Drone Based Inspection of Above Ground Storage Tanks. A Multi Criteria Evaluation Approach

Islam Asem Salah Abusohyon, Giuseppe Aiello, Antonella Certa

***Abstract** Unmanned Aerial Vehicles (UAVs) is an emergent technology with the potential to drastically change the landscape of many civil and industrial activities in the near future. A promising field of application is the inspection and monitoring of industrial plants, where UAVs can be a valid alternative to traditional approaches with a better cost-effectiveness and a higher safety level. Although the disruptive innovative potential of this technology is generally recognized, a consistent methodological approach towards the evaluation of the drawbacks and benefits of employing UAVs in critical industrial operations can hardly be found in the current scientific literature. In such context, this paper proposes a framework for assessing the effectiveness of UAV technology in industrial monitoring applications within a structured multi-objective framework. In particular, the paper compares the traditional ground-based inspection services of Above Ground Storage Tank (AST) with UAV based inspection, by means of the well-known Analytic Hierarchy Process (AHP) method considering time, cost and safety criteria. A case study is also proposed to demonstrate the effectiveness of the approach proposed.*

***Keywords:** Above Ground Storage Tank (AST), Analytics Hierarchy Process (AHP), Drone. Ground-based Inspection, Technology, Unmanned Aerial Vehicles, UAV Based Inspection.*

I. INTRODUCTION

The technology of Unmanned Aerial Vehicles (UAV), introduced at the end of World War I for military purposes, has recently emerged as one of the technologies with the highest disruptive potential in a wide landscape of applications. The employment of drones in civilian applications actually started at the beginning of the new millennium [1], when the technological maturity and the consequent cost reduction, allowed for the development of market oriented services in many application fields including logistics, environmental monitoring, security, etc. Referring to the industrial world, several scenarios can be envisaged where UAVs can effectively substitute many solutions currently employed, drastically lowering the costs and the exposure of human operators to safety risks and health threats [2]. Service providers are thus interested in identifying specific application domains where a drone based service may outperform the approaches currently employed in the industrial practice. In such regard, appropriate technical and economic analyses can be a valuable support in identifying the applications with the highest market potential, allowing for the maximization of the return on the investments (ROI). This research refers to high-risk industrial facilities such as chemical, power generation and Oil & Gas installations, where the potential benefits of the drone technology are not only limited to the economic dimension, but are also extended to safety, ergonomics, and overall performance of the organization [3]. In such situations, a consistent evaluation of the potential advantages of drone technology must take into account a multiplicity of heterogeneous criteria in a comprehensive framework. In particular, this paper investigates the potential benefits achievable by the employment of drones for the inspection of Aboveground Storage Tanks (ASTs) in high-risk industrial contexts. ASTs are oil storage structures which can be differentiated in a wide range of typologies, according to their shapes (vertical cylindrical, horizontal cylindrical, spherical or rectangular), their construction materials (metals, fiber reinforced plastics, concrete, etc.) and their technical features (open top tank, fixed roof tank, external floating roof and internal floating roof tank). With an esteemed overall global tank storage capacity of approx. 3.4 billion barrels as of March 2020 [4] tank farms are a fundamental element of the Oil & Gas supply chain, which makes of them extremely critical infrastructures, since accidental events can lead to catastrophic consequences like fires and explosions causing injuries and fatalities as well as environment pollution and economic losses. In particular, vertical cylindrical ASTs, which are the most spread oil storage structures worldwide, are exposed to the risk of failures mainly related to the corrosion of the metallic structure. To avoid such disasters tank welds and surfaces must be accurately inspected to identify possible incipient failures, generally due to corrosion. The relevant regulations (API STD 653 and API RP 575) [5, 6] provide the guidelines for periodic inspections and maintenance, and prescribe strict and precise procedures for monitoring the internal and external shell plates, the bottom plate, and the roof. The current standard industrial practice for ASTs maintenance involves different possible inspection methods based on Non Destructive Testing (NDT) technologies.

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* Correspondence Author (s)

Islam Asem Salah Abosohyon*, Department of Engineering, University of Palermo, Palermo, Italy. Email: easem288@gmail.com

Giuseppe Aiello, Department of Engineering, University of Palermo, Palermo, Italy. Email: giuseppe.aiello03@unipa.it

Antonella Certa, Department of Engineering, University of Palermo, Palermo, Italy. Email: Antonella.certa@unipa.it

The mandatory periodical inspections are typically performed off-servicing the tank and constructing a scaffold to allow skilled workers to reach the surface to inspect and perform the required tests. Such procedure is generally slow and costly, and exposes the workers to substantial risks (e.g. falls). Alternatively, rope access (RA) services have been proposed as a cost-effective alternative with the objective of reducing the inspection period and eliminate the cost of the scaffolding process. Such inspection technique however requires skilled workers, and can be hardly applied in unfavorable operating contexts. Recently, the increasing demand for cost-effective inspections services has driven the development of automated procedures as an alternative to human-based services. Performing in-service inspections, by means of automated systems could in fact result in substantial cost savings and reduced inspection times. API 653 [5] offers the regulatory foundation for such approach, allowing operators to perform online tank inspections, and to identify those situations that do not require a repair intervention. Such approach falls in the framework of the risk based inspection (RBI) policy, formalized in the API RP 580 (2016) [7] standard, which mandates the inspection to be scheduled on the basis of the information obtained from a preliminary risk analysis. The API 653 [5] regulation thus provides a detailed checklist for in-service inspections to identify those tanks that require a specific intervention because of their condition, age, and inspection history. The potential cost savings achievable by means of this methodology has originated an ample range of NDT inspection techniques such as infrared and ultrasound sensors, laser scanners [8, 9, 10, 11, 12] and, more recently, vision cameras [13, 14, 15, 16, 17, 18, 19].

Recently, a substantial attention has been focused on the development of NDT controls by means of automated inspection systems performed through mobile devices constituted by two main elements: a carrier and a sensing equipment. Depending on the characteristics of the inspection and on the techniques employed, the appropriated sensing equipment and carrier (drone, crawler, robot, etc.) are chosen. Some examples of such approach are the “Maverick” system produced by Solex Robotics in USA, “Tank Ray” produced by Raytheon in the USA and “OTIS” produced by In Tank Services [20, 21, 22]. Recently, the spread of UAV technology has gained a considerable attention both from industrial professionals and scientific researchers aiming at developing effective solutions for plant inspection through the integration of NDT analysis systems on aerial vehicles. Clearly, the integration of NDT technologies on a mobile platform is a technically challenging task when aerial vehicles are considered, due to their limited endurance and payload. The opportunity of developing semi-autonomous UAVs equipped with high-resolution digital cameras, is however an attractive and technically feasible possibility. The ability to collect a large number of georeferenced images and to reconstruct a realistic virtual model of the structure inspected could in fact be a relevant source of information to detect the presence of critical spots affected by structural or superficial damages by means of adequate image post-processing techniques. Such approach can be based on Texture analysis and filtering [23, 24], edge detection [25, 26], image segmentation [27], etc. In particular, Ellenberg et al. (2014) [28] investigated the remote sensing capabilities of a commercialized UAV (Parrot AR 2.0) for crack detection from different distances. Sankarasrinivasan et al. (2015) [29] introduced an approach that is consisted of a combination of HSV threshold techniques for real time detection of cracks. The case studies reported show that high resolution image quality enables visual identification of cracks up to 0.3 mm from the test surface. Clearly, the performance of a drone in a specific inspection task is mainly influenced by its two main components, namely the aerial platform and the sensing device. The large number of aerial platforms which are currently available in the market, and the variety of sensing devices make the technological landscape of application extremely dynamic, and the selection of the proper system for the specific application can hence be complex task. In particular, rotary wing systems (multicopters) are generally preferred for localized inspections due to their capability of hovering over a fixed point, while fixed wing systems are preferred for wide areas (e.g. pipelines)

In such context, the research proposed consists in comparing the drone technology with the technologies currently employed for the inspection of ASTs, by means of a proper Multiple Criteria Analysis (MCA) methodology. MCA methodologies have been developed to support decision makers in the comparison of several alternatives on the basis of a set of criteria and, ultimately, to identify the best performing solution. Nowadays MCA comprises a family of methods well established in the scientific literature, which can be fundamentally distinguished in two categories: compensatory and non−compensatory. In a compensatory method a weak performance of one criterion can be compensated by a good performance of another criterion, while non−compensatory methods (generally based on the outranking principle) do not allow such possibility. Some popular models like the Multi-attribute utility theory [30] and the Analytic Hierarchy Process [31] belong to the first class, while some others like TOPSIS [32], ELECTRE [33] and PROMETHEE [34] belong to the second class.

This research ultimately aims at establishing an effective multicriteria approach to the estimation of the potential benefits of drone-based inspections compared to traditional inspection systems, therefore addressing the following research questions:

1. How can different approaches to plant inspection be compared in order to support decision makers in selecting the most effective alternative?
2. What are the benefits of UAV in industrial inspections compared to the traditional industrial practice, and how can they be evaluated?

In the remainder of the paper, an original multi-criteria approach, taking into consideration the issues related to cost, time and workers’ safety is proposed in section 2. The approach proposed is then validated through a case study referred to the inspection of ASTs, and the results are discussed in section 4 by comparing the benefits and drawbacks of the existing standard industrial practice with a drone-based service, taking into account the entire lifecycle the AST. Finally, section 5 reports the conclusions and managerial insights.

II. METHODOLOGY

The methodology adopted in this paper is the well-known Analytic Hierarchy Process (AHP) which allows dealing with complex decision analysis taking into account subjective and objective information within a structured methodology based on pair-wise comparisons. A fundamental assumption of the AHP is that human judgments (and not just the underlying information) should be used in the assessment process, therefore, numerical data must be adequately provided to the decision makers, so that they can formulate their own judgments. The AHP method starts with the construction of a hierarchy of criteria which is obtained by a recursive decomposition of the main goal into its constituent sub-goals until an appropriate level of detail is achieved. The decision maker will then assign a weight for each criterion corresponding to its importance, by performing pairwise comparisons of the criteria. Assuming that m evaluation criteria are considered, and n options are to be evaluated, the criteria weights are determined through a $m \times m$ pairwise comparison matrix **A**, where each element a_{jk} represents the relative importance of the j^{th} criterion relative to the k^{th} criterion, expressed by a numerical score. Once the pairwise comparison matrix is built, its elements are normalized by dividing the column total:

$$\bar{a}_{jk} = \frac{a_{jk}}{\sum_{l=1}^{m} a_{lk}} \quad (1)$$

Finally, the criteria weight vector ***w*** is obtained by averaging the entries on each row of the normalized matrix.

$$w_j = \frac{\sum_{l=1}^{m} \bar{a}_{jl}}{m} \quad (2)$$

Once the vector of the normalized criteria weights has been determined, a pairwise alternative comparison matrix is built for each of the m criteria considered. The alternative comparison matrix **B** is thus a $n \times n$ real matrix, where each element b_{ih}^{j} represents the evaluation of the i^{th} alternative compared to the h^{th} alternative with respect to the j^{th} criterion. If the i^{th} option is better (worse) than the h^{th} option, the corresponding score will be higher (lower) than 1, while if two options are evaluated as equivalent, the corresponding value is 1. The next step consists in normalizing the scores by applying to each comparison matrix the procedure previously described. Each element of the matrix is thus divided by the sum of the entries in the same column, and then averaged on each row, thus obtaining the normalized score vectors. Finally, the $n \times m$ matrix of option scores **S** can be constructed, where each element s_{ij} represents the score of the i^{th} option with respect to the j^{th} criterion. The final step consists in ranking the alternatives though a global score in decreasing order. A further step can finally be performed in order to highlight the inconsistencies that may typically arise when the numeric values of the pairwise comparisons are derived from the subjective preferences of the decision maker(s). This is generally executed by calculating a Consistency Ratio (CR), defined as:

$$CR = \frac{CI}{RI} \quad (3)$$

The Consistency Index (CI) is obtained by first computing the scalar x as the average of the elements of the vector whose j^{th} element is the ratio of the j^{th} element of the vector $A \cdot w$ to the corresponding element of the vector w:

$$CI = \frac{x-m}{m-1} \quad (4)$$

RI is the Random Index, i.e. the consistency index when the entries of A are completely random, which for the case considered, for n = 3, the value of RI considered is 0.58.
A perfectly consistent decision maker should always obtain CI=0, but, since small values of inconsistency can be tolerated, a reliable result may be expected from the AHP method, when:

$$CR < 0.1 \quad (5)$$

A. Decision criteria

The first stage of the decision process consists of the definition of the alternatives to be evaluated and the establishment of the evaluation criteria. The case here considered refers to the ranking of different approaches for AST inspection, by taking into account the cost, time and safety criteria. The problem hence involves three alternatives, namely: scaffolding, RA and UAVs, and three decision criteria, namely: inspection time, cost, and safety. The structure of goals, criteria and alternatives is given in the following Fig. 1.

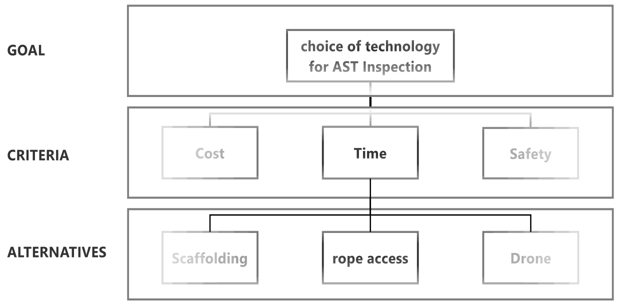

Fig. 1: Hierarchy of criteria

After the establishment of the criteria, they must be scored through a set of qualitative/quantitative indicators and related evaluation functions. Such topics are discussed below.

B. Direct inspection costs

The cost criterion has been selected to assess the economic efficiency of the alternatives based on the overall inspection costs. The cost model considered refers to the Life Cycle Cost (LCC) methodology which takes into account all the economic cost of an asset during its entire lifecycle, including the initial cost, the discounted future expenses and the final cost related to the end-of life of the asset. On the basis of such elements a complete life cycle cost is calculated in terms of net present value or annual value, including accounting/financial costs (such as, interest rates, depreciation, present value of money/discount rates, etc.). This approach is commonly suggested (e.g. by the EU Directive 24/2014) for the decisions related to industrial procurements and public tenders, in order to prevent the selection of economic alternatives which may appear convenient in the short time, but that might turn ineffective on the long run.

For such purpose, a simplified LCC analysis which does not take into account financial evaluations is generally sufficient. The analysis here proposed is hence based on the evaluation of the undiscounted lifecycle cost costs related to the AST inspection service, taking into account the expenditure related to the manpower (inspection personnel) and the unavailability of the tank serviced. The manpower cost has been correlated to the duration of the inspection task, the number of workers employed and their qualification and skills. In addition, both for the RA and the scaffolding mehtods, the cost related to taking the tank off-service and to emplying a backup storage tank must be evaluated. Clearly, such costs are affected by the uncertain nature of the servicing operation therefore this approach is exposed to risks, due to the uncertainty in future costs, interest rate and future events (repairs, renewal, etc.). Discussing such uncertainties is out of the scope of the paper, hence, for the sake of simplicity, the methodology here proposed is based on the deterministic evaluation of a standard maintenance plan, thus neglecting the effects of uncertainty.

C. Unavailability period

The unavailability period indicator is employed to take ito account the indirect costs and the non-monetary elements related to the unvailabtility of the tank during the ispection period. A traditional inspection service requires the tank to be emptied cleaned and vented in order to avoid the exposure of workers to hazardous chemicals. As a consequence, the tank serviced may remain out of commission for some weeks, and this prolonged downtime may affect the performance of the production system, originating consequences that cannot be easily monetized. Consequently, in the industrial maintenance literature, time and cost criteria are frequently considered as separate objectives [35]. Clearly, automated in-service inspection procedures are not affected by such problem, which constitutes an important advantage. In the decision framework here proposed, the inspection time has been evaluated for each alternative considered, taking into account to the entire lifecycle of the equipment serviced, analogously to the cost criterion.

D. Safety

Limiting the workers' exposure to safety risks is a main concern for plant managers, particularly when the activities require the presence of servicing companies in the plant area as in the case of inspections performed by external experts. The methodological approach to safety risk evaluation is nowadays well established in the industrial practice, and it is based on three main steps, namely: risk identification, risk assessment and risk control. This procedure requires an initial analysis of the risk scenarios, to identify the possible hazardous events and the potential consequences they may originate. This activity generally involves subject matter specialists to make judgements based on their specific experience. Once a comprehensive scenario of all the possible risk factors has been depicted, the entity of the risk can be evaluated. The assessment of risk is based on two key-measures: the probability of occurrence of a dangerous event and its impact on the organization. The evaluation of these parameters can be done through either a qualitative method which relies on linguistic scales or a quantitative method that is based a quantitative calculation of the probabilities of occurrence. Since the qualitative methods are quick and easy to use, they are usually used in the industrial practice. Based on the product of probability (P) and Impact (I), a risk factor (RF) is mathematically calculated as:

$$RF = P \cdot I \qquad (6)$$

The output values for all the risk factors are finally represented in a two-dimensional risk matrix which portraits the entity of the risk. This matrix, generally referred to as "risk map", is typically color-coded, with green, yellow and red colors indicating the risk priority from low to critical. For traditional inspection techniques, the safety issues are mainly related to the safety of the operators working on the scaffolds or hanging on the ropes, and, in the case here considered, the risks of falling from height are the most significant concern. In the case of automated inspections (not involving workers directly) the main sources of risks are related to operating the monitoring system in the industrial area. In particular, when performing a drone-based inspection, the safety risks are related to flying the aerial vehicle inside the industrial site, and the corresponding safety assessment approach and mitigation procedures are defined by the national civil aviation authorities (ENAC in Italy). In this regard, it must be pointed out that the regulatory system in the EU is still extremely fragmented since it relies on national regulatory systems which do not take into account mutual recognition. As a matter of fact, this prevents commercial service providers to perform EU-wide activities. The risks related to UAV operations will be discussed below referring to the Italian regulation [36], although several elements apply in general to all the EU regulatory systems**.** The Italian regulation makes a preliminary distinction between Remotely Piloted Aircraft Systems (RPAS), which involve a pilot to control the aerial system, and unmanned autonomous systems (UAS), that do not require a pilot intervention during the flight. The term "drone", which stands for Dynamic Remotely Operated Navigation Equipment [37] will be employed to address RPAS throughout the paper. The safety regulations for RPAs typically differentiate between critical/non-critical operations and offensive/inoffensive drones. Operations in areas where an impact on the ground cannot cause injuries to people or damages to the infrastructures are classified as "non critical" activities. Additionally, non-critical activities, must be performed within a limited air volume (coded as "V70"), within visual line of sight (VLOS), and at a safety distance from airfield traffic zones (ATZ). Contrarily, activities involving overflights of urban areas and infrastructures, restricted areas, transport systems and industrial plants are always considered critical. According to the regulations, non-critical operations can be performed after a preliminary assessment of operational risks (demanded to the operator), and the submission of a declaration of compliance to Aviation Authority. Contrarily, critical operations require a specific authorization granted after satisfactory risk assessment. The classification of offensive and non-offensive drones is instead related to the technical features of the aerial vehicle.

The Italian regulation applies to vehicles with a Maximum Take Off Weight (MTOW) less than 150 kg, and classifies them in Very Light (300 g <MTOW< 4kg), Light (4 kg <MTOW< 25kg) kg, and Heavy (MTOW > 25kg). The regulatory framework on RPAS has recently introduced the notion of intrinsically inoffensive referred to vehicles with MTOW less than 250g allowing them to operate freely in non-crowded areas.

The main sources of risk when operating a drone are the ground impact (GI) and the mid-air collision (MAC) events.

GI risk refers to the possibility of a drone crashing on humans or structures on the ground. According to the current regulations for small drones, the probability of impacting persons on the ground is related the population density in the area of operations. Conventionally, this risk is measured by the expected number of ground victims per flight hour, which can be calculated as:

$$E(casualties\,|ground\ impact) = P_f N_{exp} P_c \tag{7}$$

Where P_f is the probability of failure of the aircraft, N_{exp} is the number of people potentially involved int the crash event, while P_c is the probability the impact of the vehicle on a person on the ground causes a fatality.

While P_f is an intrinsic parameter of the vehicle employed, and P_c is related to the Kinetic Energy at Impact the number of persons potentially involved in the crash event can be calculated as the product of the crash area (A_{exp}) by the population density (ρ), as given below.

$$N_{exp} = A_{exp} \cdot \rho \tag{8}$$

The area affected by the crash event is constituted by the area of operations, which is the area directly interested by the flight plan and by a buffer area which is a safety area around the area of operations which could be involved in the crash event. For the determination of the safety area some theoretical models have been formulated based on different assumptions [38, 39, 40, 41].

Based on such considerations, the risk related to GI can be evaluated through the number of expected casualties, calculated as:

$$P_{GI} = A_{exp} \cdot \rho \cdot F_p \cdot F_d \tag{10}$$

Where F_d and F_p are correction factors referred to the non-homogenous population density and to the shelter factor, i.e. the degree of protection provided by existing structures (e.g. buildings).

For the operations to be considered safe, the expected number of ground victims per flight hour must be lower than a safety threshold provided by the FAA. When operating in industrial areas, the ground risk is generally negligible, because the area of operations can be temporarily interdicted with safety fences, while the sheltering effect of the structures is generally high.

The second critical hazard of UAV operation is related to midair collisions, which refers to the event of an UAV impacting another (manned) aircraft. Quantitative risk assessment models to evaluate likelihood of a mid-air collision event based on the gas particle model are dated back in the 70's although more recent formulations can be found in the literature [41]. The MAC risk originates when an aircraft enters and ATZ and can be calculated according to the following equations:

$$T_{MAC} = T - \frac{D \cdot sen(\delta)}{60 \cdot (V + V_W)} \tag{11}$$

$$P_{MAC} = \frac{T_{MAC}}{60} \tag{12}$$

Where : T is the maximum fliying endurance, D is the minimum distnace between the takeoff point and the ATZ, δ is the angle of the line between the takeoff point and the ATZ, V is the maximum horizontal speed, and V_W is the maximum windspeed tolerated by the vehicle.

A mitigation to the MAC risk, can be the employment of a retention system to ensure the maximum altitude is not exceeded, thus constraining operation in in V70 airspaces. In such cases the possibility of mid-air collisions can be negligible.

Once the risks related to the events have been calculated, the risk assessment procedure for RPAS prescribes the comparison of the risk evaluated for a specific mission with a reference maximum acceptable named Tolerable Level of Safety (TLS), generally referred to the likelihood of the worst possible outcome (fatality) and measured in fatalities per flight hour (FH). For small RPAs the Italian regulation considers an acceptable risk of 10^{-6} per FH referred to the ground impact, and an acceptable risk of 10^{-6}/FH. According to this method, the Safety Objective (SO), associated to the acceptable mission risk is thus calculated for GI and MAC as:

$$SO_{GI} = \frac{AR \cdot C_{RPAS}}{P_{GI}} \tag{13a}$$

$$SO_{MAC} = \frac{AR \cdot C_{RPAS}}{P_{MAC}} \tag{13b}$$

Where AR= level of Acceptable Risk (10^{-6} as safety objective) C_{RPAS} is a score of 0.1 and 0.5 related to manual and automated operations and Ra is the acceptable risk.

The SO values thus calculated are then finally compared with probability of a top (catastrophic) event (PTE), and, if the following condition is met, the risk related to the flight operations can be accepted.

$$PTE < SO \tag{14}$$

Clearly, when the risk of a midair collision or a ground impact is negligible, PMAC and PGI are both null, therefore the safety requirement is always satisfied, contrarily, specific mitigation measures must be enforced (eg. parachute, flight termination system, retention cable, etc.)

Finally, when operating in industrial areas, particular attention must be paid to the explosion risk, which is related to the possibility that the automated system is may enter an area with a dangerous concentration of explosive gases. Operations in such areas are regulated by the EU "ATEX" Directive (2014/34/EU), which contains the safety prescriptions to avoid that, in such situations, the system itself may be source of ignition for the explosion.

Areas exposed to the explosion risk are frequently present in industrial plants where storage tanks for petroleum products or chemicals are located. For operating in such areas it is thus mandatory that the drone is compliant with the ATEX regulations. This is actually a substantial limitation, since the RPAS currently available on the market generally are not ATEX compliant, except for some rare exceptions.

III. CASE STUDY: AST INSPECTION

This The case study here presented refers to the inspection of the external surface of a group of three ASTs each one having a diameter of 30 m, height of 25 m, and volume of approx. 18.000 m^3 . The external surface of the tank is approx.2.350 m^2 while the surface of the roof is 700 m^2. The purpose of the case study is to compare the traditional scaffolding and RA methods, with a drone based inspection service in terms of direct inspection cost, cost of downtime and safety. For such purpose a DJI Spark mini drone, a tiny quadcopter equipped with several innovative technologies has been employed. The vehicle has an MTOW of approx. 300g with a Maximum Flight Time of approx. 16 minutes ,and features a 25 mm camera allowing stabilized video at 1080p/30 frames per second, and 12MP still images. The system is also equipped with a GPS GOLNASS satellite positioning system and is capable of reaching a maximum speed of 14 m/s. The most significant limitations of this system are related to the tight operating conditions and to the lack of a 4K video resolution. the DJI Spark has an operating temperature range 0-40°C and the wind speed must not exceed 10 m/s, scheduling the inspections with appropriate weather conditions is thus crucial for successful operations.

In the case study here presented the drone has been kept at a distance of 20-30 meters from the structure inspected, and the overall distance flown is about 400m, and the inspection time is thus approx. 14 mins, which, considering the take-off, positioning, and landing operations exceeds the endurance of the drone mini-drone employed. The flight path was hence divided in two flights and a battery-change was scheduled.

The imagery obtained during the inspection has been post-processed in a typical photogrammetric workflow including setting ground control points, point cloud and digital surface model generation. The 3D model obtained, after image ortho-rectification and mosaicking, is given in the following Fig. 2.

Fig. 2: 3D Model of the Inspected Site

Finally, since the drone employed is not ATEX certified, the ASTs interested by the experimental activity were completely decommissioned. Concerning he safety of operations, the parameters employed for evaluating the GI and MAC risks are given in the Table 1.

Table 1: Risk analysis parameters

V_{0x}	15 m/s
h	30 m
R_{UAV}	0.2 m
R_{human}	0.3 m
Γ	30° (quadcopter)

The resulting radius of the operation area is approx. 100m, while the buffer area considered is 150m which is the minimum value prescribed by the regulation. The operation area not in proximity of any ATZ, and the limited height of the flight (30 m) nullifies the probability of a mid-air collision event. The GI impact risk P_{GI} can be calculated according to eq. 10. Considering a typical sheltering factor (F_p) and population density factor (F_d) equal to 0.2 and 1 respectively, while the population density con be considered null since the area can be interdicted to workers' access during the operations. In such conditions the risk associated to the operations is technically negligible, therefore the operations can be considered safe against an acceptable risk of 10^$^{-6}$.

The evaluation of the inspection cost for each alternative considered has been carried out according to the generalized lifecycle approach previously discussed. Considering that the scaffolding erection and dismantling costs can be evaluated at approx. 10 €/ m^2, while the scaffold hiring cost can be around 1,50 €/m^2/month, and that the inspection of the external s\urface of each tank can realistically be exectued in 7 working days by 4 trained inspectors, the overall correspoding cost can be evaluated in approx. 12000 € per tank. The cost related the RA method is referred to the labour cost of 8 high-skilled professionals, employed for 10 working days, which can realistically originate a labour cost of approx. 15000 € per tank). The direct cost of the rope access method is thus approx. 30% less than the scaffolding cost, although the unit (per hour) cost of the workers is actually higher due to their level of specialization.

In addition, both for the rope access and the scaffolding mehtods, the cost related to taking the tank off-service and to emplying a backup storage tank must be evaluated. This cost, can be estimated in approx. 1 €/m^3/month. In the case study considered, taking into account the volume of the AST and the overall inspection time for the scaffolding and rope access methods, the tank off-service costs can roughly be estimated in approx. 8500 € and 2500 € respectively for scaffolding and RA. Finally, the cost of drone inspection is related to the labour of a qualified pilot and a staff engineer, for approx. 7 days. Such time is required to perform the a prelimianry site inspection, the autorhization paperwork and the flight plan. Next, the inspection proess is actually performed in one day, and few more days are finally required to postprocess and analyze the results. The overall cost can thus be evaluated in approx. 16000 €. The total direct inspection costs for the alternatives conisdered are given in the following Table 2.

Table 2: Inspection costs

	Scaffolding (K€)	Rope Access (K€)	Drone (K€)
Site/activity preparation	66	-	5
Inspection	35	45	6
site restoration	9	-	
Other			5
TOT. Direct cost	**110**	**45**	**16**
Cost of unavailability	**25**	**7.5**	
Total Cost	**135**	**52.5**	**16**

As stated before, to obtain a reliable indicator for decision analysis, the whole AST lifecycle is considered. in particular it has been reported that for a new tank, corrosion normally becomes an issue after around 15 years and the total in-service duration of a AST is approx.50 years [42]. Guidelines from API (2009) [5] or EEMUA (2003) [43], recommend out-of-service maintenance frequencies as often as every 3 years or every 10 years, depending on the volume and the structural features of the AST. To take into account such elements, in the lifecycle analysis performed, we assumed that tank decommissioning occurs after 4 annual in-service inspections, over a total in-service duration of 50 years. In this regard it must be also considered when significant damages on the tank walls are detected during the inspection, a maintenance intervention is mandatory. Since the drone technology is only limited to inspection tasks, when a repair task is necessary, a traditional (RA or scaffolding) approach must be employed, with a consequent extra time/cost. This situation is likely to happen more often as the age of the tank increases, and in the case considered it is assumed to happen 10 times in the lifecycle of the tank. Taking into account the lifecycle maintenance plan of the AST, and neglecting the effects of time value of money, the following expected undiscounted lifecycle costs are obtained (Table 3).

Table 3: Lifecycle Inspection costs

	Inservice	off service	Lifecycle cost (K€)
scaffolding	0	50	6825
RA	0	50	2625
Drone	50	10	1027

Concerning the unavailability period, when the scaffolding method is employed a lot of time is spent in building the temporary scaffold. For the case considered, the site setup (including the time required for the ASTs to be emptied and taken offline) and scaffolding erection phase can realistically be completed by 6 workers in approx. 10-11 days, while 8 days are required to dismantle and remove the scaffold, while the inspection can be performed in approx. 1 week. The resulting overall duration is thus of approx. 25 days. When the rope access methodology is employed, the site setup operations are much faster, and four days are generally sufficient to complete the site preparation phase and to start the inspection process. This second phase, on the contrary, is generally slow because workers, suspended with ropes from the top of the tank cannot move freely around the structure. The inspection phase is therefore longer, and, in order to reduce the overall duration of the inspection, a higher number of workers is generally required. In the case study considered, the employment of 10 workers, can realistically allow to complete the inspection in approximately 7 working days. Finally, two additional days are required to remove all the anchorages and equipment, and to put the tank back in-process. The overall duration of the inspection can thus be approximately 13 days.

The drone inspection process does not require site preparation activities, but just a preliminary site-analysis and flight planning phase where the parameters related to the “mission” (i.e. flight and data acquisition) are defined. This is generally performed starting from the topology of area of interest (AOI), taking into account the intrinsic parameters of the aerial platform and the digital acquisition system employed. In this phase, it is crucial to determine the required sample distance and the longitudinal and transversal overlap of strips, based on the desired image scale and camera focal length. The flight operations will finally involve the pilot to control the mission from the ground, by means of a remote control station and a final data post-processing phase. The flight preparation phase (approx. 4 days), the actual inspection time (1 day), and data processing (2 days), result in 7 days required from the initial site inspection to end of operations. The following table (Table 4) summarizes the results obtained in a timetable.

Table 4: Inspection timetable

INSPECTION TIMETABLE			
	Week 1	Week 2	Week 3
SCAFFOLDING	S1	S2	S3
RA	RA1 RA2	RA3	
DRONE	D1 D2 D3		

S1=Site preparation; S2=Inspection; S3=Site restoration; RA1=Site preparation; RA2=Inspection; RA3=Site restoration; D1=preliminary analysis; D2=Inspection; D3=Post processing

The inspection time has been extended to the entire lifecycle of the tank similairly to the cost criterion, and with the same assumptions, obtaining the results given in table 5. The overall percent downtime thus obtained with the traditional scaffolding technique is 6.8% of the entire tank lifetyme, which is coherent with the results reported in the literature, and reduces to 0,8%, when drone inspection is employed.

Table 5: Lifecycle inspection time

	inspection time (days)	lifecycle inspection time (days)	Tank out-of-service percent period (days)
Scaffolding	25	1250	6,8%
Rope access	13	650	3,6%
Drone	7	145	0,8%

Finally, the safety criterion has been considered. Although safety is the most important indicator decsion makers take into account when selecting a service provider in critical industrial contexts, it is not easy for a decision maker to have a clear perception of the risks, particularly when a new technology is employed.

The hazards related to traditional inspection methods (i.e. scaffolding and rope access) are mainly related to working at height condition. Such approaches, hence, share a similar risk profile which is briefly summarized in Table 6. Several of the hazards identified have a relatively high probability of occurrence, and are a potential cause of fatalities, disabling injuries or illnesses. The risk associated to these operations, hence, is generally considered very high. As a risk mitigation measure, the Occupational Safety and Health Administration (OSHA) regulation requires that every employer, supervisor, and worker involved in the process must use adequate protection devices and systems including helmets and life lines/fall arrestors.

Table 6: Scaffolding and Rope Access risk profiles

Risky event	Consequence –scaffolding	Consequence – rope access
Falls from height,	Serious injury/fatality	Serious injury/fatality
falling materials	Struck-by injuries/fatality	Struck-by injuries/fatality
Incorrect set-up of the scaffolding/harness	Serious injury/fatality	Serious injury/fatality
Material Handling	Minor injuries	Minor injuries
Collapse of Scaffold or structure	Serious injury/fatality	Serious injury/fatality
Environmental conditions (wind, rain etc).	Struck-by injuries/fatality	Struck-by injuries/fatality
Fall of persons during erection and dismantle.	Serious injury/fatality	

The risk profile of a drone system, given in Table 7, involves few main sources of hazards, namely: system reliability, criticality of operations, midair collisions, ground impact, human errors and environmental conditions. The implications of such issues are reported in Table 7.

Table 7: Drone risk profile

UAV Risk Profile	
Risky event	Consequence
Mid-air collisions	Catastrophic event/fatality
Ground impact	Catastrophic event/fatality
Environmental conditions	Catastrophic event/fatality
Explosion risk (*)	Catastrophic event/fatality

(*) only when operating in ATEX classified zones

IV. RESULTS AND DISCUSSION

Once the indicators have been evaluated, the application of AHP method is presented. A preliminary step consisted in selecting a board of experts among industrial safety managers and operators and providing them with the quantitative and qualitative information reported above. The board of experts has been thus requested to formulate individual judgments by means of pairwise comparison matrices, in a linguistic form, which have been subsequently translated into numerical values from ranging from 1 to 9, according to the well-known Saaty scale (Table 8).

Table 8: Saaty scale

Value	Descritpion
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values

The first task experts are called to accomplish is to express in a linguistic form their judgments about the importance of criteria by filling the pairwise comparison matrix reported in Table 9.

Table 9: Criteria comparison matrix

	Time	Cost	Safety
Time	-		
Cost	slightly more important	-	
Safety	strongly more important	more important	-

The judgments show that safety risks are perceived as the most important criterion, while cost and time have similar importance in the decision. This reflects in the normalized criteria weights reported in the Table 10.

Table 10: Normalized criteria weights

	weight
Time	0,083308
Cost	0,193186
Safety	0,723506

Subsequently In this step, the experts are requested to score the performance of the alternatives in each criterion. The pairwise comparison matrices thus obtained are reported in the tables below Table 11, 12 and 13.

Table 11: Alternative scores with respect to the time criterion

UNAVAILABILTY PERIOD			
	Drone	RA	scaffolding
Drone	-	more/slightly more important	more important
RA		-	slightly more important
Scaffolding			-

Table 12: Alternative scores with respect to the Cost criterion

COST			
	Drone	Rope access	scaffolding
Drone	-	equally/slightly more important	more important
RA		-	slightly more important
Scaffolding			-

Table 13: Alternative scores with respect to the risk criterion

SAFETY			
	Drone	Rope access	scaffolding
Drone	-	more important	more important
RA		-	Equally/slightly more important
Scaffolding			-

The final judgment matrix is given in the following Table 14. The overall priority has also been calculated taking into account the preference of alternatives for each criterion and the corresponding weight.

Table 14: Final judgment matrix

	Time	Cost	Safety	Overall priority
Drone	0,68	0,58	0,70	0,68
RA	0,21	0,31	0,184	0,21
Scaffolding	0,10	0,11	0,115	0,11

Finally, the results of the incoherence analysis are given in the following table (Table 15):

Table 15: Incoherence analysis results

	CI	CR
Weights	0,0557	0,0961
Time	0,0657	0,0113
Cost	0,0025	0,0042
Risk	0,0440	0,0758

According to the results obtained, the drone technology for plant inspection emerges as the best choice since it is generally cheaper, faster and safer than the other alternatives. However, the difference of expected lifecycle cost between drone and RA is actually very small, as well as the difference in the overall inspection time, therefore the decision process is mainly influenced by score assigned to the safety criterion. In addition, such elements are largely dependent on the incidence of the maintenance intervention tasks: drone technology, in fact, only allows for inspection activities, but if a repair task is required, a traditional scaffolding or RA method must be employed. This has a significant negative impact on the time/cost performance of the drone based inspection. According to such considerations, also, the level of deterioration of the tank impacts the performance of the alternatives considered, and, ultimately, on the overall ranking obtained. In addition, another important element to take into account is the comparability of the results obtained by the different inspection methods. The compared alternatives, in fact, do not provide the same results, and the quality of the information obtained is comparable only to a limited extent. In particular, a skilled operator that examines the structure of the tank from a scaffold, generally performs a first visual inspection of the surface, but reserves the possibility of employing more advanced tools, if required. The drone inspection system, on the contrary is only capable of providing a digital image of the tank inspected, but no additional information can be gathered. The digital information obtained can easily be post-processed into a digital 3D model with textured surfaces and archived for further reference or to provide evidence to third parties and local authorities when necessary.

V. CONCLUSION

Although the potential of UAV technology in several industrial applications is generally recognized, a systematic evaluation of the benefits in specific applications can hardly be found in the literature. This paper addresses such topic by proposing a structured assessment framework based on the AHP method, to support plant managers in service procurement taking into account the issues related to cost, unavailability period and safety. On the basis of such methodology a case study has been developed, with the aim comparing the drone technology with the standard methods currently employed in industry for the inspection of ASTs. The results obtained show that the drone based approach can realistically outperform the currently employed methods in terms of expected lifecycle cost, expected overall downtime and safety of the workers. However, due to the impossibility of carrying out repairs by means of the drone, the cost effectiveness can be actually questioned, since it depends on the condition of the tank analyzed. The economic analysis is thus exposed to an inherent risk which might substantially alter the results obtained.

Conversely, the drone technology benefits of significant economies of scale in the inspection of multiple tanks located one close to the other (as in large tank farms). In such cases, in fact, a single flight can inspect more tanks simultaneously, which is clearly impossible when scaffolding or rope access methodologies are employed. However, even when the costs of drone inspection are higher than expected, this method can still be preferred due to its higher level of safety, which emerged as the most important decision criterion for plant managers. In this regard it must be highlighted that in a real situation the drone based service can only be performed by an ATeX drone, which nowadays can hardly be found on the market. Another open issue concerns the quality of the obtained results, which is clearly different when a drone inspection system is employed. Finally, the lack of adequate and standardized regulations in the maintenance and aviation sectors still hinders a spread of drone's technology as a real alternative inspection service in critical industrial contexts, which is a substantial obstacle to a market spread.

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AUTHORS PROFILE

Islam Asem Salah Abusohyon is a management engineer, with a PhD in Management Engineering degree from University of Genoa in Italy. Prof Abusohyon is also a scientific researcher at the University of Palermo, Italy and she is an author of publications in international journals in the field of Internet of Things, Digital Twins and advanced technologies in the manufacturing industry. Her scientific interest focuses on the digitalization and the smart transformation of the traditional processes into smart ones through the development of advanced technologies such as IoT, CPS, AI, and Digital Twins. Meanwhile, Prof. Abusohyon is cooperating with Prof. Giuseppe Aiello on national research projects granted in cooperation with relevant industrial companies operating in Italy.

Giuseppe Aiello is a production management engineer, with a PhD in Management Engineering and associate professor of Supply Chain Management at the University of Palermo, Italy. Prof. Aiello has more than 20 years of academic teaching experience and is author of more than 100 publications on international top-ranked journals. Member of the ISO TC 184, prof. Aiello is a member of several international research teams, operating in many research fields involving agroindustry, Oil & Gas, energy production, Shipbuilding and manufacturing. His scientific background is mainly in logistics and industrial plant management including ergonomics, worker’s health safety, sustainable supply chain management, and circular economy. Prof. Aiello has also been a member of the organizing committee of several international conferences and responsible of more than 10 research projects granted by national and international institutions in cooperation with relevant industrial companies operating worldwide. Prof. Aiello is also an expert advisor of institutional subjects and owns a solid background in enterprise management and business consultancy. The recent research activities have been mainly focused on the application of new emergent technologies such as autonomous robots and nanostructured materials in the manufacturing industry, coherently with the recent paradigm of industry 4.0 and with the spread of industrial IoT solutions.

Antonella Certa is a management engineer, with a PhD in "Economic Analysis, Technology Innovation and Management of the Development Policies" at Università degli Studi of Palermo. Prof. Certa is Program Coordinator of Digital Enterprise Innovation Engineering Degrees and an associate professor of Production and industrial plants management at University of Palermo, Italy. Prof. Certa has more than 15 years of academic teaching experience and she is author of publications on international top-ranked journals on research topics mainly focused on industrial plants design, maintenance management optimization and project management. Prof. Certa has also been a member of the organizing committee of several international conferences and associate editor for relevant journals.