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The Problem of Recycling of Unmanned Aerial Vehicles

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ABSTRACT

Recently an extensive growth in the market for Unmanned Aerial Vehicles (UAVs, drones) has been observed. Because of numerous advantages, their application in various areas is wide, starting with military, through civilian – specialized up to amateur. The world market for civilian commercial drones in the year 2022 has achieved a value of more than USD 30 billion, and it is estimated that by 2032 it will have achieved USD 125 billion. Great expectations of reduction of world CO_2 emissions and development of clean economy are linked with drones application in transportation and agriculture. Unfortunately, despite of the UAV – related advantages mentioned above, the problem of their comprehensive recycling seems to remain unseen. Actions aimed at recycling lithium-ion batteries used in drones have been taken, whereas the challenge of recycling the construction materials applied in UAVs seems to be ignored, which, taking into consideration the estimated growth of the UAV market and a relatively short product lifecycle, may constitute a significant ecological problem in the near future. The aim of this article is to draw attention of scientific community to the crucial but unnoticed problem, which UAV recycling will become in the near future. The authors tried to assess the extent of drones recycling problem by review of UAVs market, emphasizing the most common construction materials applied in their production, and to outline the issues related to their recycling. Proposals of solutions facilitating introduction of circular economy into UAVs market have also been put forward.

Keywords: unmanned aerial vehicles, UAV, drone, recycling.

INTRODUCTION

UAVs, commonly referred to as drones, are flying devices that do not require a pilot on board in flight – they are either piloted remotely or operate autonomously. Due to their numerous advantages, UAVs have become increasingly popular in recent years for various applications [1, 2]. The expansion UAVs has been driven by advancements in technology, functionality, and performance, particularly in terms of range and flight time [3, 4].

Because drones do not require presence of human on board the possible scope of application is widely expanded with health-hazardous and life-threatening missions e.g. rescue, military, research in hazardous environments [5–7]. The possibility of autonomous control is particularly useful in transportation and agricultural applications as it enables execution of laborious jobs without human participation.

UAVs may be equipped with additional sensors and photographic equipment; thus, they may find application for tasks such as aerial photography and videography, aerial forest fire detection, traffic monitoring and management, inspection of infrastructure, geographical monitoring, scientific data collection, meteorological sampling [8–12]. In agriculture, UAVs can be used to monitor crops in remote areas and provide farmers with real-time data on crop health, allowing for more efficient and targeted use of resources like water and fertilizer [10, 13, 14]. Additionally, UAV mounted Base Stations can be used to enhance communication coverage for ground user devices and to enhance internet of everything capabilities [9, 15].

Another advantage of UAVs is their cost-effectiveness. In many cases, UAVs can perform tasks more efficiently and at a lower cost than traditional methods. For example, in infrastructure inspections like bridges, power lines, and pipelines, UAVs can be used to quickly and easily inspect hard-to-reach areas, reducing the need for expensive equipment and human labor.

The application of UAV in package delivery seems particularly promising, as the share of low weight packages is becoming dominant, and this trend has been additionally reinforced by Covid19 pandemic. Utilization of UAV in this market sector signifies reduction of transportation costs, improvement of service quality and reduction of delivery time [16–19]. The potential use of UAV in medicines delivery to hardly accessible areas and to areas of warfare seems to be highly encouraging [20]. Moreover, numerous pieces of research indicate that employment of drones for delivery of small packages will transfer to reduction of CO_2 emission and air pollution [21–25] . Thus, it is no surprise that gigantic corporations such as Amazon, DHL, and Google are working on launching a fleet of package delivery drones [26, 27].

One may not ignore the application of UAVs in hobby application, where they are produced in large batches with main design determinant being low price.

One of the most common uses of UAVs is in military operations. UAVs equipped with cameras and other sensors can be used for surveillance, reconnaissance, and intelligence gathering in dangerous or hard-to-reach areas. They can also be used for targeted strikes against enemy targets, without putting pilots at risk. The wide range of UAV applications has made unmanned aerial vehicles so complex that no uniform classification has been created. Multiple criteria for classifying unmanned aerial vehicles exist, and it is closely related to the constant development of their construction, capabilities, and applications.

The primary classification based on aerial platform enables distinction of the following drone types: fixed wing, flapping wing, rotary wing, tilt rotor, ducted fan, helicopter, ornithopter and unconventional types [8, 28]. In case of mass, the UAV may be categorized into very light (0–5 kg), light (5–50 kg), middle (50–200 kg), heavy (200–2000 kg), very heavy (over 2000 kg). There are also other classifications of drones in use based on the following parameters: application (civilian, military), mode of control (automatic, manual, semiautomatic), mode of take-off (vertical start, runway, launcher), power source (battery, solar power, hydrogen, gasoline, ground source, no source of power) or altitude (flight altitude), range, flight duration, construction type, mode of propulsion (combustion, electric or hybrid engine), airspace class in which the operation is to be performed, application, designation, the sort of operation to be performed [28–32].

Another commonly used classification presented in Table 1 is UVA classification created by Unmanned Vehicle Systems International [29].

UAVs have become an increasingly important tool in many industries. The world market for civilian commercial drones in the year 2022 has achieved a value of over USD 30 billion and it is estimated that by the year 2032 it will have achieved USD 125 billion [33].

Unfortunately, despite all the UAV-related advantages mentioned above, a problem of their complex recycling seems to remain unnoticed While efforts have been made to recycle electronic components and lithium-ion batteries used

Table 1. Classification according to UVSI (unmanned vehicles systems international) (the indicated values are maximum values) [29]

Class	Range of operation	Flight time	Altitude
Nano	1 km	10 min	100 m
Mikro	10 km	1 h	150 m
Mini	10 kg	2 h	300 m
Close range Cr	30 km	4 h	3000 m
Short range Sr	70 km	6 h	3000 m
Medium range Mr	200 km	10 h	5000 m
Medium altitude long endurance (Male)	> 500 kg	24 h	13000 m
Medium altitude long endurance (Male)	> 2000 kg	> 20 h	20000 m

in drones [34, 35], the major challenge lies in recycling the construction materials employed in UAVs, which appears to be largely ignored. This issue becomes particularly problematic due to the strict determination of their weight and construction materials based on their intended applications, leading to various difficulties in recycling. Taking into consideration the estimated growth in the market for UAVs, their relatively short lifecycle and the lack of appropriate steps aimed at their recycling undertaken it may be predicted that huge ecological problem will appear in the nearest future. Furthermore, the absence of actions in the field of drone recycling goes against the principles of a clean circular economy and clean economy development policies adopted in many countries [36–38]. For instance, the European Union (EU) aims to have all its products using resale or recyclable plastic packaging by the year 2030, with the goal of achieving a climate-neutral state in the EU by 2050 [30, 31].

Addressing the recycling challenges posed by UAVs is crucial for promoting sustainability and environmental responsibility in the rapidly expanding drone industry. Encouraging research, development, and implementation of eco-friendly materials and recycling methods for UAVs should be a priority to align with the broader clean economy goals.

SCALE OF THE PROBLEM

Only in the year 2020, the value of world market for commercial drones was equal to USD 13.44 billion, which translated into almost 700000 pcs [27]. In that year, the commercial drones found the broadest application in the construction and agriculture market (Fig. 1). In 2022 commercial drones marker increased up to USD 30 billion [33], and it is forecasted to reach USD 35.28 billion in 2024 [39]. The market for military drones in 2020 amounted to USD 5.6 billion, with estimated constant growth in the nearest decade [40].

The above data indicates that as of today, the market for UAV both in quantitative and quota approach is so developed, that the problem of complex recycling of drones may not be ignored, especially taking into consideration their short lifecycle. What is more, it is estimated, that by the end of 2029 the number of civilian drones worldwide will amount to almost 56 million pieces, and the value of the market will

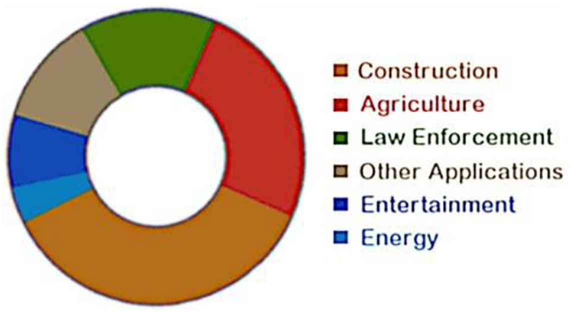

Figure 1. Global drones market in 2020: revenue (percentage) by application [41]

supersede USD 108 billion [42, 43]. It is anticipated, that within a decade a level of expenditure for military drones will constitute 40 percent of all military procurement in the USA [40].

The problem of UAV recycling is complex, and is a result of materials utilized for their construction, selection of which is strictly related to their application. The primary requirement for materials used in aircraft is their low specific weight as the reduction of mass of a flying object translates to greater range, longer flight duration and higher payload. The next required attribute of materials utilized in drones is durability and resistance to vibrations. Materials, which fulfil these requirements, are carbon and glass fibre composites, light metal alloys, particularly aluminium, titanium and magnesium, wood and thermoplastic polymers. Auxiliary materials such as steel, copper, rubber etc. are also used in UAV production to a lesser extent [29, 44–47].

In order to determine the magnitude of the problem, six drone categories, with which the greatest recycling challenges are connected, have been distinguished according to their application: drones for amateur, construction, video and photography (media), transportation, agricultural and military applications.

Amateur application UAVs are characterised primarily by low manufacturing cost and high production volume, hence the dominating materials used for their construction are thermoplastic materials formed in injection moulding machines and glass fibre composites [29, 45]. The biggest problems in their recycling are short product lifecycle and limited access to specialized recycling required in particular with regard to composites – the end user is not registered, and the product is simply discarded in trash bin after it is worn out, and its structure is never subject to an adequate recycling. The drones used for construction applications are currently used in tasks such as: building surveys, topographic and land surveys, construction site inspections, equipment tracking and auto mapping, remote monitoring, integration of laser scanning and aerial photogrammetry, thermal imaging recording [48, 49]. UAVs for construction applications are equipped mainly with measuring and photographic equipment, which results in an expensive build of medium weight and for this reason, the materials dominating in the structure of this type of UAVs are mainly carbon and glass composites, recycling of which has low efficiency and requires a specialized process (in particular, this applies to carbon composites). Furthermore, these drones constitute the majority of commercial UAV market and their mass is relatively high. There are no efficient procedures which oblige the users to transfer the drones to specialised recycling, which is economically unprofitable anyway and targeted mainly for large objects, such as wind turbines' blades [29, 45, 50–54].

The drones for video and photography applications are characterised by similar recycling challenges as the construction application drones, because of the similar scope of operation and similarity of carried payload.

The application of UAVs in agriculture started at the beginning of 1990s, and in mid 2000s, UAVs were already spraying ca. 10% of rice fields in Japan [41, 55]. It is estimated, that along transportation, the agriculture will represent the strongest developing area of drone application [27, 41, 56]. In crop production the UAVs are used for monitoring of growth and crops' quality parameters, automated and optimized spraying process and monitoring and optimization of water irrigation, whereas in livestock production they are used for herd supervision, monitoring and optimization of water and feed consumption [57–59]. The widespread use of drones in agricultural production will result in decrease of CO_2 emission and reduction of utilization of crop protection products and water, and in improvement of harvest quality through optimal resources management, which will have a beneficial influence on the development of clean economy [10, 21, 26, 27, 60–62].

Agricultural drones recycling will pose a significant challenge due to huge and dynamically developing market, one of the biggest single unit curb weight among the commercially available drones, and the fact, that mainly carbon composites are used in their construction [29, 45]. The advantage of this market is a relatively long product lifecycle.

The most promising commercial drone application is transportation, thus the greatest growth of this area of use is predicted in the entire market for UAV [16, 27, 63, 64]. Corporations such as Amazon, DHL and Google have been working on solutions that would enable transport drones application in everyday use for years. Thanks to their specifications, UAVs enable a better management of delivery rout by its shortening and optimization [21, 23, 26, 55, 60, 61]. This would allow to vastly limit the costs of transportation, increase the service quality and speed of delivery, and in ecological aspect would decrease the CO_2 emissions and improve air quality [25]. The air corridors for UAVs are being tested currently. The test highway for UAVs, the "Arrow Drone Zone" is located In the Great Britain. If the solution will prove itself, the network of sky highways shall become widespread, which will become a substantial step towards mass commercial application of UAVs in transportation. Currently, China is leader in the transport application of UAVs. One of the largest drone used in logistics is SF Express, with maximum take-off weight of over 5000 kg, a range of over 1 thousand km and cruise speed of 180 km/h.

The transportation drones are middle to very heavy weight, and due to the carried loads, carbon fibre prevails in their construction, which, taking into consideration a significant development of this area of UAV application, will translate to a massive amount and weight of hard-to-recycle waste.

The military application drones' recycling is a separate subject, because these types of constructions are covered by military confidentiality. The most expensive materials are used in their production, and ecological aspect is a secondary issue in production of those. The military drones are produced within a very broad range of unitary specific weight, from the lightest to the heaviest among all drones in existence [65–67].

The next chapters will present the common materials used in UAV production. Their benefits and drawbacks as UAV construction materials will be discussed, as well as recycling methods available for them. This will enable to indicate the materials, which are the more environment friendly then the most common ones nowadays, and to propose other solutions, which will lead to policy of closed product's life cycle.

AN OVERVIEW OF UAV CONSTRUCTION MATERIALS AND THEIR RECYCLING METHODS

The selection of material has an essential influence on the quality and reliability of an aircraft. Aeronautical constructions have special requirements. Light and mechanically durable materials are sought after. Currently, materials most commonly used for UAV construction are carbon and glass fibre composites, light metal alloys, in particular aluminium, titanium, magnesium, wood and thermoplastic polymers. In aeronautical industry the constant competition exists between metal and composite materials – up to this time, the share of composite materials in aircraft construction was continuously increasing, but the problems with recycling, the rising pressure from ecologists and the priority rule of balanced development should force the search for compromise solutions, designating the new directions of UAV construction at the same time.

The authors propose that one of the key aspects of the development of drones should be the necessity of taking into consideration the balanced recycling of construction materials, including the selection of optimum materials in terms of overall influence of UAV on the environment.

Composites

The composite materials currently play a central role in the design and manufacturing of drones. These materials may be formed into complex shapes achieving a better aerodynamics than in case of the same components manufactured from metal. The most popular materials in this range are glass fibre-reinforced plastics (GFRP) and carbon fibre-reinforced plastics (CFRP)[68]. Besides the above-mentioned materials, the aramid fibre-reinforced plastics (AFRP) are also applied . Recently, the grave problem related to recycling of composites from aircraft and wind turbine blades has been noticed. In Germany in 2009 the law prohibiting the stockpiling of compound waste was introduced, in 2019–2020 the first big wave of wind turbines retired from operation appeared and additionally the accelerated decommissioning of aeroplanes due to COVID-19 pandemic substantially increased the amount of stored composite waste [53]. For this reason, the problem of composite materials recycling has become severe and requires a swift reaction. Such social and technological pressure will rise only in the incoming decade, because other countries may follow Germany's steps by limiting ad forbidding the possibility of waste stockpiling. This problem will pose even greater challenge in case of drones, because of their mass production and small unitary weight, which causes their recycling to be economically unviable.

Glass fiber-reinforced plastics

Glass fiber-reinforced plastics (GFRP) is a term, which describes a composite material built of glass fibres that have been saturated with polymer resin. The components joined by this method make up a material, which is durable, lightweight, corrosion resistant and yields good possibilities in terms of machining and forming. A characteristic feature of glass fibres is high tensile strength with a relatively low Young modulus, and at the same time high elastic modulus at shear stress [50]. GFRP recycling in every case is a quite complex process. Presently the primary methods of recycling are mechanical, thermal and chemical recycling[69]. Mechanical recycling is a method of shredding the waste into smaller parts also known as recyclates. The process begins with cutting and shredding GFRP composites into smaller pieces. The smaller size enables better possibilities of separating fibres from the resin matrix. The recyclates are then sorted depending on their size. The efficient reuse of GFRT recyclates is based on the size of recyclate fragments, which results from the fact, that shortening of the fibres disables the possibility to obtain the primary strength of the composite. Presently, recyclates are reused most often as fillers or strengthening materials. Unfortunately, application of GF recyclates as fillers is economically unviable due to availability of much cheaper filler materials [50, 53, 70]. Another possibility of recyclate reuse is its application as a concrete additive [50, 71, 72].

Thermal recycling of GFRP leads to separation of fibres from the matrix by application of pyrolysis process. Currently pyrolysis is one of the most commonly used processes of aeronautical composites recycling. The process consists in heating of GFRP to high temperature (400–700 °C) in an inert atmosphere, during which the decomposition of organic fraction occurs. The polymer matrix undergoes decomposition into the mixture of liquid and gaseous hydrocarbons, which may be used as a fuel, and the glass fibre is recovered.

Unfortunately, the glass fibres strength is reduced by almost 50% [70, 73].

Chemical recycling of GFRP is a process, in which the matrix' polymers are chemically converted into monomers, or partially depolymerized to oligomers as a result of chemical reaction. After the polymer matrix is dissolved the fibres, which have undergone recycling area washed in order to remove miniscule superficial residue. This process allows to recover long fibres with undeteriorated mechanical properties. The process is characterised by degradation of resin. These, however, are very costly techniques utilized mainly at laboratory scale and their commercialization poses many difficulties [50, 73].

Carbon fiber-reinforced plastics

Carbon fibre-reinforced plastics (CFRP) is a term describing a composite material build of carbon fibres embedded in polymer matrix. The carbon fibre composites are not only lighter, but also have higher strength and stiffness per unit of mass in comparison to other composites. Even better ratios of stiffness to weight may be observed when comparing CFRP to steel – they are up to five times stronger than steel and carbon fibre has a Young modulus at the level reaching 1000 GPa. CFRP has low thermal expansion coefficient (lower then steel and aluminium) and is characterised by very high fatigue strength. The principal disadvantages of carbon fibre application are lower impact resistance compared to other composites and a relatively high price – from a few to a few dozen times higher in comparison to glass fibre composites [50, 73, 74].

Recycling of carbon composites is incredibly demanding technologically because of their complex construction and lattice characteristics of thermosetting resins. An additional obstacle is the application of metal additives, fibre adhesion improving and weight reducing additives etc. The simplest solution, which is burning with energy recovery, is economically unviable and problematic due to overly high carbon fibre degradation temperature [50, 73].

Mechanical recycling of CFRP consists in breaking the composite into smaller parts by processes of breaking, crushing, grinding or other mechanical processes. The resulting fragmented elements are segregated into resin-rich and fiber-rich. The mechanical recycling does not recover single fibers. The mechanical recycling is an extremely energy-consuming process, and its biggest disadvantages are deterioration of mechanical properties and degradation of structure, which limits the possibility of material reuse. The typical application of mechanically recycled composites based on carbon fiber is their addition as fillers or composite's reinforcement, in construction industry e.g. for tarmac or concrete production [50, 73, 75].

During thermal recycling of CFRP the resin is decomposed separating the reinforcing fibers and fillers. This process is based on thermal decomposition of organic particles in the atmosphere of inert gas (e.g. nitrogen). In the pyrolysis process, the previously cut CFRP elements are heated up to high temperature in almost oxygen-free environment. The polymer matrix is separated and carbon fibers are recovered. The principal disadvantage is, that an oxidization process is needed to remove the char deposited on the fiber. The excess char results in reduced quality of bonding between the fibers and the new polymer [50, 53, 73, 75].

Chemical recycling methods of CFRP are based on reactive environment. The polymer resin undergoes decomposition into relatively large oligomers, whereas the carbon fibers remain neutral to the chemical environment. The advantage of this method is high efficiency of high quality carbon fibers recovery. The fundamental disadvantages of this method are high costs and numerous problems with introduction into service at industrial scale. The chemical solvents used in the method tend to be toxic to the environment [50, 73, 75].

Thermoplastic polymers

The UAVs mass-produced for hobby applications are made of thermoplastic polymers. The characteristics of these materials are low density, good mechanical properties, durability, corrosion resistance, ease of forming with injection molding and low price. These materials are commonly used in 3D printing [76, 77]. The can be divided into three types:

- Crystalline thermoplastics, which have highest mechanical impact resistance. Examples are polypropylene (PP), low-density polyethylene (LDPE), and high-density polyethylene (HDPE);
- Amorphous thermoplastics usually transparent, representative polymers are poly vinyl chloride (PVC), polymethylmethacrylate (PMMA),

polycarbonate (PC), polystyrene (PS), and acrylonitrilebutadiene styrene (ABS);
- Semi-crystalline polymers properties of which are combination of the two mentioned above. Examples are polyester polybutylene terephthalate (PBT) and polyamide imide (PAI) [78, 79].

The basic methods of thermoplastic polymers recycling are mechanical and chemical recycling and energy recovery. The most commonly utilized recycling method is mechanical recycling, in which the material undergoes mechanical break up and forming into granulates, flakes or pellets, which are melted and used for manufacturing of new products. The method is commonly used in waste recycling process and for this reason the drones made of thermoplastics do not require specialized recycling method. Chemical recycling has been developed at an industrial scale mostly for polypropylene (PP) and high-density polyethylene (HDPE). The energy recovery method may not be ecologically viable due to the toxic substances that can be created in this process [78, 79].

Biodegradable polymers

The biodegradable polymer used for UAVs production is PLA (polylactic acid), which is fully biodegradable and may be obtained e.g. from corn meal. It is characterized by low density, good mechanical properties and ease of forming and possibility of application in 3D printing technology. For ecological reasons it seems to be a good alternative for commonly utilized thermoplastics, unfortunately because of a relatively high price it is used mainly in low production volume and prototype drones manufactured by 3D printing technology [79, 80].

Wood

The wood had been used in aircraft construction from the moment aviation was born. Nowadays the application of wood in flying objects is limited. Wood is characterized by high durability, but unfortunately also by relatively high specific weight. What is more, because of its natural origin, material selection and adequate preparation (among others drying, protection against external conditions) is mandatory to obtain a high-quality product. Additional problems in operation of UAVs with wooden elements are construction displacements related to the variation in wood's humidity in different operating conditions. Even the slightest displacements cause changes in the geometry of aircraft, which have influence on the aerodynamic characteristics. Because of the reasons mentioned above, as of today, wood in drones is used mainly for the production of propellers and support structure of lifting surfaces [45, 81, 82].

Light metals alloys

All metals commonly used in flying objects, in particular, alloys thereof are much easier to recycle than their composite counterparts are – after proper heat treatment, they may be reused. The metals most commonly used in UAV production are aluminum, titanium and magnesium alloys [29].

Aluminum alloys

Aluminum alloys are one of the most important construction materials utilized in aeronautical industry, including UAVs. The main components of aluminum alloys in aircraft, apart from aluminum, are copper, silicone, manganese, magnesium and zinc, and in low percentage quantities: nickel, iron, titanium, chromium, beryllium and others. Various construction components are produced from aluminum alloys, including: beams, ribs, frames, plating, pylons of lifting surfaces as well as connective components – rivets (rivet nuts) [45, 83]. Aluminum alloys have specific strength and stiffness, good ductility and corrosion resistance. They have low price and excellent manufacturability and reliability. Aluminum alloys offer a wide range of material properties, through adjusting compositions and heat treatment methods [81, 83, 84].

Titanium alloys

Titanium alloys are metallic elements with high mechanical strength in relation to their specific weight. They are very light and characterized by high melting point. Titanium alloys have an outstanding chemical properties, remarkable corrosion resistance (comparable to resistance of platinum) and low heat and electrical conductivity. The titanium alloys are characterized by high tensile yield strength [85]. The application of titanium alloys allows to increase the strength of construction and reduction of its mass at the same time. The disadvantages are high costs and difficulties during machining. For this reason, it is used only in the modern UAVs for professional applications.

Titanium alloys are used to produce, among others, strength components, connective items (rivets, bolts, pins etc.), power transmission parts and load bearing structures [45, 81, 83, 86].

Magnesium alloys

Magnesium alloys are the lightest of all construction metals and for this reason, it is a perfect choice for application in aircraft, where weight is a critical component of the design. Magnesium is a metal characterized by high strength, good heat removal and vibration damping. Because of its mechanical properties, it is easy to machine by various methods. It can be easily joined with other metals, which yields alloys with desirable, more advantageous properties for particular applications. Utilization of pure magnesium in flying apparatus is rare because of its flammability in high temperatures and low corrosion resistance in damp environment. Magnesium alloys are used for production of construction components and frames, transmission boxes, covers, housings of electronics and flight and undercarriage control systems in highly specialized drones [81, 87, 88].

COURSE OF RECYCLING-RELATED ACTIONS

Ecological responsibility and pursuit of a closed product's lifecycle requires a range of urgent and multi-track actions in the UAV recycling area. The authors propose some courses of recycling-related actions:

Eco-friendly materials

Low budget mass-produced drones should be made of biodegradable materials, or materials that may be recycled by available common recycling processes, so that after being discarded they could be properly recycled [89].

When feasible, carbon fiber and glass fiber composites used in UAV construction should be substituted with materials that are easier to recycle, such as light metal alloys

Waste and recycling regulations for UAVs

When the use of composite materials in UAV construction is unavoidable due to construction restraints or to achieve ecological benefits, owners of such UAVs should be obligated to deliver them to an appropriate recycling process after their operating period is over. This could be facilitated through record-keeping of drones or by introducing a deposit refund system (DRS).

The obligatory registration of drones, which is becoming common in many countries [67,68], could be used for record keeping of UAVs, which require specialized recycling. UAVs could be equipped with a unique identifier similar to vehicle registration. Moreover registration data could contain detailed information about waste management strategies.

UAVs parts could be tagged by use of Taggant technology [90]. Taggants are materials that can be applied to or incorporated within an object to make it identifiable, facilitating the sorting and recycling process.

Laws and regulations should be established to obligate manufacturers and importers to introduce appropriately certified eco-friendly UAVs with minimized negative environmental influence into the market.

To ensure the correct functioning of the drone recycling system, the existence of adequate specialized recycling points responsible for recycling through processes typical for the applied materials must be secured.

New recycling technologies dedicated to UAVs

Because as of today, the process of carbon and glass fiber recycling is not satisfactory, and requires further research, during the development of new recycling methods small form factor objects should be taken into consideration.

Rational resource allocation

The research should be undertaken to estimate the balances and losses in relation to the applied construction materials, work time and impact on the environment.

Research shall be undertaken to develop criteria for the selection of construction materials for drone production, depending on their target application and weight, so that the negative impact on the environment during manufacturing and operation is limited; the possibility and accessibility to recycling and minimization of CO_2 production.

CONCLUSIONS

The main target of the article is to draw attention of scientific environment and public opinion to the grave, but unnoticed problem that recycling of UAV will become in the closest years. The data presented in the article indicates, that as of today the market for UAV both in quantitative as well as quota terms is highly developed and is characterized by dynamic growth, hence the problem of complex drone recycling may no longer be ignored. It is a pressing problem resulting in particular from the short product life cycle and the fact, that materials commonly applied in drones production, principally composites, pose a significant challenge in recycling process. The authors put forward a proposal, that one of the key aspects of the development of drone technology should be the necessity of considering the balanced recycling of construction materials, including the selection of materials, which are optimal in terms of overall influence of UAVs on the environment, and necessity of actions, which target delivery of worn out drones to specialized recycling.

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