Exploring high-performance wooden drone structures through speculative design

Dylan Cawthorne
University of Southern Denmark
Unmanned Aerial Systems Center
Odense, Denmark
dyca@sdu.dk

Nicolai Iversen
University of Southern Denmark
Unmanned Aerial Systems Center
Odense, Denmark
niiv@sdu.dk

***Abstract*— Although we aspire to make decisions based on logic and systematic analysis, it has been argued that engineers' technical decisions can be influenced by their ideologies about progress and the future - including the material selection process. In this work, we address this potential influence through a holistic and exploratory speculative design process, asking "what are some implications of the use of wood in high-performance drone structures, and what will a high-performance wooden drone structure look like?" A wooden prototype search and rescue drone, developed for use in Denmark, is built, tested and analyzed through quantitative and qualitative means as part of the exploration process. We find that wood offers unique features including lower toxicity during manufacturing and increased environmental sustainability. In addition, when properly designed a wooden drone structure has a significantly higher stiffness to weight ratio ($8.8*10^6$) compared to a typical non-optimized carbon fiber and epoxy composite plate ($7.6*10^4$) or tube ($1.1*10^6$). Historical examples are utilized which suggest that actual material performance may be less important than the ideologies of progress surrounding the material, and hence that engineers may not always make decisions based purely on performance. Thus, here speculative design is used not only as a way to explore the material "path less traveled", but also as an approach to examine the legitimacy of wood as a structural drone material - and more broadly, to discuss the role ideologies play in modern engineering practice.**

Index Terms*— *Speculative design, drones, wooden structures, ethics, ideologies of progress.

I. INTRODUCTION

Drone use is increasing at a rapid rate with 108 countries utilizing the technology [1]; soon, drones could become a significant addition to the 50 million metric tons of global electronic waste being produced annually [2]. Composites, such as fiberglass or carbon fiber reinforced epoxy, are often used in drone structures, where they are valued for their high performance and reputation as high-tech materials. Composites can have excellent mechanical performance; however, in practice, their shapes and layups are non-optimized, and low-quality materials are often used to reduce cost. Previous research by the authors [3] showed that the carbon fiber tubes and plates used in a drone structure were the largest contributors to greenhouse gas (GhG) emissions due to extraction and manufacturing of raw materials. Human toxicity during manufacturing was almost ten times greater than that of a carbon fiber reinforced thermoplastic sandwich panel with a balsa wood core.

This work has been supported internally by the SDU UAS Center

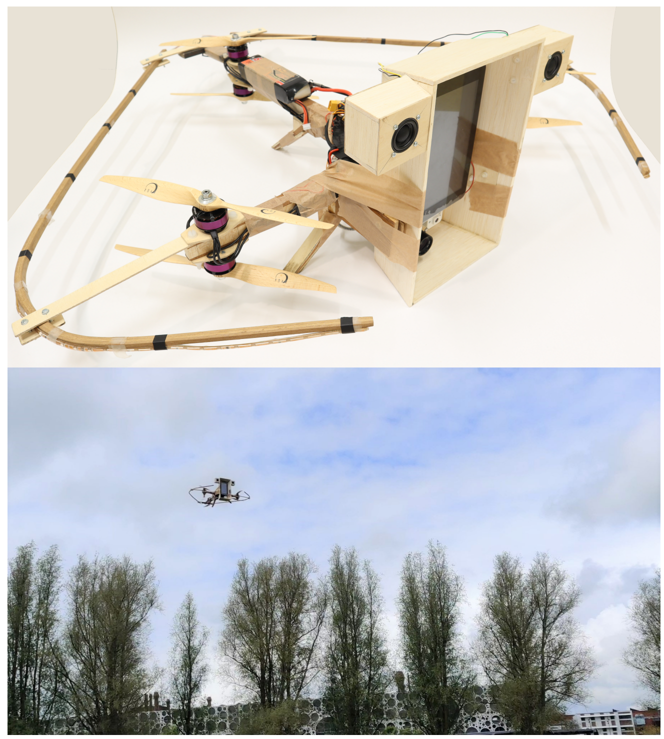

Fig. 1. Top: The prototype wooden-frame drone was developed for use in Denmark to assist in land-based search and rescue operations. The frame - comprised of a mahogany and balsa sandwich structure - exhibited high stiffness and low weight. Bottom: The final drone was able to withstand outdoor testing (upper photo by the authors; lower photo by Andreas Aagaard Asmussen and Nikolaj Pihl Thomsen).

Thus, on parameters such as environmental sustainability and human health, carbon fiber reinforced epoxies perform poorly. In the previous analysis it was found that the contribution to GhG and human toxicity of the balsa wood core was minimal hinting at the potential of wooden structures; here, the approach is extended by replacing the carbon fiber reinforced thermoplastic with wood to produce an all-wooden structure.

Many prototype, do-it-yourself (DIY), and educational drone structures have been made of wood. In the "maker" community, simple drones using wooden sticks for arms have been built, and for education thin plywood is often utilized with parts being laser-cut so they can be glued and bolted together to form the arms and body of the drone [4]. These structures are not optimized for high strength and low weight, but they can perform well in terms of ease of manufacture, environmental sustainability, and human health. Still, the authors are not aware of any studies where *high-performance* wood drone structures have been developed, and this is the research gap we aim to address.

This study explores if optimized wooden drone structures might out-perform the standard composite structures currently seen in drones, and if the use of wood could lead to a future with reduced environmental impact and safer working conditions. The main contributions of the paper are as follows:

- Development of a speculative design, high-performance wooden drone structure shown in Fig. 1
- Exploration of the historical development of aircraft structural materials and its possible relevance to drones
- Discussion of ideologies of progress and the high-tech
- Comparison of standard composite structures with wooden structures both quantitatively and qualitatively

II. METHODS

The speculative design methodology has been described in [5] as "a kind of design that is used as a tool to create not only things but ideas", and "as a means of speculating about how things could be - to imagine possible futures". The authors introduce the "probable, plausible, possible, preferable" model, shown in Fig. 2, to illustrate how one can - at the present time - identify a speculative or preferable future, and design for that rather than being confined to designing for the most probable future. For example, in the book the authors propose a speculative design scenario where the United Kingdom is divided into four regions each with different socio-political ideologies; they then design vehicles that would fit into each of these worlds. The "Digitarians" embrace technology, and the speculative design exercise results in highly networked electric vehicles, while the "Bio-Liberals" utilize slow-moving, natural-gas powered four-wheeled bicycle-like vehicles [6].

In this work, we take a speculative, holistic, and exploratory approach utilizing inspiration from the development of aircraft over the past 100 years: from wooden construction, to metal, to composite - and explore the option of using wood again - this time, in a drone context. We consider the design, manufacturing, and end-of-life phases of the speculative drone's life-cycle, and propose the following overall research question:

What are some implications of the use of wood in high-performance drone structures, and what will a high-performance wooden drone structure look like?

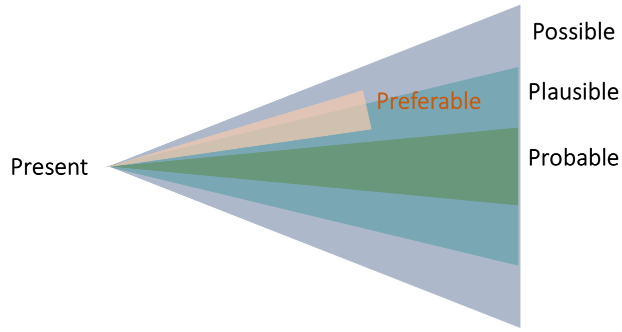

Fig. 2. The 4P, or "probable, plausible, possible, preferable" model is a useful tool in speculative design. Using it facilitates the investigation of potentially preferable futures, rather than those that are simply more probable. Graphic by the authors, based on [5]

III. ANALYSIS

A. A Preferable Future

We begin by introducing a *preferable future* which forms the basis of the speculative design exercise and facilitates exploration of the overall research question:

In this preferable future, environmental sustainability, human health, and meaningful work are highly prioritized. The speed of technological "progress" is slowed to a more controllable pace, and there is emphasis on the use of local resources rather than on the global supply chain. Environmentally unsustainable practices and the use of non-renewable resources such as those based on petroleum are discarded; natural and renewable resources such as trees are grown in vast numbers and utilized locally. Unsafe working conditions are not accepted by the workers themselves, labor unions, and the public at large - both at home and abroad. Technology is developed cautiously and in close collaboration with multiple stakeholders, and care is taken that the new technology does not create unnecessary problems. Engineers, designers, and factory workers enjoy and take pride in their work, and the results of their efforts are utilized locally giving them insight into the impact they have on their community. A large portion of the workforce is in the manufacturing sector which produces the goods needed by the community, and skills and expertise in craft trades are as highly respected as those of knowledge workers.

B. Ideologies of Materials and "Progress"

This preferable future's alternative ideology of progress will play a key role in the material selection process [7]. In the book *Wings of wood, wings of metal*, historian of technology Eric Schatzberg proposes that the ideology of metal as a modern material inspired aircraft engineers and funders to pursue metal construction *despite* it's initially inferior performance [8]. In the period between 1914 and 1945 American aircraft engineers pursued the ideal of the "new style" of aircraft which was to be made of metal like the other engineering feats of the day - bridges, ships, and trains [8]. The metal alloys of the day had high strength and hardness, but also high density resulting in complex structures and thin parts which were subject to buckling - a problem that lower-density wooden structures were much less prone to.

During World War II the wooden aircraft de Havilland Mosquito was initially highly criticized and struggled to secure funding - possibly due to its incompatibility with the dominant ideology of progress. It was nicknamed "Freeman's Folly" after Sir Wilfrid Freeman, the Air Chief Marshal who touted the aircraft's merits. However, the Mosquito was arguably one of the most successful aircraft of the war, with over 7,000 aircraft produced [9]. The bomber was one of the fastest production aircraft of the time, and was so fast that its designers omitted defensive weapons - the Mosquito could simply outrun its adversaries. There were other advantages of wooden construction: it activated the under-utilized craft skills of small woodworking shops around the United Kingdom so they could support the war effort [9].

In the preferable future of our speculative design exercise, an alternative ideology of progress - one of environmental conservation and enhancement of human wellbeing - provides a context in which wooden drone construction could potentially thrive. As well, there is an intimate connection between materials and manufacturing processes, and wooden construction could support meaningful human work and the development of highly skilled craftspeople.

C. Wood and Composite Materials

Wood can be described as "nature's composite material". A fiber-reinforced composite material consists of high-strength and stiffness reinforcing fibers embedded into a distinctly different matrix material which supports and protects the fibers [10]. The fibers act as the principal load-carrying members while the matrix acts as a medium for transferring loads between the fibers. The composite is very strong in the direction of the fibers, but can be significantly weaker in other orientations.

There are a number of natural occurring high performance composite materials including bones, teeth, and wood [11]. Wood consists of two distinct materials: cellulose fibers, encapsulated by a lignin cellulose polymer matrix. The properties of this natural composite depend on the species, moisture content, growth rate, and many other parameters. As with any fiber reinforced composite material the material properties vary depending on the fiber direction; thus, trees can be seen as topology-optimized structures optimizing strength by growing at the most efficient rate to self support and withstand the external forces from the environment. The mechanical properties of different types of wood - such as density, stiffness, and strength - vary significant between species, enabling many different material combinations to be used in order to create optimized structures. For example, the high stiffness per unit weight of hardwoods such as mahogany and walnut can be utilized in conjunction with the low density but sufficient compressive strength of end-grain balsa wood to create a high-performance sandwich structure.

In engineered composite materials, the fiber directions along with the reinforcement and matrix materials can also be chosen to create unique properties, which can be optimized to withstand the mechanical and environmental demands of the final part. In drone structural applications the most commonly used composite is carbon fibers embedded into a matrix of epoxy polymer [10]. As mentioned earlier, previous work by the authors identified poor environmental and health performance of these materials with high greenhouse gas emissions from manufacturing, and most critically, toxicity to human health during manufacturing. These risks would be deemed unacceptable in the preferable future of the speculative design exercise, so alternative materials would be explored.

D. Drone Mechanics and Shape

In this section we address the second, more specific, part of the overall research question: *what will a high-performance wooden drone structure look like?* We do so by first identifying the forces on the drone frame as shown in Fig. 3, and then comparing the high-performance wooden drone structure with the typical construction approaches used in "high-tech" carbon fiber reinforced epoxy structures as shown in Fig. 4. We use theory to predict the strength, stiffness, and weight performance of wooden and carbon fiber structures, and then we test real drone arms to find the actual performance of the wooden construction in comparison with a flat carbon fiber plate and a hollow carbon fiber tube.

1) Theoretical prediction: To predict the mechanical performance of a Y-copter drone's structure, a combination of material properties and geometries are needed. This process starts by defining the loading scenario (i.e. external forces) of the frame during extreme flight maneuvers. The free body diagram in Fig. 3 reveals the primary forces acting on the frame. The frame's construction can be broken down into three arms and a hub connecting the arms at the origin point (O). A worst-case loading scenario is shown where the drone's weight acts downward at the center of gravity experiencing acceleration in a pull-out maneuver ($m \cdot g$, where g is the combined load from gravitation and change in direction). Here, the thrust from the propellers generate upward forces $F1, F2, F3$ equal to the magnitude of $m \cdot g$, which results in bending along the drone's arms towards the hub origin. During this scenario the other forces acting on

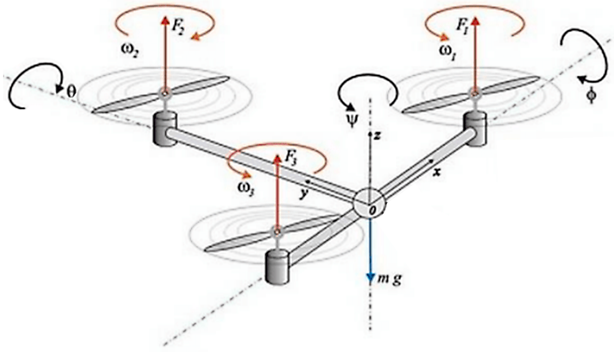

Fig. 3. Free body diagram showing the primary loads of a Y-copter drone frame accelerating in a worst-case loading scenario: high-speed pull-out after a dive. (Graphic by the authors)

the drone's frame $\omega_1, \omega_2, \omega_3$, and θ, ϕ, ψ are neglected due to low magnitude compared to the bending of the arms.

In basic static structures this scenario is referred to as the *cantilevered beam problem*, and an optimized geometry to design structurally efficient (i.e. high stiffness, high strength, low weight) is the I-beam cross-section. This shape has a high area moment of inertia as much of the material is far away from the neutral axis which provides geometrical stiffness.

Fig. 4. Two examples of commercial Y-copter drone frames [12][13]. The fiber patterns reveals the fiber directions - at least of the outermost layers. Two typical construction approaches are shown: arms made of flat plates with 0/90 degree fibers (left), and arms made of hollow tubes, also with 0/90 degree fibers (right).

By examining the commercial drone frames in Fig. 4 it is clear that the plate (Fig. 4, left) is a non-optimized geometry for this load since it is very thin and most of the material is near the neutral axis. The geometry of a tube (Fig. 4, right) is optimized for resisting compressive forces and internal pressures, but not for bending as occurs in drone arms.

Commercial drone frames often use structurally inefficient carbon-epoxy composites; as seen in Fig. 4, the commercial frames are build from 0/90 degree (fiber direction) tubes and 0/90 plates. Such layups are non-optimized for the loading scenario as many fibers are not placed in the primary loading direction along the length of the arms. One way of optimizing the structural properties of a fiber reinforced composite part is by aligning fibers in the directions of the forces, but in a 0/90 layup half of the fibers are not aligned with the primary forces. Optimizing the fiber orientation could result in increase stiffness and strength and/or reduced weight.

However, this design could increase manufacturing time due to increased complexity in manufacturing. Currently, 0/90 carbon fiber tubes and plates are the least expensive types available, which might be the reason for their common appearance in commercial drones.

Similar opportunities for optimization are present in structural design when using wood. The prototype drone's all-wooden structure in Fig. 1 consists of arms made as built-up sandwich panels - a type of I-beam that uses different materials instead of differing geometry to place the stiffer material far from the neutral axis. The arms consist of solid hardwood skins made from mahogany (*khaya spp.*) with an inner core of end-grain balsa (*ochroma spp.*) [14]. Later, a more optimized arm was designed for mechanical testing, with walnut (*juglans nigra*) [14] skins and end-grain balsa core. A non-toxic water-based outdoor-rated PVA (polyvinyl acetate) adhesive was utilized to bond the skins to the core.

TABLE I

PREDICTED STRUCTURAL PROPERTIES

	Wood	CFRP Tube	CFRP Plate
Dimensions $[mm]$	W: 15, H: 20	Ø16 outer	W: 22, H: 4,8
Weight/Length $[g/m]$	82,5	75	170
Stiffness $[N/mm^2]$	7,1e8	8,3e7	1,3e7
Stiffness/Weight Ratio	8,6e6	1,1e6	7,6e4

Using classical laminate theory [10] and the authors' previous work [3], the sandwich structure, carbon fiber tube, and carbon fiber plate were compared on important metrics in Table I. The structural elements were all compared using equal lengths of 200 mm. The predicted results show that the wooden sandwich structure offers significant performance increase with an improvement in the bending stiffness to weight ratio of more than 7 times compared to the tube, and more than 100 times compared to the plate.

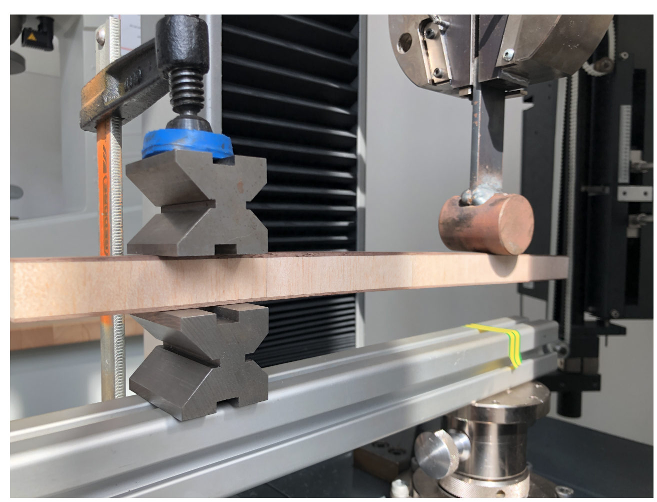

Fig. 5. The test setup during an iteration with the wooden sandwich beam (photo by the authors)

2) Mechanical testing: To verify the structural elements in an actual test scenario, a fixture was designed and manufactured for the three types of drone arms. In a cantilevered beam scenario (as explained in Sec. III-D.1) a force is applied to the free end of the arm, while a load cell measures the applied force and an extensometer measures the total deflection as seen in Fig. 5. The setup was installed on a Zwick Z050 static testing machine.

Fig. 6 shows the results of the cantilevered beam experiments, with applied force shown on the vertical axis and deflection of the arm on the horizontal axis. As predicted the wooden arm performs better than the plate, but counter to the prediction the carbon fiber tube exhibited higher stiffness than the wooden arm.

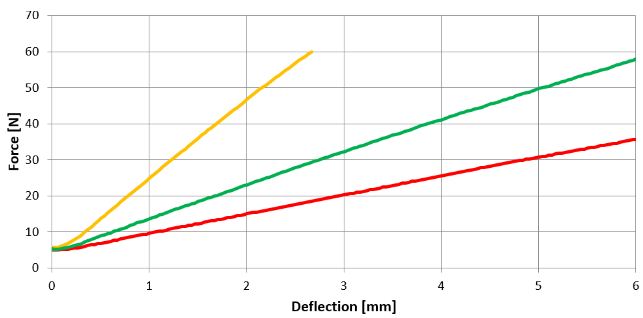

Fig. 6. The test results of the CFRP tube (orange), CFRP plate (red) and the wooden sandwich (green). The wooden drone arm exhibited higher stiffness than the plate, but lower stiffness than the tube.

Based on the generated data set the rigidity and rigidity/weight ratios were calculated and documented in Table II. Please note that *stiffness* in Table I and *rigidity* in Table II cannot be directly compared. It was though used to compare the difference in rigidity between the CFRP parts as in the predicted results. With the same difference between the plate and tube, there is a strong indication of lower performance in the wooden sandwich structure than predicted. The rigidity to weight ratio in the experimental result was 3.3 times higher for the wooden structure compared to the plate, which is a high-performance structure, but approximately 30 times less than predicted.

It is important to also consider the boundary conditions of the predicted results since they can be cause of the deviations between prediction and test. The equations assume perfect bonding between the balsa core and walnut sheets as well as perfectly aligned fiber directions, which is not achievable in practice. Also, the end-grain balsa used in the core was only available in sections, making it suspect to slipping translating to loss of the "sandwiched" effect. Lastly, the material properties could deviate from the data sheets used in the theoretical results. The deviation from predicted performance suggest that further development of the manufacturing techniques used to build wooden drone structures could increase their performance significantly.

E. Manufacturing

Different materials support the thriving of different industries, educations, infrastructures, and organizational structures [15]. The wide-spread use of wooden drone structures would lead to the growing of mahogany, walnut, and balsa trees, the training of woodworking craftspeople, the building of woodworking shops, and potentially an increase in the social status of craft skills. Wooden drones could be built using high-rate craft manufacturing: multi-skilled craftspeople building customized drones using locally-sourced wood for local/regional customers in a type of non-alienating production [16]. Each craftsperson would be responsible for the construction of a drone from start to finish increasing flexibility in work tasks, knowledge, and sense of pride and ownership in the finished product [17]. High levels of customization would lead to products that meet the user's needs without excess capabilities, making the drones more difficult to misuse and supporting capability caution [18]. Custom drones built using a high level of handcraft and natural materials would be unique due to differing requirements, variations in the wood, and the skill of the craftsperson. Therefore, their performance would vary slightly giving each drone it's own individual character - like the unique sound produced by a hand-crafted wooden violin.

TABLE II
TESTED STRUCTURAL PROPERTIES

	Wood	CFRP Tube	CFRP Plate
Dimensions $[mm]$	W: 15, H: 20	16 OD, 14 ID	W: 22, H: 4,8
Weight/Length $[g/m]$	82,5	75	170
Rigidity $[N/mm]$	9,1	21,0	5,3
Rigidity/Weight Ratio	0,11	0,28	0,03

The safe manufacturing of wooden drones requires adequate infrastructure investments in dust extraction in addition to measures to prevent fire in the workshop similar to those required in a composites machining facility. Additionally, the sustainable and renewable sourcing of wood materials would be necessary. This process can be eased by utilizing locally-grown sources to ensure that sustainable forestry is being practiced in the materials supply chain; in Denmark where the prototype drone was developed. Outside of Scandinavia, other high-performance wood species include European and American walnut, spruce, and birch [14]. Bamboo also has favorable properties, and grows rapidly in many parts of the world [14]. Cork is a promising impact-absorbing and sound-damping material, which could be used as a crumple-zone to reduce damage to the drone, animals, or humans in a crash [14].

There are safety risks during manufacturing of wooden drone structures, such as cuts from woodworking saws and abrasions from sanders. Additionally, toxic adhesives such as epoxies used in contemporary composite manufacturing would be replaced with modern non-toxic, water-based, outdoor-rated PVA adhesives as in the prototype drone structure. The wooden structure could be made water resistant by impregnating the outer surfaces with bees wax.

Currently, we see the production of non-renewable petroleum-based carbon fibers and epoxy, the training of composite fabricators, the building of composite production facilities, and the development of automated composite fabrication robots in order to increase quality and reduce labor costs. Manufacturing of composite drone airframes are a significant contributor to human health risks during manufacturing [19].

There are different human values supported by each material, design, and manufacturing approach. The speculative design exercise reminds us that engineer should at least be aware of the values that they are upholding in their work, and be aware of alternatives to the commonly-held values in their industry. This can lead to unique designs like - high-performance wooden drone structures - as we have attempted to demonstrate here.

F. Communication, naming, and branding

The words used when describing a technology will influence its perception, and many examples of this are given in reference [8]. Bakelite, "the first synthetic polymer plastic", "invented in 1907 by the Belgian-born American chemist Leo Baekeland, was the trade name for a class of thermosetting plastics made from phenol-formaldehyde resins" [8]. The developers aimed to distance their product from earlier (natural) celluloid-based plastics, and used branding to associate Bakelite instead with "modern, machine-age aesthetics" and a utopian "Plastic Age" [8]. At the construction level commercial companies used a similar approach, capitalizing on the positive perception of plastics at the time by branding wood-plastic composites as "Duramold" [8]. "Duramold was indeed one of the most significant applications of phenolic resins to aircraft structures, and hence a suitable topic for plastics research. But...Duramold consisted mainly of thin wood veneers, and thus was one of those materials on the boundary between wood and plastics. By taking advantage of Duramold's association with plastics, the developers of Duramold helped put wood back on the agenda of aviation research in the United States [8]."

In this work, we have chosen to use the term "high-performance wooden drone structures", but the historical account suggests that it could be wise to re-brand wood at the material level like Bakelite, or at the construction level like Duramold. Perhaps aligning the wood material and sandwich construction with the preferable future - one with increased environmental sustainability, human health, and craft skills - could inform the new name and branding.

IV. DISCUSSION

There are important differences between the design, manufacturing, and performance of wooden and composite structures making the material selection process a complex one which cannot be analyzed purely on the basis of a few quantitative metrics. Using a certain materials is not a "silver bullet" for building a "good" drone, and each material has implications which much be considered. As Schatzberg details, to a certain extent investments in research and development become self-fulfilling prophecies: the more time, money, and engineering skill devoted to design and development with a material, the better its performance becomes. As well, a change in the prioritization of different performance parameters can change over time, and we can envision the possibility that criteria such as environmental sustainability and human health become increasingly in focus in the future. Under these circumstances, wooden drone structures could become more attractive. In more general terms, utilizing speculative design and thereby being explicit in the type of preferable future engineers are designing for could prevent some of the negative impacts of materials and technologies that are arising now.

Wooden structures are becoming more accepted in modern architecture [20], and the speculative design approach used here suggests this as a possible future for drone structures as well - that wooden drones could eventually be more widely accepted in the drone engineering community and considered high tech and high-performance in their own right - at least on some parameters. The choice of parameters to compare here is critical, as inclusion/exclusion, or prioritization of one aspect of performance will favor some materials over others. Here, we have seen that prioritization of environmental sustainability and human health might give advantages to previously underutilized materials, such as wood.

V. LIMITATIONS AND FUTURE WORK

There are important limitations to this work. First, we ask many more questions than we answer - a feature of speculative design [5]. For example, we do not address empirical question such as "what ideology of progress exists in the drone domain?", "do drone engineers see wood as a low-performance material", and "how are competing requirements such as human health and drone performance prioritized?" These are important area for further research, and this data would enhance the proceeding analysis considerably. Limited testing of the wooden structures and the wooden drone were performed; the aim was to provide some early indications of the material's performance, but considerable additional research and development will be required to fully characterize the materials, ensure their long-term reliability, environmental sustainability, and verify their reduced impact on human health. In addition, communication, naming, and branding could be developed to improve upon the term "high-performance wooden drone structures".

VI. CONCLUSION

The proceeding speculative design exercise indicates that high-performance wooden drone structures have many promising attributes. And in some cases they offer higher performance than contemporary carbon fiber reinforced epoxies - both in mechanical performance as well as in environmental impacts and human toxicity during manufacturing [3]. There are numerous challenges in analyzing different, non-homogeneous materials that require differing designs; here, these challenges have been addressed through an exploratory and holistic speculative design process utilizing historical context-setting and quantitative and qualitative analyses. Interestingly, history shows that the actual material performance may be less important than the ideologies of progress surrounding the material, and hence why engineers may not always make decisions based purely on logic. We hope this work encourages engineers to explore wood as a structural material for high-performance drone structures. Furthermore, the method can help engineers to be aware of their own ideologies about the future, and how these ideologies might impact their technical decision-making, so they can ultimately design for a more preferable future.

REFERENCES

[1] Austin Choi-Fitzpatrick, Dana Chavarria, Elizabeth Cychosz, John Paul Dingens, Michael Duffey, Katherine Koebel, Sirisack Siriphanh, Merlyn Yurika Tulen, Heath Watanabe, Tautvydas Juskauskas, et al. Up in the air: A global estimate of non-violent drone use 2009-2015. 2016.

[2] Keshav Parajuly. *Circular economy in e-waste management: Resource recovery and design for end-of-life, PhD Thesis*. PhD thesis, University of Southern Denmark Odense, 2017.

[3] Nicolai Iversen, Morten Birkved, and Dylan Cawthorne. Value sensitive design and environmental impact potential assessment for enhanced sustainability in unmanned aerial systems. In *IEEE International Symposium on Technology and Society 2020: IEEEXplore*, 2020.

[4] SDU. Byg din egen drone (danish) build your own drone, 2016, URL: https://www.sdu.dk/da/forskning/sduuascenter/education/sdu+drone+-+byg+din+egen+drone.

[5] Anthony Dunne and Fiona Raby. *Speculative everything: design, fiction, and social dreaming*. MIT press, 2013.

[6] Anthony Dunne and Fiona Raby. United micro kingdoms: A design fiction, 2021, URL: http://unitedmicrokingdoms.org/.

[7] Stanford Encyclopedia of Philosophy. Progress, 2011, URL: https://plato.stanford.edu/entries/progress/.

[8] Eric Schatzberg. *Wings of wood, wings of metal: culture and technical choice in American airplane materials, 1914-1945*. Princeton University Press, 1999.

[9] Calgary Mosquito Society. Mosquito construction (video), 2016, URL: https://youtu.be/kVqEs2t-17g.

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

[11] Donald R Askeland and Wendelin J Wright. *Essentials of materials science & engineering*. Cengage Learning, 2013.

[12] ReaAcc. Lr 267 carbon tricopter frame, 2020, URL: https://www.aliexpress.com/item/4000865908977.html, accessed 10-06-2021.

[13] HobbyKing. Titus 600 carbon tricopter frame, 2020, URL: https://hobbyking.com/en_us/hobbykingtm-titus-600-carbon-fiber-tri-copter-frame-with-integrated-pcb.html, accessed 10-06-2021.

[14] Granta Design. Ces edupack 2017.

[15] Langdon Winner. Do artifacts have politics? *Daedalus*, pages 121–136, 1980.

[16] Stig Børsen Hansen. *Philosophers of Technology*. De Gruyter, 2020.

[17] Wuokko Knocke. Gender, ethnicity and technological change. *Economic and Industrial Democracy*, 15(1):11–34, 1994.

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

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

[20] Arch Daily. Open platform and jaja architects win competition to design denmark's first wooden parking house, 2020, URL: https://www.archdaily.com/931430/open-platform-and-jaja-architects-win-competition-to-design-denmarks-first-wooden-parking-house.