Medium						Low						Low					
30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1

Figure 6 – Numerical Risk Representation as a Risk-Scale

This is one point where the *Airbus* internal implementation of the analysis differs from the standard implementation described in ED203A and shows the novelty in this area. The standard implementation uses an increase in value to describe "how secure" the system is, e.g. a value of 30 being the best possible value. In *Airbus*, the value which describes the residual risk with 1 being the best possible value. Without any Security barriers the Risk is at its starting value of 30.

Security Measures

After finding the correct impact-class for a given function, and therefore the fitting risk-scale, the goal of reducing the risk can be achieved through reducing the likelihood which in turn can be reduced through the implementation of security measures. The effectivity is hereby the reduction of likelihood the security measure provides, the type defines what aspect of an potential attack is hardened. In terms of the analysis this could be the preparation, window of opportunity or execution of an attack.

Name	Description	Effectivity
Name of the Security Measure	What does the Security Measure do and how?	Effectivity Value
	Why is the Security Measure provide Security?	SM Type
	Rationale	**Type**

Figure 7 – Security Measure Components

In order for a security measure to provide an actual reduction to the likelihood it needs to fulfill several conditions:

- Dissimilarity, need to implement different security concepts.
- Independence, cannot be bound to another security measure being functional.
- Segregation, cannot be circumvented with the same action as another Security Measure.

The security measures are then created until their combined effectiveness is able to reduce the likelihood to the desired, usually Low, level of residual risk.

3.3 Model based Analysis

Using the previously mentioned System Model, it is possible to use another analysis approach based on models. Such a model based approach allows for an automated analysis of a system for potential concatenations of attack paths which could lead to an Impact.
These analyses can range widely in complexity with varying degrees of complexity and information added to the model. A simple model based on the drone system could look as follows:

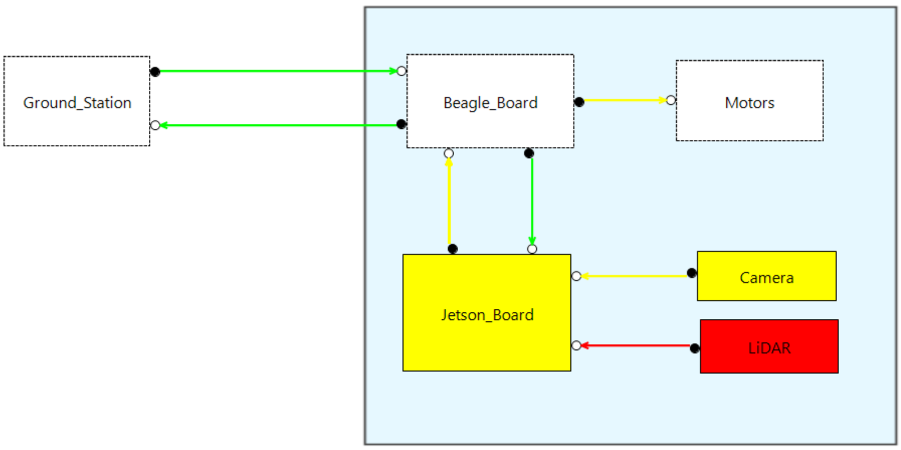

Figure 8 – Model Based Analysis

This model, created in the safety-focused software SimfiaNeo, implements the functions of the individual modules, data communication paths and dependencies on data.
When generating a Failure, colored in red, on the LiDAR, the dataflow from LiDAR to the Jetson Board also fails completely. At the same time the Camera module experiences issues which impair

it's functionality while sill being somewhat responsive. This, yellow colored issue, propagates to the Jetson Board as well.
In the example the Jetson Board mostly relies on the LiDAR with the Camera as a backup. Due to this, the Jetson Board will also be impaired considering that it now has to rely on a partially impaired backup. From here on, the now impaired "Send Waypoints to BB" function causes impaired data to flow to the motors.
It should be noted that there is no actual Impact on the Beagle Board and the Motors, since their related functions "Control Motors" and "Steer / Lift Drone" are actually still functioning correctly, just based on impaired data. Analogous to the modular expansion of the solution space through the security analysis is the provision of synthetically prepared damage images of the vehicle.

4. Data Generation

Based on some AAM manufacturers and operators, AAM vehicles are said to have reduced maintenance costs of around 50% compared to helicopters. The reason for this is that eVTOL manufacturers use carbon composite materials for the fuselage of the vehicle. One advantage of such materials is that they are less susceptible to corrosion.
An extension to [20], which also represents a general problem in the area of MRO is availability of MRO related dataset. We have divided the task of damage generation into the following questions: Which materials are used in most eVTOLs? What typical damage occurs with these materials? Which damage types of damage can be depicted in the 3D models using graphical programs? Available literature[41, 42] shows that the manufacturers use composite materials, aluminum alloys and titanium to build surfaces of eVTOLs (see Table 3).

4.1 Damage Type Identification

Composites, such as carbon fiber-reinforced polymers (CFRP) and fiberglass composites, are widely used in aerospace due to their high strength-to-weight ratio. They can be susceptible to delamination, impact damage, and fatigue, especially when exposed to harsh environmental conditions or subjected to repeated stresses during flight. Aluminum alloys are commonly used in aviation for their strength and lightweight properties. They can be prone to corrosion, especially in humid or saltwater environments. It can also experience fatigue and crack growth over time due to cyclic loading.
Titanium is known for its high strength, lightness, and corrosion resistance, making it suitable for critical components in aerospace applications. While titanium is highly corrosion-resistant, it can be susceptible to damage from certain aggressive chemical environments. Additionally, improper handling during manufacturing or maintenance processes can lead to damage or stress concentration points.

Material	Composite materials	Composite materials Metallic Materials	Aluminum Composite materials (Carbon fiber impregnated with epoxy resin)
OEM	*Joby Aviation*, *Vertical Aerospace*, *Volocopter*, *eHang*, *Kitty Hawk*	*Lilium*, *Airbus*	*Terrafugia*

Table 3 – Surface Materials ordered by companies in the market according to [41] [42]

Over the identification of the damages, we summarized the damage types for composite materials to Porosity, Delamination, Matrix crack, Fiber breakage, Fiber matrix debond, Scratches, Impact Damage, Hard Landings and Structural Design Flaws [43]. Types of damages in metallic materials überschneiden sich mit composite materialien im Bereich Corrosion und Structural Design Flaws [44].

4.2 Simulator

Camera-assisted damage identification approaches have gained traction in recent years, furthermore, the application of deep learning models has proven to improve the accuracy in the identification of various patterns or objects in a given image. However, such approaches require a large amount

of data that can be used to train the models. Traditional approaches for the collection of training data involve taking thousands of pictures and labeling them manually. This process can be inefficient in terms of time and labor costs involved. A new paradigm suggests the usage of 3D CAD models for generating synthetic data that can be used to train deep learning models.
Generating synthetic data from 3D CAD models requires accurate modeling of the details of the scene such as the geometry, texture, material, etc. Advanced 3D modeling software such as AutoDesk, Solidworks, etc. allows accurate modeling of geometries and materials however, they fail to capture the effects of damages that can occur over time. To achieve this we developed a damage modeling pipeline that takes a 3D CAD model of the eVTOL and outputs a new CAD model that contains damages. At the end, the model is combined back and exported to be saved. Figure 11 describes

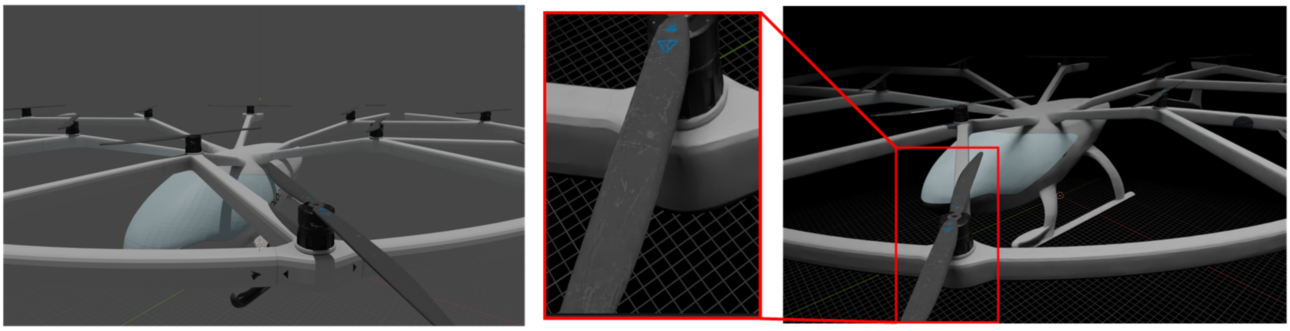

Figure 9 – (Left) Volocopter Volocity without any damage and (right) after applying the damage textures to the model

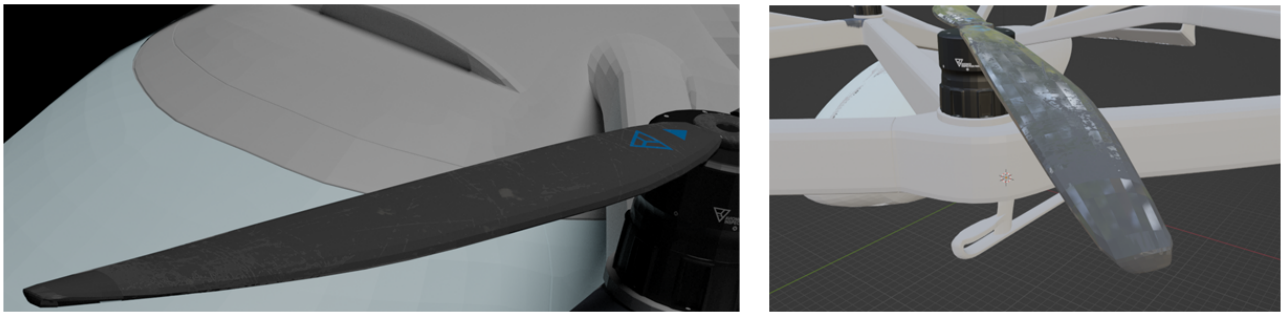

Figure 10 – (Left) Volocopter Volocity propeller with cracks and (right) the implemented scratches on the propellers of the model

the model generation pipeline in the overall functionaly sequence space. In the upper part of Figure 11, the tool from Section 2.1and our latest paper is referenced. This tool can now be modularly expanded, as each functional block existing in the functional space can be described by attributes such as security measures and image data. In the middle of figure 11, the data generation pipeline is depicted. The pipeline first takes in the 3D CAD model and splits it into individual meshes labeled by the part name. For example, in the case of the Volocopter Volocity model, it can be broadly split into motors, propellers, outer body, glass panes, etc. Simultaneously, the corresponding damage textures are loaded for each of these identified parts. These textures represent the most commonly occurring damages during the airline operation lifetime, such as scratches, dents, corrosion, etc. . Once the meshes are split, they are then assigned their respective damage textures. In the lower part of Figure 11, the calculated risk values from the security and safety analysis are entered as attributes into the functional space. For modeling the damages on the 3D CAD model, *Blender* an open source 3D modeling software was utilized that also provides a python API for automating this process, we focused on scratches and dents and simulated the implemented damage data in the simulator environment *Microsoft Airsim*. The results of this work are being integrated analogous to the attribute properties illustrated in image 2 of the vertiport functional workflow.
For our application, we used a 3D CAD model of Volocopter for damage modeling. Figure 9 illustrates the original CAD model of the Volocopter without any damages. Figure 9 contains a render of the

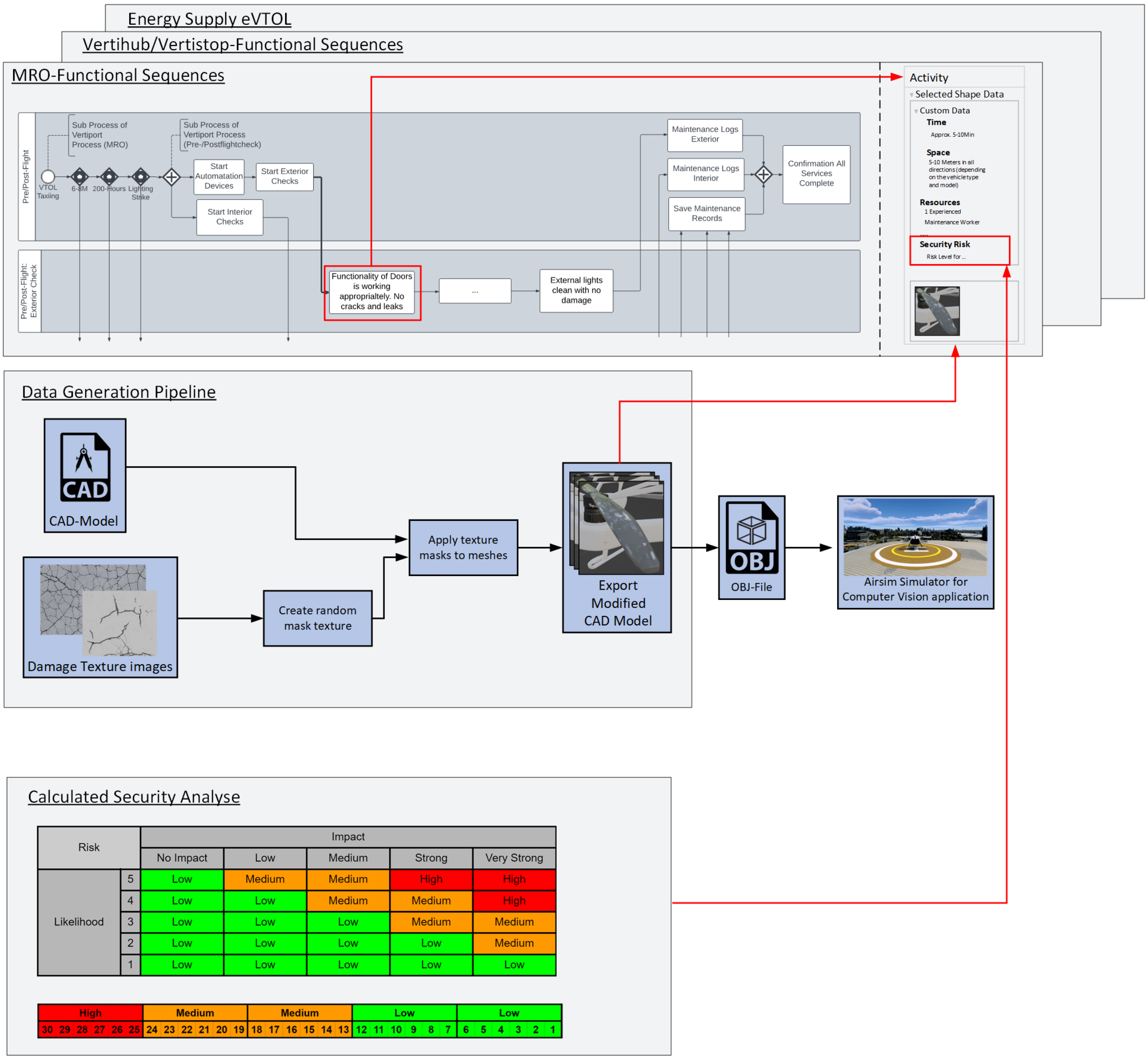

Figure 11 – (Top) Overwiew of modular functional Solution Space extended with further information (middle) the CAD model-based data generation pipeline and (bottom) the risk calculation from the security analysis

damaged model after the pipeline. A close-up view of the propeller can be seen before and after damage modeling in figure 10.

The obtained synthetic image data can be further used for training AI models for damage identification. Since, in practice, such AI models require a large amount of data, this challenge can be tackled as a such large amount of data can easily be generated through simulation. Hence, this reduces the amount of time a maintenance worker spends on taking images of the damages and labeling them manually for AI-based camera-assisted damage identification tasks.

5. Future Work and Outlook

This paper gives an overview over the maintenance and inspection publications for eVTOLs and represents an alternative representation over a spanned solution space, which is modularly extensible. The tool we presented in the previous paper, which uses so-called swimmlanes, has been modularly extended in this paper to prove that we have created a vehicle-independent, temporally changeable and spatially extensible modern method for representing vertiports, stops and hubs. To ensure that our concept can be used in the industry with low risk from a safety perspective, we have integrated a safety and a security analysis into the functional space, which are based on the Airbus industrial standard. In this model-based analysis, we have considered the automated maintenance of the multi-

copter vehicle security measures are then created until their combined effectiveness is able to reduce the likelihood to the desired, usually Low, level of residual risk. This procedure was carried out for the majority of the functional sequences, which are not listed here as this would exceed the scope of this publication.
The developed data generation pipeline is generalizable and can also be easily transferred to any other vehicle type, where only the respective part of the vehicle and their corresponding damage texture images have to be mapped correctly. The data generation pipeline can be further improved by providing high-quality 3D CAD models with more realistic surface textures as well as a highly detailed model of the image texture. Furthermore, a different approach to damage texture modeling can be used that allows creation of 3D damages in the CAD model.
In the next phase of our research, we plan to extend the tool to different vehicle types, to include a more detailed hydrogen supply for the vehicles and to add the attribute of necessary certification like the Airman Certification Standards (ACS) for Aviation Maintenance Technicians (AMT) for every functional sequence [45]. We are planning an automated connection to the simulator so that the user only has to enter the vehicle type to start the tool and a pipeline for maintenance, inspection, safety measures and other functional processes at the Vertiport and Vertistop is generated as a result.

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8. Copyright Statement

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