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Value Sensitive Design and Environmental Impact Potential Assessment for Enhanced Sustainability in Unmanned Aerial Systems

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***Abstract*— Value sensitive design (VSD) is an approach that facilitates the pro-active incorporation of human values into technological design. The VSD literature, as well as empirical studies, identify environmental sustainability as a human value with importance in design, and therefore importance in Unmanned Aerial Systems (UAS) design. UAS have begun to spark significant public interest and environmental changes. However, there are few studies that address how to design UAS for these changes, and none that take VSD as their point of departure. In this work, the environmental sustainability of UAS are analyzed using VSD and environmental impact potential assessment (EIPA) approaches. VSD envisioning cards are used as design prompts to identify relevant social and environmental impacts for two case studies to illustrate the approach: a healthcare application, and a powerline inspection application. The environmental impact potential is assessed, along with consideration of the drone's materials and manufacturing processes which have an effect on toxicity to humans, water depletion, and acidification. Then, general insights into how UAS can be designed for enhanced environmental sustainability are discussed. The results show high sensitivity to changes in defining the system boundaries and in defining relevant UAS scenarios, as a direct comparison of drone and non-drone scenarios is not possible. Thus, VSD and EIPA approaches can provide a nuanced way to analyze UAS applications, leading to positive social impacts and enhanced environmental sustainability in UAS in the future.**

***Index Terms*— Value Sensitive Design, Drones, Sustainability, Environmental Impact Potential Assessment, Public Interest Technology**

I. INTRODUCTION

UAS have the potential to perform many tasks which support environmental sustainability. For example, these autonomous or semi-autonomous flying robots may be useful in mapping the thickness of sea ice [1], monitoring the emissions of cargo ships [2], tracking wildfires [3], or spreading beneficial organisms for organic farming [4]. And the vehicles themselves may also be designed with sustainability in mind, such as those using solar [5] and hydrogen fuel-cell [6] power sources, vehicles made from renewable [7] or biodegradable materials [8].

UAS are still a relatively new technology, and researchers, companies, and governments might want to know where to focus their resources. This leads to two related research questions:

1) *How important is it to consider the environmental impact of the application for which the drone is used?*
2) *How important is it to consider the environmental impact of the drone system itself?*

In this work, these questions will be addressed using both qualitative and quantitative analyses.

Currently, there are no studies that address how to design and use UAS for environmental sustainability *from a VSD perspective*. And many of the existing analyses of drone environmental impacts are quantitative in nature and performed using a life cycle assessment (LCA) methodology [9][10][11][12].

II. VALUE-SENSITIVE DESIGN

Value sensitive design (VSD) is an approach that facilitates the pro-active incorporation of human values into technological design [13][14]. The VSD literature [15], as well as current drone projects [16][17][18], identify the public interest in environmental sustainability as a human value of significant importance. A full VSD analysis contains three phases: 1. a *conceptual phase* which addresses philosophical and ethical considerations and where direct and indirect stakeholders (those impacted by the technology) are identified and their values gathered. 2. an *empirical phase*, where the social impacts of the technology are studied, often using social science tools such as interviews, focus groups, surveys, and where value-eliciting prototypes are presented, and 3. a *technological phase* where engineering and design are used to develop an artefact (i.e. drone, piece of software) that aims to support the values of the stakeholders and takes into consideration the social context and social impacts. This process has been called the *"translation of values into design requirements"* [14], all the way to the specification of the materials the drone will be built from.

VSD envisioning cards are design prompts that facilitate *"attending to human values during design processes"* [19]. This tool can be used early in the design process to identify social and ethical impacts of a new technology, such as impacts due to widespread and ubiquitous adoption, or impacts on future generations - stakeholders that are not yet born. It is not a substitute for stakeholder engagement, but

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a preliminary analysis tool for identification of stakeholders to engage with as well as a tool for highlighting issues to study more deeply.

A VSD-perspective has recently been applied to analyze different uses of drones (such as policing or agriculture) [20], as well as analyze and re-design humanitarian [21] and healthcare [22] drones.

VSD is a particularly useful methodology in analyzing the environmental impact of UAS because it facilitates a holistic comparison of the existing way an activity is performed with the way it could - or should - be performed with a UAS. In other words, the comparison scenarios, or the choice of ”functional units” is to ensure common ground for comparison of different cases. Direct comparison between non-drone and drone scenarios is not possible, so a VSD approach informs which scenarios should be compared, and contextualizes the heterogeneous results. *”The capabilities of a drone are not directly comparable to other technology. This presents challenges when trying to assess the consequences of displacing additional technology”* [11]. In addition, *”results of Life Cycle Assessment are critically dependent on the system boundaries, notably the choice of attributional or consequential modelling”* [23]. However, LCA and EIPA have the advantage of being able to quantify changes initiated by the technology. Therefore, VSD and EIPA are used together in this study.

In an analysis of UAS used in a humanitarian context for the transportation of medical samples, it was found that the drone excels at carrying small/lightweight blood spot tests (10 grams each) over difficult terrain, while the typical motorcycle transportation is much less expensive (in one scenario, over 1000% less expensive), and best for heavy cargo [24]. And although they are fairly common in medical transportation and e-commerce [25], small and lightweight packages of under 2 kg are typically assumed to make the drone scenario more favorable.

When comparing UAS with existing, truck-based delivery networks, the number and arrangement of additional warehouses required (due to the UAS shorter range) can make the UAS scenario less attractive [9].

In summary, it is not possible to directly compare UAS to non-UAS scenarios - for example, there are significant privacy concerns when UAS are used [26] [27] [28] [29] [30] and this is a difficult ”cost” to quantify when comparing UAS with other technologies.

These challenges - in defining the system boundaries, and in defining relevant UAS scenarios - are both addressed here with a VSD approach combined with EIPA.

III. HUMAN VALUES AND ENVIRONMENTAL SUSTAINABILITY

One definition of environmental sustainability within the context of technological design is *”sustaining ecosystems such that they meet the needs of the present without compromising future generations”* [31].

Approaching sustainability from a VSD perspective means performing a conceptual analysis, examining the ethical and philosophical framing of the technological design space.

IV. METHODS

In this work, three methods were used: a macro-level VSD-informed preliminary analysis using VSD envisioning cards, a system-level EIPA analysis, and a micro-level analysis using classical laminate theory to analyze and improve the composite plate the drone’s frame is made from.

The VSD envisioning cards [19] [32] are divided into four themes: 1. Stakeholders are people that interact with or are impacted by the technology being developed, either directly - as direct stakeholders, such as a drone operator - or indirectly - as indirect stakeholder, such as members of the general public that see the UAS in operation. 2. Value deals with human values - “what a person or group of people consider important in life” [19]. Examples of human values are privacy, human welfare (physical, psychological, and material), and environmental sustainability [15]. 3. Pervasiveness focuses on the impacts of widespread adoption of a technology. For example, rather than only thinking about the immediate application, considering what would happen if drones were everywhere. 4. Time includes broadening the scope of the time interval considered - for example, thinking about how future generations might come to be impacted by UAS, or the long-term environmental impacts of the technology.

The environmental impact potential assessment was preformed by modelling the systems in OpenLCA (open source life cycle analysis modelling software) [33] based on inventory data from ecoinvent 3.4 [34] using the International Reference Life Cycle Data Systems (ILCD) 2011 impact assessment methodology [35]. The European Composite Industry Association’s (EuCIA) *Eco Impact Calculator*, was introduced to analyse climate change in *kg CO2 equivalent* for specific material types. The calculator also utilizes the ILCD impact assessment methodology, with background datasets from the databases in SimaPro 8.0.2 (using Ecoinvent for equal data foundation), supplemented by industry data obtained by completed questionnaires [36].

The mechanical analysis was carried out using classical laminate theory [37], to validate the performance of more sustainable composite materials for the drone’s frame.

V. CASE STUDY 1 - HEALTHDRONE

The first case study involves the transportation of urgent blood samples from the island clinic in Ærø Denmark, to the regional hospital in Svendborg, Denmark [38] - a straight-line distance of about 25 km. A prototype of the drone is seen in Fig. 1. Currently, all medical samples are transported by a courier driving a van which must utilize the ferry, and is therefore dependent on the ferry schedule which leads to waiting time.

A. Stakeholders

Some of the direct stakeholders include the drone operators, healthcare staff and doctors that interact with the drone, courier drivers and, possibly, aircraft pilots flying low

Fig. 1. Prototype blood sample transportation drone (photo by the authors)

in the area. Relevant indirect stakeholders are the general public that is exposed to the drone during its operation, especially those living near the clinic and hospital, as well as non-human animals, especially birds - the flight route from Ærø to Svendborg passes through a protected area for birds [39]. Animals cannot speak for themselves, so ornithologists and conservationists may serve as a proxy to protect their interests [40].

B. Value

There are several human values at stake in this analysis, including the value of safety to those in nearby aircraft and to indirect stakeholders on the ground which could be struck by a drone. The value of privacy is relevant especially to those the drone flies over, but to society in general if people feel they are being watched by drones at all times. The value of human welfare is particularly relevant here - which includes physical welfare from potentially faster healthcare the drone can deliver - but also the impact to material welfare including jobs gained and lost due to the introduction of the drone. The value of calmness is uniquely important to the island community of Ærø, where serenity and peacefulness are a main feature of the location. And the value of environmental sustainability is crucial, and which can be framed in several ways [41]: as **anthropocentrism**, which is centered on human interests, and where nature should only be protected to the extent it benefits humans. **Zoocentrism**, where animals should be equally respected as ethical subjects. **Sentientism**, where sentience or the ability to feel pleasure or pain, qualify as relevant ethical subjects. **Biocentrism**, such that all living things are considered, including plants and trees. And finally **ecocentrism**, where humans are a part of nature and cannot be separated from it; everything has ethical importance, including rivers, rocks, and the Earth as a whole. The choice of framing has an influence on how human values are prioritized relative to those of non-human animals, plants, and the ecosystem at large, and this choice will have an impact on the resulting technological design.

C. Pervasiveness

One benefit of drone technology is its ability to bypass difficult terrain. Here, the drone can transport the samples over the ocean without waiting for the ferry, and potentially lead to better health outcomes for patients such as reduced use of broad-spectrum antibiotics and reduced utilization of quarantine. However, as drones become part of the health-care system, less funding could be committed to building traditional infrastructure such as ferries, bridges, and roads.

It could also become difficult or impossible to ”opt out” or avoid exposure to drones. Even those living on remote islands, and who may have chosen to live there for the peace and quiet, would not be able to avoid the chances that a drone will fly over them or their property.

D. Time

In the long-term, drones will likely add to job loss facilitated by automation. This job loss could become widespread enough to have serious consequences upon individuals and societies. A person’s self-worth can be tightly linked with their occupation, and job loss will challenge this. Rich countries such as Denmark may be particularly susceptible to this risk, as there are high economic incentives to replace expensive workers with automation. Finally, HealthDrone could lead to a ’rebound effect’, where its (real or perceived) ”efficiency” and speed leads to increased use, and, paradoxically, to an increased environmental impact.

E. Environmental impact potential assessment modelling and results

In a comparison of the climate change induced impact gains by this drone application, we compare the blood sample transport from Ærø to Svendborg (distance - 24,1 km by ferry and 2,4 km road transport). The business as usual scenario carries two blood samples in a car, which drives/sails back and forth to Ærø. In the drone fly back scenario, a 1,5 kg drone transports the two samples to Svendborg by air and returns to Ærø (after recharging) on its own. In the drone drive back scenario, the drone is driven back from Svendborg to Ærø along with other commercial goods (100 kg) when convenient (Transport service in Fig. 3). The 1,5 kg drone was modelled by determining the mass of its constituent materials and calculating their introduced climate change. The categories for this drone (as seen in Fig. 2 includes expanded polystyrene (EPS) for the body, wings,

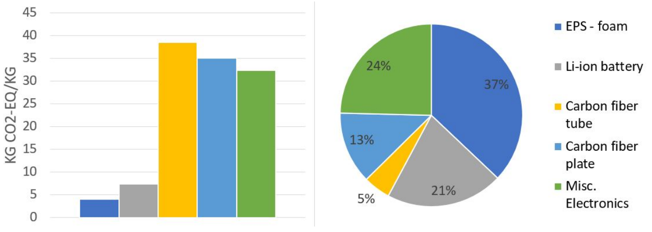


Fig. 2. Left: GHG emissions from extraction and manufacturing of materials found in the drone. Right: Material decomposition of the drone total mass

and tail, Lithium-ion battery cells for the power source, carbon fiber (epoxy) for the frame and spars, and misc. electronics for the control and navigation electronics. In Fig. 2 it is clear that extraction and manufacture of carbon fiber (epoxy) materials and electronics are the biggest contributors to GHG emissions, and combined they are responsible for a significant amount (42%) of the total drone mass.

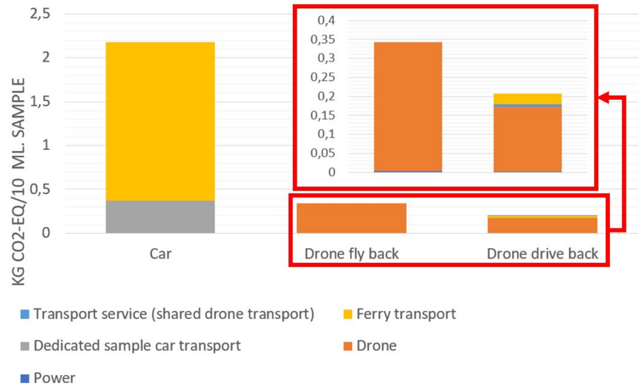


Fig. 3. GHG emissions associated with 3 ways of transporting 10 ml blood samples from Ærø to Svendborg for analysis

As is observed from Fig. 3, a dedicated car transport from Ærø to Svendborg yield emissions of GHGs equivalent to applying 2,2 kg CO2-eq/10 ml sample. Alternatively, if drones are used for the sample transport are allowed to fly back on their own power the emission can be cut to 0,35 kg CO2-eq/10 ml sample, and in the case the drones are transported back by car (along with other goods) to 0,2 kg CO2-eq/10 ml sample. The savings of applying drones if assessed in a conventional LCA approach, leads to cutting the GHG emissions by a factor 6-11 depending on the return transport of the drone.

Important to notice from the analysis is the functional unit. If the samples to be transported are collected in batches of 20, the car would easily carry this. The results will decrease the emissions to 0,21 kg CO2-eq/10 ml sample, making it competitive with the drone drive back scenario. On the contrary, the collection of samples for transportation increase the lead time for the samples to arrive at the hospital.

F. *Design for environmental sustainability in HealthDrone*

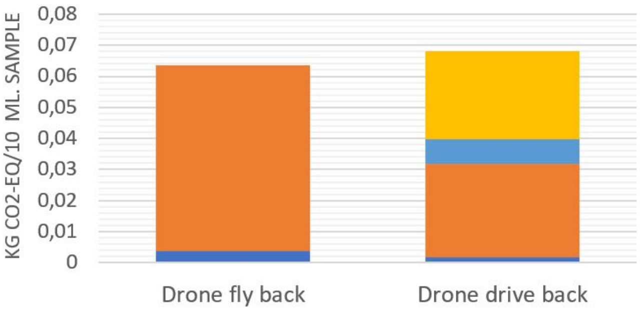


Fig. 4. GHG emissions with EoL-design assumption

From section V-E, there is a clear benefit towards any of the proposed drone solutions. In the proposed solution it is clearly observed that the manufacturing of the drones contributes the most to the total GHGs emission. In this analysis the drones were assumed to have a duty-life of 250 flights, before recycling. The assumption was based on the estimated life of the Li-ion batteries, servomotors and physical wear to the EPS. Through end-of-life (EoL) design optimization this process can be optimized [42]. If the drone design allows the end-user to reuse the remaining (non-broken) components, the analysis revealed a further reduction of the GHG emissions. From Figure 4, the proposed drone solutions has been further optimized to 0,06-0,07 kg CO2-eq/10ml sample. It was also observed that the drone fly back case was now the most sustainable considering climate change only. Further optimization can be achieved through reconditioning of the components exposed to considerable wear as also discussed by *Peeters et. al.* [42].

VI. CASE STUDY 2 - DRONES4ENERGY

Fig. 5. Drones4Energy prototype multicopter (photo by the authors)

The danish research project ”Drones4Energy” [17], aims towards building an autonomous drone system which can detect and report faults in overhead powerlines. The drones will work in swarms which have access to the powerline locations from an open data source, and fly towards the desired location through a generated path to inspect powerlines and towers. Currently, drones are limited in their range and flight times by battery and recharging technologies. So in addition, the drone will be designed to harvest energy by perching on the powerline and wireless recharge its batteries from the electromagnetic field, to ensure continuous inspection. Currently, the inspection process involves flying a helicopter in close proximity to the powerline to do visual inspection of the grid.

A. *Stakeholders*

A successful implementation of recharging from powerlines would facilitate the ubiquity of any drone technology in general. Powerlines are present in most daily environments. A continuously operating drone swarm along the grid will lead to an omnipresence of drones, increasing the amount of in-direct or even direct stakeholders significantly. The constant presence of drones will introduce a social impact in various ways depending on the individual's perception of the technology. It could eventually merge into a natural part of the environment, or lead to more push-back from the public and other stakeholders. For the direct stakeholders, the project eliminates the need of human inspectors, but instead creates engineering positions to develop and mature the technology, and ground station tasks. Hereby, putting the ”thing” in danger instead of the human (the value of human safety, discussed in the next section).

B. *Value*

Inspection of powerlines is a time consuming task for humans to conduct. It is a combination of great precision, danger and risk when the human inspector jumps from a flying helicopter to a powerline distributing more than 400.000 volts, to crawl along the lines performing visual inspection [43]. This process of manual inspection limits the frequency of the inspection to minimize cost and human risk. The drone facilitated inspection introduces continuous inspection of the grid and its infrastructure, yielding higher failure detection, decreasing the risk of dangerous incidents. In other words, increasing safety in the operation. In general within engineering, *safety* is a well considered value, but *security*, and investing time in designing with capability cautiousness [44] can be easily overlooked. As introduced in section VI-D, over-trust in a non-secured technology could lead to creating a platform with the critical potential of mis-use. Through good or bad incidents, the trust in the technology can be dramatically changed. Eg. human injury afflicted on in-direct stakeholders could stop the project, as well as successful inspection could lead to increased interest from investors etc.

As seen in figure 5, a drone with visible embedded peripherals, extensive wiring and exotic materials, is, by most people, perceived as a high-tech instrument. And even though this might be appealing to engineers and technicians, the public in the area of operation might not value a high-tech or futuristic drone in their environment. Perception of these drones is critical to secure acceptance and trust if/when the technology becomes pervasive, especially in the early introduction phase. Since the system is autonomous, the possibility of human interaction between operator and any stakeholder is removed. This interaction can in other cases help increase calmness and trust in the drone activities. But the case when no operator is in sight should be investigated carefully. Here, nonverbal human-drone interactions (eg. symbols, markings, color of energy companies etc.) stating the purpose of the operation and its legitimacy could potentially facilitate the public need for information and lower the uncertainties of the event.

C. *Pervasiveness*

The widespread use of the technology would lead to a significant amount of in-direct stakeholders. Drones4Energy could be seen as a best practice introducing a new power source for the community, and drone technology in general becomes ubiquitous. With the pervasiveness comes great inspection frequency and accuracy, which translate to a more reliable energy grid without power losses etc. In places like Denmark the powergrid is accessible, but in areas with mountains, and nature growing close to the powerlines, the technology really comes into its own.

D. *Time*

The widespread adoption of the technology over time, and the possibility of Governmental Organizations (GO) potentially operating it, makes it near-impossible to opt-out. This could lead to conflicts, especially in areas of the world, where GO's are not trusted by the society, or when there is a risk of non-GO's potentially hijacking and operating the system. In some areas stakeholders could also be afraid of drones. Since the project originates from Denmark, it could be beneficial to introduce the technology to the public in widespread news, creating awareness of its looks and purposes, lowering the perceived risk [45]. But, presenting *”the drone for good”* this way, could potentially lead to an over-trusted mindset among the public and hereby a perfect cover for mis-use (drug trafficking, spying etc.).

E. *Environmental impact potential assessment and results*

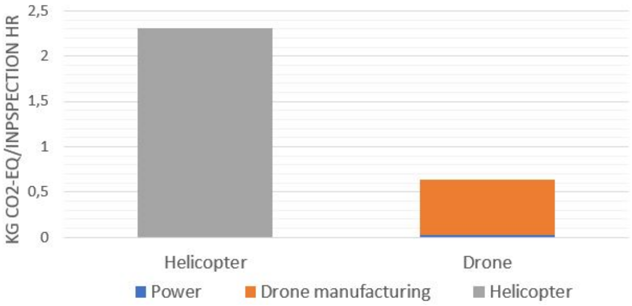


Fig. 6. GHG emissions compared on kg CO2-equivalent per inspection hour.

For this case study the regular helicopter inspection service was compared to the introduced drone service. Since utility helicopters offer more than 37.000 hours of flight and more than 40 years of lifetime [46], the GHG emission from manufacture was negligible compared to the potential impact from its operation. In the drone scenario we introduce a swarm of four multicopter drones (as in Fig. 5). Manufacturing was modelled from mass amount of the carbon fiber based frame, misc. electronics and Li-Po battery according to Fig. 7. The drones was estimated to last for 250 hours.

As illustrated in Fig. 6, the helicopter inspection yield emissions of 2,3 kg CO2-eq/Hr. The emission can be cut to 0,63 kg CO2-eq/Hr by introducing the drone swarm, which corresponds to cutting the emissions by a factor of almost 4.

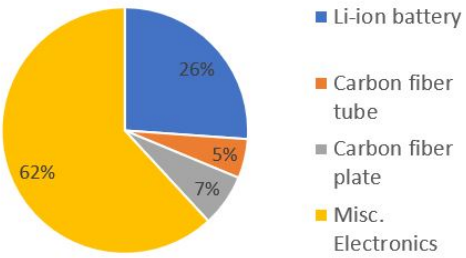


Fig. 7. Material decomposition of the total drone mass.

F. Design for environmental sustainability in Drones4Energy

As in the HealthDrone case study, the drone manufacture were the biggest contributor to the total introduced impact, even though the four multicopters have a higher power consumption. By incorporating EoL considerations to reuse components with large GHGs emission potentials (Misc. electronics and carbon fiber epoxy materials), the total amount of GHG emissions can be lowered further. With this type of multicopter drone, the LiPo battery, propellers, motors and small electronic components are limiting the life time of the system. By replacing only worn out parts and reusing the remaining components the total emission was lowered by a factor of 13 to the equivalent of 0,17 kg CO2-eq/Hr. However, drone manufacture was still introducing a significantly larger climate burden compared to the power consumption. For further optimisation of the case study the drone durability has the highest impact. A task specific configuration would be preferred to increase the durability of the drone. If the drone durability increases from 250 to 1000 hours, the emission will be lowered to 0,06 kg CO2-eq/Hr making the drone manufacture insignificant compared to its power consumption during operation.

VII. SUSTAINABILITY OF MATERIALS

Through the quantitative environmental performance assessment of the two case-studies it was observed that the biggest contributor - on a mass unit - to GHG emissions was carbon fiber reinforced epoxy (CFRE) materials. Different approaches can be studied to reduce emission rates, such as re-use as proposed previously.

CFRE is often recognized as “the golden standard” of fiber-reinforced composite materials due to its high performing mechanical properties. The offering of high strength and great stiffness at low mass has made it a material present in almost any drone frame available on the market today [47][48]. As well as making it a preferred material in custom drone frames often used in research applications[49].

During manufacture it is a well-known and high severity risk when working with epoxy, which could cause toxic eczema, or sensitization, which can give allergic contact dermatitis, or even cancer-related diseases [50]. Epoxy is characterized as a thermoset matrix (resin) system. By mixing the epoxy with a catalyst, a high density of covalent crosslinks between the polymer chains arise, making the cured material insoluble and resistive towards heat degradation. Due to these properties the process of recycling epoxy materials is complex and induces considerable environmental impact [51]. Figure 8 shows the Lanskin’s ladder (or Waste Hierachy), which provides the designer with an overview of EoL options as well as priority of preferred methods (described in European WEEE Directive [52]). From the model, the preferred method is to ”Reduce” or ”Prevent” any hazardous waste in the design. To mitigate these hazardous drawbacks a panel made from COMFIL-C 30037-8 [53] carbon fiber with 80% 0-degree and 20% 90-degree fibers, and a modified polyethylene terephthalate thermoplastic matrix (LPET) was proposed in a sandwich configuration. These skins were combined with a natural and renewable FLEXOKORE [54] end grain balsa wood as core material. Unlike the thermoset properties of epoxy, the LPET is heat degradable. By utilizing the right recycling methods for the material, it can be recycled into reuse-applications [55]. Sandwich panels are based on different materials using the material properties of each one to enhance the structural properties of the panel. The composition of a general sandwich panel consists of two thin, stiff skins (the faces) and a thicker and lighter material with good compressive and shear properties to resist the forces at the neutral axis as the core. As a result of this configuration, sandwich panels in general have smaller deformations and higher stiffness to mass ratio. In other words, the sandwich becomes an efficient structural element with the stiffer skins placed as far from the center of neutral axis as possible. The skins form an efficient stress couple or resisting moment, counteracting any external bending moment. The core resists shear and stabilize the faces against buckling or wrinkling by transferring loads between the skins, making the proposed sustainable plate competitive against the “golden standard” plate.

Fig. 8. Lanskin’s ladder (Waste Hierachy)

A. Mechanical design and comparison

A common structural material for drone frames was found to be 4 mm CFRE plates manufactured from a plain weave fiber mat resulting in fibers oriented in 0°- and 90°-directions. To compare the performance a specimen was designed for bending with the length 150 mm and width 25 mm.

1) "The golden standard" CFRE 4mm plate: Assuming a 450 gsm Toray T300 pitch based carbon fiber mat [56] using Araldite LY556 Epoxy resin [57] as matrix material. Assuming fiber volume fraction of 60% and six layers configured as [0, 90, 0 ,90, 0 ,90]. Each layer has a cured thickness of 0,67 mm to achieve the final 4 mm thickness. With these assumptions the Young's modulus for the CFRE plate was calculated using classical laminate theory as $E_b = 68,8GPa$ for the 0°-direction (direction of applied bending moment). To determine the area moment of inertia Euler-Bernoulli beam theory was used:

$$I_x = \frac{b \cdot h^3}{12} = 133,3mm^4 \tag{1}$$

Where b is the beam width and h is the thickness of the beam. The flexural rigidity (or bending stiffness) of the beam was then calculated as:

$$EI_{b,CFRE} = Eb \cdot I_x = 9173,3GPa \cdot mm^4 \tag{2}$$

The CFRE plate has a density of $\rho_{CFRE} = 1563kg/m^3$ resulting in a total specimen mass of $m_{CFRE} = 23,4g$.

2) Sustainable sandwich plate - SSP: To achieve equivalent flexural rigidity as the current CFRE plate the expression in 3 was used.

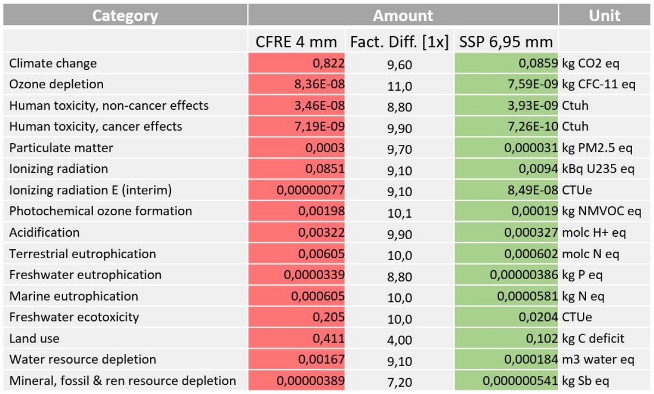
$$EI_{b,SSP} = \frac{E_s \cdot b \cdot t^3}{6} + 2 \cdot E_S \cdot b \cdot t \cdot \left(\frac{d+t}{2}\right)^2 + \frac{E_c \cdot b \cdot d^3}{12} \tag{3}$$

Where:
$E_s = Modulus\ of\ skin\ material$
$E_c = Modulus\ of\ the\ core\ material (E_c << E_s)$
$b = Plate\ width,\ t = Skin\ thickness,\ d = Core\ thickness$

The core material has a defined thickness of 6,35mm and a modulus of 0,159 GPa. Using classical laminate theory with these materials the bending modulus for the skin in the 0°-direction was determined as 44,3 GPa. As expected a lower result compared to the CFRE plate due to the thermoplastic resin. The required skin thickness was then determined through equation 3 as $t = 0,3mm$ or one fiber-reinforcement layer per skin. The total plate thickness to achieve equivalent flexural rigidity then equals 6,95 mm. With a combined density (at this thickness) of $\rho_{SSP} = 156,4kg/m^3$ the total specimen mass was $m_{SSP} = 4,1g$, or around one fifth the baseline weight.

B. Environmental comparison of materials

Using the EuCIA Eco Impact Calculator, a sustainability report was generated for both specimen's described in Sec. VII. The Fig. 9 provides a side-by-side comparison of the environmental impact of manufacturing one sample using the CFRE or SSP material. The difference was calculated as the difference factor from the CFRE to the SSP value. As observed, the proposed SSP solution provides a cleaner and safer result in every category compared by the calculator. Due to the minimization of carbon fibers, the total amount of *kg CO2 eq* produced from manufacturing was found to be almost 10 times higher for the CFRE specimen compared to the SSP specimen. The comparison also clearly illustrates how the toxicity effects of the epoxy-based matrix system induces a 10 times higher risk of both cancer- and non-cancer related disease for humans, as well as inflicting increased eutrophication rates to freshwater, and marine life.



Category	Amount			Unit
	CFRE 4 mm	Fact. Diff. [1x]	SSP 6,95 mm	
Climate change	0,822	9,60	0,0859	kg CO2 eq
Ozone depletion	8,36E-08	11,0	7,59E-09	kg CFC-11 eq
Human toxicity, non-cancer effects	3,46E-08	8,80	3,93E-09	Ctuh
Human toxicity, cancer effects	7,19E-09	9,90	7,26E-10	Ctuh
Particulate matter	0,0003	9,70	0,000031	kg PM2.5 eq
Ionizing radiation	0,0851	9,10	0,0094	kBq U235 eq
Ionizing radiation E (interim)	0,00000077	9,10	8,49E-08	CTUe
Photochemical ozone formation	0,00198	10,1	0,00019	kg NMVOC eq
Acidification	0,00322	9,90	0,000327	molc H+ eq
Terrestrial eutrophication	0,00605	10,0	0,000602	molc N eq
Freshwater eutrophication	0,0000339	8,80	0,00000386	kg P eq
Marine eutrophication	0,000605	10,0	0,0000581	kg N eq
Freshwater ecotoxicity	0,205	10,0	0,0204	CTUe
Land use	0,411	4,00	0,102	kg C deficit
Water resource depletion	0,00167	9,10	0,000184	m3 water eq
Mineral, fossil & ren resource depletion	0,00000389	7,20	0,000000541	kg Sb eq

Fig. 9. Eco-report comparison of CFRE and SSP

VIII. DISCUSSION

Using a VSD envisioning card analysis, the two case-studies were found to have similarities when defining their social and ethical impacts.

Looking to both of the case-studies, the proposed drone solutions lower the environmental impact potential significantly. When exploring the opportunity of further optimization of the drone solutions, it was found in both studies to be drone manufacture which contributes to induce the largest climate burden. Even though the case-studies correlate on that claim, it can not be generalized for other cases. *Neuberger et. al.* [58] found drone manufacture only responsible for 5% of the total energy consumption. It could hereby be said, that the first step towards sustainability optimization is understanding the specific drone system with a holistic approach as well as the application the drones replace.

When zooming in to component level of the drone manufacture, it is clear that electronics and epoxy based (carbon fiber) composite materials are the biggest contributors to climate burdens. Preventing them can be done using the proposed material solutions or considering design features allowing the end-user to reuse or recondition the parts contributing to circular economy. But to achieve this in practical terms, the considerations have to be introduced early in the design process.

Van de Poel [59] compares new technology with "social experiments" which introduce uncertainties and the need for learning. As with drones; there are potential positive and negative impacts when introduced. But what is important to remember, is that the drone design and the way in which the drone application is introduced will determine if it is an experiment worth pursuing. Looking to the case studies, overlapping considerations were identified. Early awareness of (or collaboration with) the direct and in-direct stakeholders and their knowledge of the introduced technology is important to incorporate perception- and security measures. Especially in an era of "maximization", where drones are found more appealing if their capabilities are "high-tech" and even easier to use. But if security is not considered as an equal requirement as performance in the early design-stage, there could be *"a dark side to our drone future"* as Rogers describe it in [60]. Here Rogers stresses the importance of this, with reference to how commercial platforms developed for the benefit of society were used to cause harm. With the increasing interest in drone solutions, the holistic approach of VSD helps clarify the needs from the surrounding environment to enable successful technology implementation. In general, physical takeoff/landing areas and air traffic management systems are necessary and often well-considered in many projects. But also integrated safety mechanisms bringing down drone systems safely if compromised has to be considered. As well as a national counter-drone units with the necessary capabilities and knowledge to act when drone actors are breaking the established laws and regulations.

IX. CONCLUSION

The specifics of the case - the system boundaries and relevant scenarios - will determine where the research focus should be placed. As such, the research questions can be answered: *depending on the use-case, either the drone application or the system itself may be the most significant driver of environmental impact*.

A. Future work

Future work will seek to combine these findings in determining guidelines and suggest design solutions, for engineers to use when designing UAS and counter-UAS, with focus on harnessing the technology's great potential while prioritising sustainability, human values and collaboration with relevant stakeholders for surrounding infrastructure needs.

REFERENCES

[1] Holly Hansen. Drones conservation: Monitoring arctic sea ice, 2019, URL: https://www.rotordronepro.com/monitoring-arctic-sea-ice/, accessed 25-08-2020.

[2] Danish Maritime Authority. Sulphur-sniffing drone to patrol danish waters, 2019, accessed 25-08-2020.

[3] Chi Yuan, Zhixiang Liu, and Youmin Zhang. Uav-based forest fire detection and tracking using image processing techniques. In *2015 International Conference on Unmanned Aircraft Systems (ICUAS)*, pages 639–643. IEEE, 2015.

[4] University of Southern Denmark. Ecodrone, 2020, accessed 25-08-2020.

[5] NASA. Helios prototype, 2001, URL: https://www.nasa.gov/centers/dryden/news/ResearchUpdate/Helios/, accessed 25-08-2020.

[6] Karen Swider-Lyons, Richard O'Neil Stroman, Benjamin D Gould, Joseph A Rodgers, Joseph Mackrell, MIchael Schuette, and Gregory Page. Hydrogen fuel cells for small unmanned air vehicles. *Ecs Transactions*, 64(3):963, 2014.

[7] Canadian Science Publisher. Student group develops eco-friendly drone using 3-d printing, 2019, accessed 25-08-2020.

[8] NASA CNN Business. The flying fungus: Nasa's biodegradable drone that flies and dies, 2014, accessed 25-08-2020.

[9] Joshuah K Stolaroff, Constantine Samaras, Emma R O'Neill, Alia Lubers, Alexandra S Mitchell, and Daniel Ceperley. Energy use and life cycle greenhouse gas emissions of drones for commercial package delivery. *Nature communications*, 9(1):1–13, 2018.

[10] Miguel A Figliozzi. Lifecycle modeling and assessment of unmanned aerial vehicles (drones) co2e emissions. *Transportation Research Part D: Transport and Environment*, 57:251–261, 2017.

[11] Briana Neuberger. An exploration of commercial unmanned aerial vehicles (uavs) through life cycle assessments. 2017.

[12] Jiyoon Park, Solhee Kim, and Kyo Suh. A comparative analysis of the environmental benefits of drone-based delivery services in urban and rural areas. *Sustainability*, 10(3):888, 2018.

[13] Batya Friedman and David G Hendry. *Value sensitive design: Shaping technology with moral imagination*. Mit Press, 2019.

[14] Ibo Van de Poel. Translating values into design requirements. In *Philosophy and engineering: Reflections on practice, principles and process*, pages 253–266. Springer, 2013.

[15] Mary L Cummings. Integrating ethics in design through the value-sensitive design approach. *Science and Engineering Ethics*, 12(4):701–715, 2006.

[16] HealthDrone. Healthdrone website, 2019, URL: http://www.danskekommuner.dk/Global/Artikelbilleder/2015/DK-3/DK-3-side-26-27.pdf, accessed 25-03-2019.

[17] Drones4Energy. Official project web page, https://drones4energy.dk/, accessed 02-05-2020.

[18] WeRobotics. Werobotics: Robotics for the benefit of all, 2018, URL: https://werobotics.org, accessed 24-02-2019.

[19] Batya Friedman and David Hendry. The envisioning cards: a toolkit for catalyzing humanistic and technical imaginations. In *Proceedings of the SIGCHI conference on human factors in computing systems*, pages 1145–1148, 2012.

[20] Aimee Van Wynsberghe and Michael Nagenborg. Chapter 8: Civilizing drones by design. *Drones and Responsibility: Legal, Philosophical and Socio-Technical Perspectives on Remotely Controlled Weapons*, page 148, 2016.

[21] Dylan Cawthorne and Alessandra Cenci. Value sensitive design of a humanitarian cargo drone. In *2019 International Conference on Unmanned Aircraft Systems (ICUAS)*, pages 1117–1125. IEEE, 2019.

[22] Dylan Cawthorne and Aimee Robbins-Van Wynsberghe. From healthdrone to frugaldrone: Value-sensitive design of a blood sample transportation drone. In *2019 IEEE International Symposium on Technology and Society (ISTAS)*, pages 1–7. IEEE, 2019.

[23] Bo P Weidema, Massimo Pizzol, Jannick Schmidt, and Greg Thoma. Attributional or consequential life cycle assessment: A matter of social responsibility. *Journal of Cleaner Production*, 174:305–314, 2018.

[24] N Phillips, C Blauvelt, M Ziba, J Sherman, E Saka, E Bancroft, and A Wilcox. Costs associated with the use of unmanned aerial vehicles for transportation of laboratory samples in malawi. *Seattle: VillageReach*, 2016.

[25] Connie Guglielmo. Turns out amazon, touting drone delivery, does sell lots of products that weigh less than 5 pounds, 2017, URL: https://www.forbes.com/sites/connieguglielmo/2013/12/02/turns-out-amazon-touting-drone-delivery-does-sell-lots-of-products-that-weigh-less-than-5-pounds/.

[26] Rocci Luppicini and Arthur So. A technoethical review of commercial drone use in the context of governance, ethics, and privacy. *Technology in Society*, 46:109–119, 2016.

[27] Philip Boucher. 'you wouldn't have your granny using them': drawing boundaries between acceptable and unacceptable applications of civil drones. *Science and engineering ethics*, 22(5):1391–1418, 2016.

[28] Rebecca L Scharf. Drone invasion: Unmanned aerial vehicles and the right to privacy. *Ind. LJ*, 94:1065, 2019.

[29] Yang Wang, Huichuan Xia, Yaxing Yao, and Yun Huang. Flying eyes and hidden controllers: A qualitative study of people's privacy perceptions of civilian drones in the us. *Proceedings on Privacy Enhancing Technologies*, 2016(3):172–190, 2016.

[30] Roger Clarke and Lyria Bennett Moses. The regulation of civilian drones' impacts on public safety. *Computer law & security review*, 30(3):263–285, 2014.

[31] Batya Friedman, Peter H Kahn, Alan Borning, and Alina Huldtgren. Value sensitive design and information systems. In *Early engagement and new technologies: Opening up the laboratory*, pages 55–95. Springer, 2013.

[32] Batya Friedman, LP Nathan, Shaun Kane, and John Lin. Envisioning cards. *University of Washington, Seattle, WA, USA*, 2011.

[33] Green Delta. openlca release, berlin, germany, 2019, URL: https://www.openlca.org/openlca-1-9-release/, accessed 02-08-2020.

[34] Ecoinvent. Ecoinvent version 3.4, zurich, switzerland, 2017, URL: https://www.ecoinvent.org/database/older-versions/ecoinvent-34/ecoinvent-34.html, accessed 02-08-2020.

[35] Italy European Commission Joint Research Center. European platform on life cycle assessment, 2011, URL: https://eplca.jrc.ec.europa.eu/uploads/LCIA-characterization-factors-of-the-ILCD.pdf, accessed 02-08-2020.

[36] European Composites Industry Association. Eucia eco impact calculator backround report, 2019, URL: http://ecocalculator.eucia.eu/Account/TermsAndConditionsDownload, accessed 10-08-2020.

[37] Pankar K Mallick. *Fiber-reinforced composites: materials, manufacturing, and design*. CRC press, 2007.

[38] HealthDrone. Healthdrone project website (danish), 2019, URL: https://sundhedsdroner.dk/index.php?page=projektet-2, accessed 13-3-2019.

[39] European Environment Agency. European protected sites, 2020, URL: https://www.eea.europa.eu/data-and-maps/explore-interactive-maps/european-protected-areas-1.

[40] Danish Ornithological Society. Danmarks fugle - denmark's birds, 2019, URL:https://dofbasen.dk/ART/, accessed 14-3-2019.

[41] Mickey Gjerris. Animal ethics - lecture slides, university of copenhagen, philosophy of science and research ethics course, 2018.

[42] Jef R Peeters et al. Design for end of life: a design methodology for the early stages of an innovation process. In *DS 74: Proceedings of the 14th International Conference on Engineering & Product Design Education (E&PDE12) Design Education for Future Wellbeing, Antwerp, Belguim, 06-07.9. 2012*, pages 185–190, 2012.

[43] VIDEO. Manual high voltage powerline inspection, https://www.youtube.com/watch?v=oBJyyEAw-6g, accessed 12-05-2020.

[44] Dylan Cawthorne and Arne Devos. Capability caution in uav design. In *2020 International Conference on Unmanned Aircraft Systems (ICUAS)*, pages 1572–1581. IEEE, 2020.

[45] Reece A Clothier, Dominique A Greer, Duncan G Greer, and Amisha M Mehta. Risk perception and the public acceptance of drones. *Risk analysis*, 35(6):1167–1183, 2015.

[46] AIRBUS. As350 utility helicopter, 2001, URL: https://www.airbus.com/helicopters/civil-helicopters/intermediate-single/h125.htmldidyouknow, accessed 02-09-2020.

[47] DJI. Dji matrice 200 specifications, https://compassdrone.com/matrice-200-series/, accessed 12-05-2020.

[48] FreeFly systems. Alta-6 specifications, https://freeflysystems.com/alta-6/specs, accessed 12-05-2020.

[49] Tarot RC. Tarot drone frame specification, http://www.tarotrc.com/Product/Detail.aspx?Lang=enId=7641bc7f-e656-4d04-a075-13d7b81f96e0, accessed 12-05-2020.

[50] Arbejdstilsynet. At-vejledning 9.3.3, https://at.dk/regler/at-vejledninger/arbejde-epoxy-isocyanatholdige-produkter-9-3-3/, accessed 20-05-2020.

[51] AD La Rosa, DR Banatao, SJ Pastine, A Latteri, and G Cicala. Recycling treatment of carbon fibre/epoxy composites: Materials recovery and characterization and environmental impacts through life cycle assessment. *Composites Part B: Engineering*, 104:17–25, 2016.

[52] European-Parliament. Directive 2002/96/ec of the european parliament and of the council of 27 january 2003 on waste electrical and electronic equipment (weee). 2003.

[53] COMFIL. Comfil-c 30037-8 carbon-lpet technical datasheet, https://www.comfil.biz/fabric, accessed 01-04-2020.

[54] East Coast Fibreglass Supplies. Mechanical properties for flexokore end grain balsa, http://www.ecfibreglasssupplies.co.uk/ images/TechnicalDataSheet/2477.pdf, accessed 01-04-2020.

[55] Géraldine Oliveux, Luke O Dandy, and Gary A Leeke. Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties. *Progress in Materials Science*, 72:61–99, 2015.

[56] TorayCa Composites. T300 mechanical properties, https://www.fibermaxcomposites.com/shop/datasheets/T300.pdf, accessed 01-04-2020.

[57] Araldite. Araldite ly556 aradur 906 accelerator dy070 datasheet, accessed 01-04-2020.

[58] Briana Neuberger. An exploration of commercial unmanned aerial vehicles (uavs) through life cycle assessments. 2017.

[59] Ibo Van de Poel. An ethical framework for evaluating experimental technology. *Science and engineering ethics*, 22(3):667–686, 2016.

[60] James Rogers. The dark side of our drone future, 2019, URL: https://thebulletin.org/2019/10/the-dark-side-of-our-drone-future/ , accessed 24-08-2020.