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Advanced Processes and Materials

Manufacture of Wind Turbine Blade (ACMA6000)

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Abstract

This report presents the design and evaluation of a small-scale wind turbine blade for farmhouse energy demand. The annual electrical demand was estimated as 5290 kWh/year, giving an average required power of 603.88 W. Simplified aerodynamic calculations gave a rotor radius of 1.24 m, with the blade divided into five radial sections. A NACA 4412 airfoil was scaled across the span using chord taper and BEM-informed twist. Candidate materials were compared using Ansys Granta EduPack and a weighted decision matrix. CFRP was selected for its low density, stiffness, tensile strength and fatigue resistance. Vacuum-bagged CFRP manufacture was selected as the preferred production route. A SolidWorks model demonstrated the tapered and twisted blade geometry, with further BEM optimisation and FEA recommended.

Table of Contents

Abstract	2
List of Figures and Tables	5
1. Introduction	7
2. Literature Review	8
2.1 Small-scale wind turbines and blade design	8
2.2 Blade Element Momentum theory and blade twist	8
2.3 NACA Airfoils and aerodynamic performance	9
2.4 Wind turbine blade materials.....	9
2.5 Manufacturing routes for turbine blades.....	10
3 Design Requirements and Calculations	11
3.1 Farmhouse energy demand	11
3.2 Rotor sizing	12
3.3 Blade section geometry	14
3.4 Lift and drag estimation.....	15
3.5 BEM-inspired twist distribution.....	17
4 Material Selection and Mechanical Property Analysis	19
4.1 Material selection requirements and candidate materials	19
4.2 Mechanical properties comparison	20
4.3 Environmental and cost comparison.....	21
4.4 Weighted decision matrix.....	23
4.5 Final material selection	24
5 Exploration of Manufacturing Routes	25
5.1 Possible manufacturing methods	25
5.2 Comparative manufacturing analysis.....	26
5.3 Selected manufacturing route	27
5.4 Indicative cost evaluation.....	28
6 CAD Modelling and Engineering Drawings	29
6.1 SolidWorks modelling method	29
6.2 Final Twisted blade model.....	30
6.3 Engineering drawing outputs.....	32
7 Discussion	34
7.1 Evaluation of final design.....	34
7.2 Design limitations.....	34

7.3	Recommendations for improvement.....	35
8	Conclusion.....	36
	References	37
	Appendices.....	39
	Appendix A – Wind Turbine Blade Design Calculations and Supporting Dataset	39
	Appendix B – NACA 4412 Airfoil Coordinate Data	40
	Appendix C – Granta EduPack Material Selection Evidence	45
	Appendix D – SolidWorks CAD Model and Engineering Drawing	49
	Appendix E – Cost Evaluation Spreadsheet	61
	Appendix F – Simplified Structural Bending Load Check	62

List of Figures and Tables

Table 1: Farmhouse energy demand summary.....	12
Table 2: Rotor sizing calculation parameters.....	14
Table 3: Blade section geometry.	15
Table 4: Estimated lift and drag forces for each blade section.	17
Table 5: BEM-inspired blade twist distribution.....	18
Table 6: Candidate materials selected for wind turbine comparison.....	20
Table 7: Mechanical property comparison of candidate materials.	20
Table 8: Environmental and cost comparison of candidate materials.....	22
Table 9: Weighted decision matrix for candidate blade materials.	23
Table 10: Comparative analysis of possible manufacturing routes.	26
Table 11: Indicative cost estimate for vacuum-bagged CFRP blade manufacture	28
Figure 1: Typical household annual energy demand per appliance/load	12
Figure 2: Granta EduPack Young's modulus versus density chart for candidate blade materials.	21
Figure 3: Granta EduPack embodied energy versus density chart for candidate blade materials.	22
Figure 4: Excel weighted decision matrix and Granta material property data used for candidate material selection.....	24
Figure 5: Imported NACA 4412 airfoil curves positioned along the blade span in SolidWorks.	29
Figure 6: A lofted boss feature to connect profiles and create blade body.....	30
Figure 7: Final twisted SolidWorks blade model with CFRP material appearance (view 1).	31
Figure 8: Final twisted SolidWorks blade model with CFRP material appearance (view 2).	31
Figure 9: Final twisted SolidWorks blade model with CFRP material appearance (view 3).	32
Figure 10: Engineering drawing of final wind turbine blade showing isometric and orthographic views, design radius, modelled airfoil section length, chord taper and CAD root/tip transitions.....	33
Figure 11: Wind turbine blade design calculations and supporting dataset.....	39
Figure 12: Excel worksheet showing NACA 4412 coordinate generation for blade section 1.	40
Figure 13: Excel worksheet showing NACA 4412 coordinate generation for blade section 2.	41
Figure 14: Excel worksheet showing NACA 4412 coordinate generation for blade section 3.	42
Figure 15: Excel worksheet showing NACA 4412 coordinate generation for blade section 4.	43
Figure 16: Excel worksheet showing NACA 4412 coordinate generation for blade section 5.	44
Figure 17: Granta EduPack embodied energy versus density chart used to compare the environmental burden and mass efficiency of GFRP, CFRP and aluminium 6061-T6.....	45
Figure 18: Granta EduPack tensile strength versus density chart used to compare strength-to-weight suitability of GFRP, CFRP and aluminium 6061-T6.....	46
Figure 19: Granta EduPack Young's modulus versus density chart used to compare stiffness and density of GFRP, CFRP and aluminium 6061-T6.....	47

Figure 20: Excel material selection worksheet showing Granta EduPack material data and weighted decision matrix.....	48
Figure 21: SolidWorks measurement of Plane 1 at 247.6 mm from the rotor centre.	49
Figure 22: SolidWorks measurement of Plane 2 at 495.2 mm from the rotor centre.	50
Figure 23: SolidWorks measurement of Plane 3 at 742.7 mm from the rotor centre.	51
Figure 24: SolidWorks measurement of Plane 4 at 990.3 mm from the rotor centre.	52
Figure 25: SolidWorks measurement of Plane 5 at 1237.9 mm from the rotor centre.....	53
Figure 26: SolidWorks loft setup showing the five imported NACA 4412 airfoil curves selected as blade profiles.	54
Figure 27: SolidWorks blade model showing the five reference planes, rotor centre plane, blade tip plane and overall design radius of 1237.90 mm.	55
Figure 28: SolidWorks blade model showing spanwise twist and section orientation across the five reference planes.....	56
Figure 29: Final SolidWorks CFRP blade model showing tapered geometry, root transition and closed blade tip.....	57
Figure 30: Final SolidWorks CFRP blade model showing tapered geometry, spanwise twist, root transition and closed blade tip.....	58
Figure 31: SolidWorks engineering drawing showing final blade views, design radius, modelled airfoil section length, chord taper and section data.	59
Figure 32: SolidWorks engineering drawing showing final blade views, design radius, modelled airfoil section length, chord taper, twist distribution and section data.....	60
Figure 33: Excel cost evaluation worksheet showing input assumptions, vacuum-bagged CFRP blade cost estimate, manufacturing cost comparison, cost-performance trade-off and cost breakdown chart.	61
Figure 34: Excel simplified bending load check using calculated blade section lift forces.	62

1. Introduction

Renewable energy systems are increasingly important for reducing reliance on grid electricity and fossil fuels, particularly for rural and agricultural users. Small-scale wind turbines can contribute to local electricity demand where a suitable wind resource is available, but their performance depends strongly on rotor blade design. The blade must convert wind energy into rotational motion while remaining lightweight, stiff and resistant to repeated aerodynamic loading.

This work develops a small-scale wind turbine blade for farmhouse energy supply. The design process includes energy demand estimation, rotor sizing, blade geometry development, airfoil selection, material evaluation, manufacturing route assessment and CAD modelling. A NACA 4412 airfoil was used to define the blade sections, with chord taper applied along the span.

The blade geometry was based on simplified aerodynamic calculations rather than full Blade Element Momentum optimisation. However, BEM principles were used to justify the inclusion of spanwise twist, since relative wind angle varies along the blade radius. Candidate materials were compared using Ansys Granta EduPack and a weighted decision matrix, considering mechanical performance, cost, environmental impact and manufacturability. The final CAD model demonstrates the selected chord taper, twist distribution and CFRP material application.

2. Literature Review

2.1 Small-scale wind turbines and blade design

Small-scale wind turbines are used for decentralised power generation where electricity is required close to the point of use. For rural properties, suitability depends on the available wind resource, expected energy demand and the ability of the rotor to extract useful power from variable wind conditions. The blade is a critical component because it governs aerodynamic efficiency, torque generation and structural loading.

Horizontal-axis wind turbines commonly use airfoil-shaped blades to generate lift as air passes over the blade surface. The resulting lift force produces torque about the rotor hub, while drag resists rotation. Key design parameters include airfoil profile, chord length, blade radius, twist angle and number of blades. Khalil et al. (2020) identify airfoil type, chord distribution and twist distribution as important factors influencing small wind turbine performance, while Akbari et al. (2023) show that blade number and airfoil selection affect chord and twist requirements.

2.2 Blade Element Momentum theory and blade twist

Blade Element Momentum theory is widely used for horizontal-axis wind turbine analysis because it combines rotor momentum theory with blade element theory. Momentum theory considers the change in airflow through the rotor, while blade element theory divides the blade into radial sections so local aerodynamic forces can be assessed (Ageze, Hu and Wu, 2017; Wood and Golmirzaee, 2023).

A key outcome of BEM theory is that blade geometry should vary with radius. Local blade velocity increases towards the tip, changing the relative wind angle experienced by each section. Twist is therefore required so that sections operate closer to their intended angle of attack. Chord distribution is also influenced by radial position, with larger inner chords supporting load and smaller outer chords reducing

drag and blade mass. BEM methods are commonly used to determine chord and twist distributions, although these may be simplified or linearised for manufacture (Tahani et al., 2017).

2.3 NACA Airfoils and aerodynamic performance

Airfoil selection affects lift generation, drag and rotor efficiency. For horizontal-axis wind turbine, each blade section acts as an airfoil; lift contributes to useful torque, while drag resists rotation. A suitable profile should therefore provide an appropriate lift-to-drag ratio over the expected operating range.

NACA airfoils are widely used in blade design because their geometry is clearly defined and can be generated mathematically. The four-digit NACA system identifies maximum camber, camber position and maximum thickness as percentages of chord length. For NACA 4412, the profile has 4% maximum camber, maximum camber at 40% of the chord and 12% maximum thickness. This makes it suitable for spreadsheet-based coordinate generation and CAD modelling.

NACA 4412 has been used in small wind turbine studies because its cambered geometry can generate useful lift at relatively low angles of attack (Umar et al., 2022; Yin, Xie and Yao, 2022). However, airfoil performance is affected by Reynolds number and angle of attack, which is relevant to small turbines operating at lower rotational speeds and variable wind conditions (Nakhchi, Naung and Rahmati, 2021).

2.4 Wind turbine blade materials

Blade material selection must balance aerodynamic performance with structural reliability. A suitable blade material requires low density to reduce rotating mass, adequate stiffness to limit deformation, tensile strength to resist loading and fatigue resistance for cyclic operation.

Fibre-reinforced polymer composites are widely used for wind turbine blades because they provide high strength-to-weight performance and can be manufactured

into complex aerodynamic forms. GFRP offers a practical balance between cost, performance and manufacturability, while CFRP provides higher stiffness and strength at lower density but has poorer end-of-life recyclability. Mishnaevsky et al. (2017) identify fibre-reinforced polymer composites as the dominant material group for modern blade manufacture, with fatigue behaviour and structural reliability being major selection factors. Brøndsted, Lilholt and Lystrup (2005) also highlight fatigue loading as a key design concern for composite wind turbine blades.

2.5 Manufacturing routes for turbine blades

The manufacturing route affects blade quality, cost, repeatability and structural performance. For composite blades, the process must produce an accurate aerodynamic profile while controlling fibre alignment, resin distribution and void content. Poor laminate quality can reduce stiffness, strength and fatigue life.

Traditional wet hand lay-up is simple and low cost, but it is labour intensive and quality depends heavily on operator skill. Wind turbine blade manufacture has therefore moved from open-mould hand lay-up towards more controlled composite processes, including vacuum infusion and VARTM (Mishnaevsky et al., 2017). Vacuum bagging, resin transfer moulding and vacuum-assisted resin infusion improve laminate consolidation, reduce air entrapment and support more consistent fibre-reinforced composite structures. For smaller blades, vacuum bagging can offer a practical balance between quality, cost and process complexity.

3 Design Requirements and Calculations

The design calculations used the farmhouse energy demand and assumed wind conditions to define rotor size, blade section positions, chord distribution, force estimates and twist values for CAD modelling.

3.1 Farmhouse energy demand

Farmhouse electrical demand was estimated from the annual energy use of the main appliance using:

$$E = P \times t$$

where

E is the energy consumption,

P is the appliance power rating and

t is the operating time.

The total annual demand was calculated as 5290 kWh/year, equivalent to 440.83 kWh/month, 14.49 kWh/day and an average power requirement of 603.88 W, as shown in Table 1. This value was used as the target power output for rotor sizing. The full appliance breakdown is shown in Figure 1.

Table 1: Farmhouse energy demand summary.

Parameter	Value
Annual energy demand	5290 kWh/year
Monthly energy demand	440.83 kWh/month
Daily energy demand	14.49 kWh/day
Average required power	603.88 W

Appliance / Load	Estimated annual use, kWh/year
Fridge-Freezer	350
Additional Freezer	300
Lighting (LED)	250
TV and Entertainment	250
Broadband / Router	120
Laptops / Office	350
Kettle	250
Electric Oven / Cooking Support	500
Microwave / Small Appliances	150
Washing Machine	220
Dishwasher	300
Tumble Dryer	700
Combi Boiler controls / pump	150
Vacuum / Cleaning	80
Phone / Tablet Charging	50
Standby / Miscellaneous	520
Outdoor Lighting / Security	250
Garage / Workshop	500
Total	5290

Figure 1: Typical household annual energy demand per appliance/load

3.2 Rotor sizing

The rotor radius was calculated using the wind power equation:

$$P = \frac{1}{2} \rho A V^3 C_p$$

where

P is the turbine power output,

ρ is air density,

A is the swept rotor area,

V is wind speed and

C_p is the power coefficient.

The equation was rearranged to calculate the required swept area:

$$A = \frac{P}{0.5\rho V^3 C_p}$$

The rotor radius was then calculated from:

$$R = \sqrt{\frac{A}{\pi}}$$

Using $P = 603.88 \text{ W}$, $\rho = 1.225 \text{ kg/m}^3$, $V = 8 \text{ m/s}$ and $C_p = 0.4$, the required rotor radius was 1.24 m, giving a rotor diameter of 2.48 m. The radius defined the blade span.

Table 2: Rotor sizing calculation parameters.

Parameter	Symbol	Value
Required power	P	603.88 W
Air density	ρ	1.225 kg/m ³
Wind speed	V	8 m/s
Power coefficient	C_p	0.4
Rotor radius	R	1.24 m
Rotor diameter	D	2.48 m

3.3 Blade section geometry

The blade span was divided into five radial sections using non-dimensional radius values of $r/R = 0.2, 0.4, 0.6, 0.8$ and 1.0 . These positions were used to define the airfoil sections for blade geometry and CAD model.

The section radius was calculated using:

$$r = \left(\frac{r}{R}\right) R$$

A linear chord taper was applied from the inner blade section to the tip. The chord reduced from 0.180 m at $r/R = 0.2$ to 0.040 m at $r/R = 1.0$.

The chord distribution was calculated using:

$$c = c_{root} - \left(\frac{\frac{r}{R} - 0.2}{1.0 - 0.2}\right) (c_{root} - c_{tip})$$

where

c is the local chord length,

c_{root} is the chord at the inner blade section and

c_{tip} is the chord at the blade tip.

Table 3: Blade section geometry.

Section	r/R	Radius position, r (m)	Chord length, c (m)
Section 1	0.2	0.2476	0.180
Section 2	0.4	0.4952	0.145
Section 3	0.6	0.7427	0.110
Section 4	0.8	0.9903	0.075
Section 5	1.0	1.2379	0.040

A linear taper was used to retain a finite tip chord for CAD modelling and manufacture. This is consistent with the drawing requirement for spanwise sections and is supported by literature showing that chord and twist distributions may be linearised for manufacturability (Tahani et al., 2017).

3.4 Lift and drag estimation

Lift and drag were estimated for each blade section using simplified aerodynamic force equations:

$$L = \frac{1}{2} \rho V^2 C_L A$$

$$D = \frac{1}{2} \rho V^2 C_D A$$

where

L is lift force,

D is drag force,

ρ is air density,

V is wind speed,

C_L is the lift coefficient,

C_D is the drag coefficient and

A is the representative blade section area.

The calculation used:

$$V = 8 \text{ m/s},$$

$$\rho = 1.225 \text{ kg/m}^3,$$

$$C_L = 1.2 \text{ and}$$

$$C_D = 0.05.$$

The representative area was based on chord length, so the larger inner sections produced greater aerodynamic force than the smaller tip.

Table 4: Estimated lift and drag forces for each blade section.

Section	Chord length, c (m)	Lift force, L (N)	Drag force, D (N)
Section 1	0.180	8.467	0.353
Section 2	0.145	6.821	0.284
Section 3	0.110	5.174	0.216
Section 4	0.075	3.528	0.147
Section 5	0.040	1.882	0.078

Lift and drag reduced from the inner section to the tip as chord length decreased. This supports the tapered geometry, which maintains loading area near the inner region while reducing drag and material use towards the tip.

3.5 BEM-inspired twist distribution

Spanwise twist was included because BEM theory shows that local flow conditions vary along the radius as tangential speed increases towards the tip. This changes the relative wind angle at each section and affects the required twist distribution (Tahani et al., 2017).

Full BEM optimisation was not carried out because it would require local tip-speed ratio, inflow angle, induction factors, angle of attack and iterative convergence at each radial section. Instead, a simplified twist distribution was used, with higher twist near the root and lower twist towards the tip.

The twist values in Table 5 were applied to the airfoil coordinate data before lofting in SolidWorks.

Table 5: BEM-inspired blade twist distribution.

Section	Radius position, r (m)	Chord length, c (m)	Twist angle
Section 1	0.2476	0.180	20°
Section 2	0.4952	0.145	14°
Section 3	0.7427	0.110	9°
Section 4	0.9903	0.075	5°
Section 5	1.2379	0.040	2°

4 Material Selection and Mechanical Property Analysis

Material selection was based on structural performance, mass, fatigue resistance, cost, environmental impact and manufacturability. A wind turbine blade must remain lightweight to reduce rotor inertia while providing sufficient stiffness, tensile strength and fatigue resistance under repeated aerodynamic loading. Candidate materials were compared using Ansys Granta EduPack 2026 R1, Level 3 MaterialUniverse, supported by a weighted decision matrix.

4.1 Material selection requirements and candidate materials

The main material requirements were low density, stiffness, tensile strength, fatigue resistance, reasonable cost, acceptable environmental impact and suitability for blade manufacture. These criteria reflect cyclic loading, mass and deformation requirements.

Three candidate materials were selected: GFRP, CFRP and aluminium 6061-T6. GFRP was included as a practical composite option with good manufacturability and moderate cost. CFRP was included because of its high stiffness-to-weight and strength-to-weight performance. Aluminium 6061-T6 was used as a metallic benchmark because it offers good availability, low cost and recyclability, although its higher density is a disadvantage for rotating blade structures.

Table 6: Candidate materials selected for wind turbine comparison.

Candidate material	Material type	Reason for inclusion
GFRP	Polymer composite	Practical lightweight composite option with good manufacturability.
CFRP	Polymer composite	High-performance lightweight composite with strong stiffness and fatigue properties.
Aluminium 6061-T6	Metal alloy	Recyclable, low-cost metallic benchmark with good general engineering properties.

4.2 Mechanical properties comparison

The candidate materials were compared using density, Young's modulus, tensile strength and fatigue strength. These properties directly influence blade mass, deformation, load resistance and durability during cyclic operation.

Table 7: Mechanical property comparison of candidate materials.

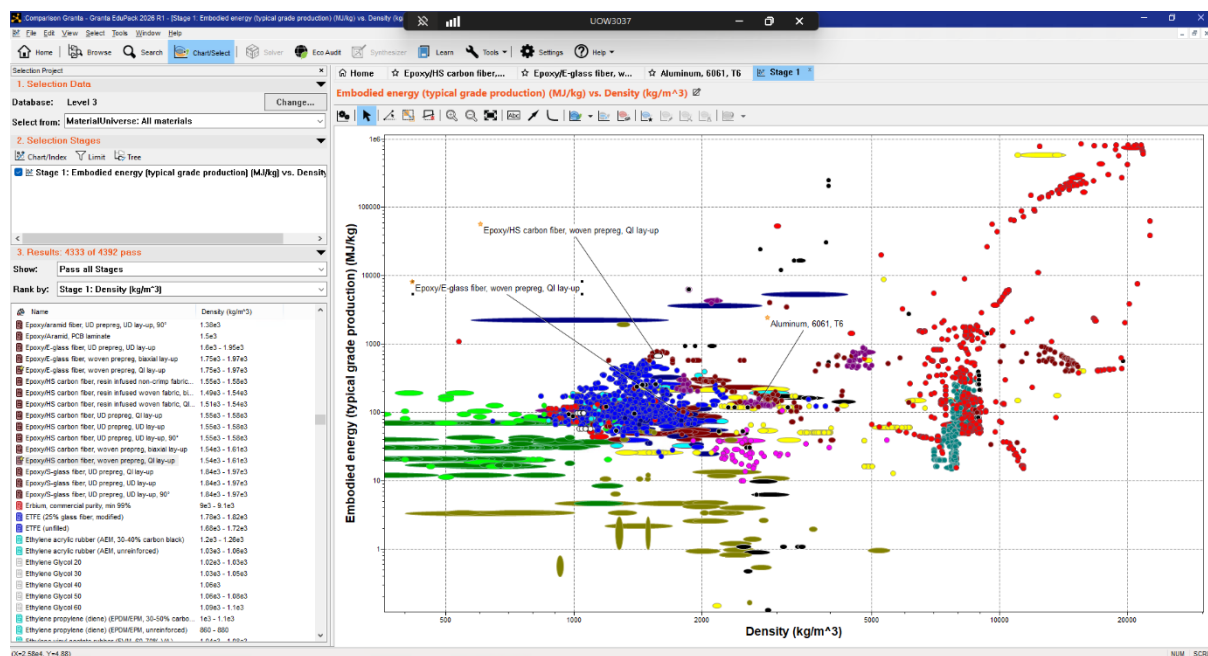
Material	Density (kg/m ³)	Young's modulus (GPa)	Tensile strength (MPa)	Fatigue strength at 10 ⁷ cycles (MPa)
GFRP	1750-1970	21-21.8	207-304	41.3-91.1
CFRP	1510-1540	41-46	383-552	210-359
Aluminium 6061-T6	2690-2730	66.6-70	290-338	112-131

The Granta EduPack Young's modulus versus density chart was used to compare stiffness against material mass. CFRP provided the strongest mechanical suitability, combining the lowest density with the highest tensile and fatigue strength. Aluminium 6061-T6 had the highest Young's modulus, but its greater density reduced its suitability for a lightweight rotating blade. GFRP remained a balanced composite option, although its stiffness and fatigue strength were lower than CFRP.

Cost and environmental impact were assessed using material price, embodied energy, carbon dioxide impact and recyclability from Granta EduPack. These factors were included because blade material selection must account for manufacture and end-of-life impact, not mechanical performance alone.

Table 8: Environmental and cost comparison of candidate materials.

Materials	Price (£/kg)	Embodied energy (MJ/kg)	CO ₂ impact (kg.kg)	Recyclability
GFRP	25.5-28	101-111	6.22-6.86	Yes, but limited functional recycling
CFRP	13.3-15.4	634-699	44.1-48.7	No
Aluminium 6061-T6	2.16-2.42	127-141 typical	8.91-9.79 typical	Yes

**Figure 3:** Granta EduPack embodied energy versus density chart for candidate blade materials.

The embodied energy versus density chart shows the trade-off between lightweight performance and environmental burden. CFRP had the lowest density but the highest embodied energy and carbon dioxide impact. GFRP showed a lower environmental impact than CFRP, while aluminium 6061-T6 offered the lowest material cost and best recyclability. However, aluminium's higher density remained a disadvantage for the blade application.

4.4 Weighted decision matrix

A weighted decision matrix was used to compare the candidate materials against the main blade requirements. The highest weighting was assigned to the low density, strength and stiffness, and fatigue resistance because these have the greatest influence on blade performance and durability. Environmental impact, cost and manufacturability were included as practical selection constraints.

Table 9: Weighted decision matrix for candidate blade materials.

Criteria	Weighting	GFRP	CFRP	Aluminium 6061-T6
Low density / low blade mass	25%	4	5	2
Strength and stiffness	25%	3	5	4
Fatigue resistance	20%	3	5	4
Environmental impact / recyclability	15%	4	1	3
Cost	10%	3	4	5
Manufacturability	5%	4	3	4
Weighted total	100%	3.45	4.20	3.45

Material	Exact Granta record	Density, kg/m ³	Young's Modulus, GPa	Tensile Strength, MPa	Fatigue Strength at 10 ⁷ cycles, MPa	Fracture Toughness, MPa·m ^{1/2}	Price, GBP/kg	Embodied Energy, MJ/kg	CO ₂ Impact, kg/kg	Recyclable	Notes
GFRP	Epoxy/E-glass fiber, woven prepreg, QI lay-up	1750-1970	21-21.8	207-304	41.3-81.1	19.3-31	25.5-28	101-111	6.22-6.86	Yes; but functional recycle: No	Balanced composite option; good strength-to-weight and suitable for blade manufacture
CFRP	Epoxy/HB carbon fiber, resin-infused woven fabric, QI lay-up	1510-1540	41-46	383-552	210-359	20.2-24.4	13.3-15.4	634-699	44.1-48.7	No	Highest mechanical performance, but high embodied energy and CO ₂ impact
Aluminium 6061-T6	Aluminium, 6061, T6	2690-2730	66.6-70	290-338	112-131	30-36	2.16-2.42	127-141 typical / 169-187 virgin	8.91-9.79 typical / 12.2-13.4 virgin	Yes	Strong and recyclable, but heavier than the composite options

Source: Ansys Granta EduPack 2026 R1, Level 3 MaterialUniverse

Selection Criterion	Weighting	GFRP Score	GFRP Weighted	CFRP Score	CFRP Weighted	Aluminium Score	Aluminium Weighted
Low density / low blade mass	25%	4	1	5	1.25	2	0.5
Strength and stiffness	25%	3	0.75	5	1.25	4	1
Fatigue resistance	20%	3	0.6	5	1	4	0.8
Environmental impact / recyclability	15%	4	0.6	1	0.15	3	0.45
Cost	10%	3	0.3	4	0.4	5	0.5
Manufacturability	5%	4	0.2	3	0.15	4	0.2
Total score	100%		3.45		4.20		3.45

CFRP achieved the highest weighted score due to its superior mechanical properties, fatigue resistance and low density. However, GFRP remains a strong practical alternative where reduced environmental impact and balanced performance are prioritised. Aluminium 6061-T6 is recyclable and low cost, but its higher density makes it less suitable for a lightweight rotating turbine blade.

Figure 4: Excel weighted decision matrix and Granta material property data used for candidate material selection.

CFRP achieved the highest weighted score of 4.20, while GFRP and aluminium 6061-T6 both scored 3.45. GFRP performed well as a balanced composite option, while aluminium was limited by its higher density despite lower cost and recyclability.

4.5 Final material selection

CFRP was selected as the preferred blade material because it provided the strongest combination of low density, tensile strength, stiffness and fatigue resistance. These properties were prioritised because the blade must resist repeated aerodynamic loading while minimising rotating mass.

The main limitation of CFRP is its higher environmental impact and poor recyclability compared with GFRP and aluminium 6061-T6. However, the weighted decision matrix showed that its mechanical advantages outweighed these drawbacks for the proposed blade.

5 Exploration of Manufacturing Routes

The manufacturing route affects blade accuracy, laminate quality, cost and repeatability. For a CFRP wind turbine blade, the process must produce the aerodynamic profile while controlling the fibre alignment, resin distribution and void content as these influence stiffness, strength, fatigue performance and surface finish.

5.1 Possible manufacturing methods

Several manufacturing routes were considered for the candidate materials. Aluminium 6061-T6 could be machined, extruded or formed, offering good dimensional accuracy and recyclability. However, its higher density and the difficulty of producing thin aerodynamic profiles make it less suitable for a lightweight rotating blade.

For GFRP and CFRP, suitable composite routes include hand lay-up, vacuum bagging, resin transfer moulding and vacuum-assisted resin transfer moulding. Composite blade manufacture has developed from open-mould hand lay-up towards more controlled processes such as vacuum infusion and VARTM, which improves laminate quality and process repeatability (Mishnaevsky et al., 2017).

Hand lay-up is simple and low cost but depends heavily on operator skill and can lead to voids, uneven resin content and inconsistent fibre placement. These defects are important because laminate quality affects behaviour and long-term structural reliability under repeated loading (Brøndsted, Lilholt and Lystrup, 2005). Additive manufacturing was considered for prototype blades or mould tooling, but printed polymer parts generally lack the structural reliability and fatigue resistance of fibre-reinforced composite laminates.

5.2 Comparative manufacturing analysis

The possible manufacturing routes were compared in terms of material suitability, cost, production time, scalability, likely defects and environmental impact.

Table 10: Comparative analysis of possible manufacturing routes.

Manufacturing route	Suitable material	Advantages	Limitations / defects	Overall suitability
Hand lay-up	GFRP / CFRP	Low tooling cost, simple equipment, suitable for prototypes	Labour intensive, variable resin content, air voids, inconsistent surface finish	Suitable for low-cost prototype work
Vacuum bagging	GFRP / CFRP	Improved fibre consolidation, reduced air entrapment, better surface finish than hand lay-up	Required vacuum pump, bagging materials and careful sealing	Very suitable for small scale composite blade production
Resin transfer moulding / VARTM	GFRP / CFRP	Good resin control, lower void content, repeatable laminate quality, scalable	More complex tooling and process setup	Suitable for higher-quality or larger-scale production
Aluminium machining / forming	Aluminium 6061-T6	Accurate, recyclable, established manufacturing route	Higher blade mass, difficult to form from thin aerodynamic profiles, material waste from machining	Less suitable for this lightweight blade
Additive manufacturing	Polymers / prototype composites	Rapid prototyping, useful for moulds or design trials	Lower structural reliability, surface finish concerns, limited fatigue performance	Suitable mainly for prototypes or tooling

Composite manufacturing routes are more suitable than aluminium-based methods for the selected blade. Aluminium machining or forming can produce accurate parts, but blade mass would be higher than for composite alternatives. Additive manufacturing may support design trials or mould production, but it is less appropriate for the final blade due to fatigue and surface finish concerns.

Hand lay-up is the simplest composite process, but it carries greater risk of voids, variable resin content and inconsistent laminate quality. Vacuum bagging improves this by compacting the laminate and reducing air entrapment. VARTM provides stronger process control and scalability but requires more complex tooling. For a small-scale CFRP blade, vacuum bagging provides the strongest balance between manufacturing quality, cost and practical implementation.

5.3 Selected manufacturing route

Vacuum-bagged CFRP composite manufacture was selected as the preferred route. This process offers better laminate consolidation than open hand lay-up while avoiding the higher tooling complexity of full resin transfer moulding or industrial VARTM.

The process would involve preparing a blade mould, laying carbon fibre reinforcement, applying epoxy resin and compacting the laminate under a vacuum pressure. This reduces voids, improves resin distribution and maintains fibre alignment. The main limitations are vacuum sealing, resin control, curing conditions, PPE requirements and safe handling of epoxy resin and carbon fibre dust.

5.4 Indicative cost evaluation

An indicative cost evaluation was completed for the selected vacuum-bagged CFRP route. The estimate included CFRP reinforcement, epoxy resin, vacuum bagging consumables, mould/tooling, labour, equipment and defect mitigation costs.

For one prototype blade, the estimated cost was approximately £143, based on a nominal 1.0 kg material assumption. This is not a supplier quotation but supports cost-performance comparison. CFRP is harder to justify on cost and environmental grounds than aluminium or GFRP, but its lower density, stiffness and fatigue resistance support its selection. Detailed assumptions are provided in Appendix E.

Table 11: Indicative cost estimate for vacuum-bagged CFRP blade manufacture

Cost category	Estimated cost (£)
CFRP reinforcement	15
Epoxy resin	10
Vacuum bagging consumables	20
Mould / tooling allowance	40
Labour	45
Defect / rework allowance	13
Estimated total	143

Vacuum bagging was selected because it improves consolidation and defect control while avoiding the higher tooling cost of RTM or VARTM.

6 CAD Modelling and Engineering Drawings

A SolidWorks model converted the calculated blade geometry into a three-dimensional form, checking NACA 4412 section positions, chord taper, spanwise twist and CFRP material appearance. Hub fixing and full turbine assembly were outside the design scope.

6.1 SolidWorks modelling method

The blade was modelled from NACA 4412 coordinate data generated in Excel. Five airfoil profiles were scaled to the calculated chord lengths and positioned at the radial stations defined in Section 3.3. Reference planes were created at each station, and the airfoil curves imported into SolidWorks as spanwise profiles. A lofted boss/base feature connected the profiles into the tapered blade body shown in Figures 5 and 6.

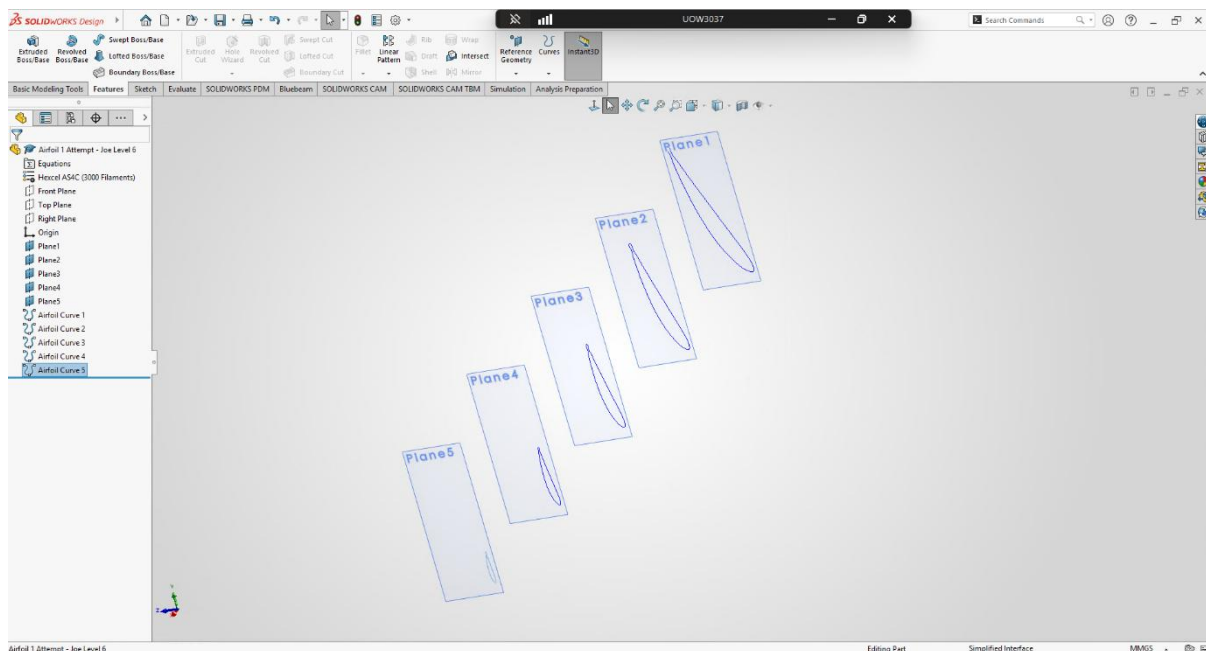


Figure 5: Imported NACA 4412 airfoil curves positioned along the blade span in SolidWorks.

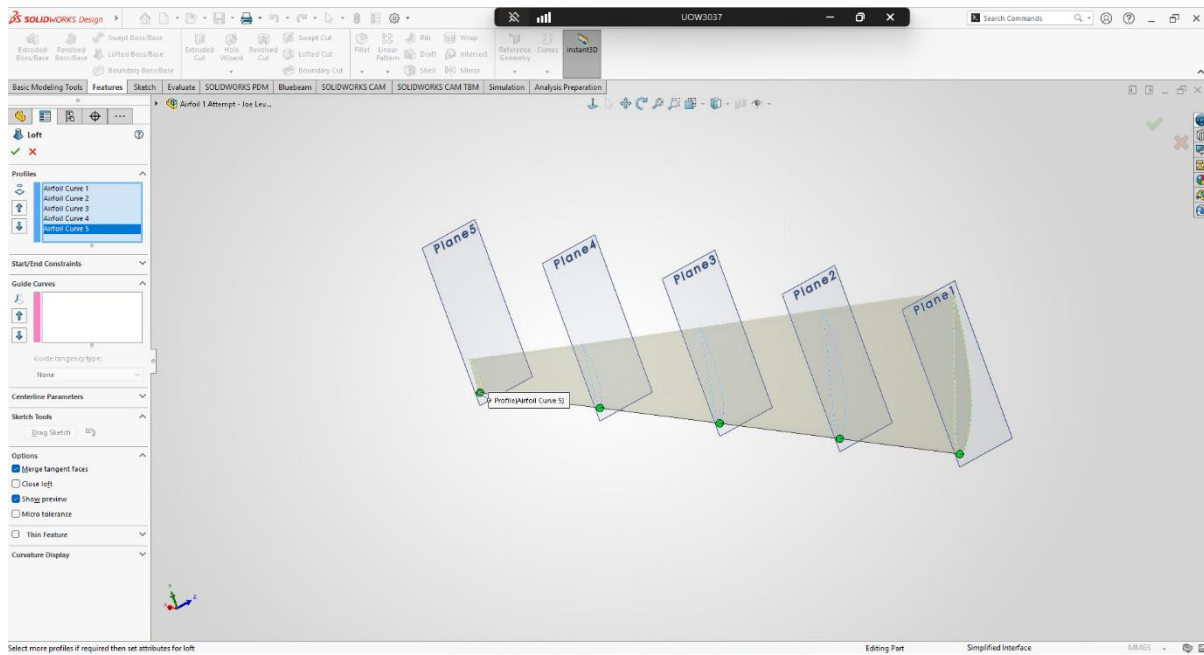


Figure 6: A lofted boss feature to connect profiles and create blade body.

6.2 Final Twisted blade model

The initial loft showed chord taper but no twist. Airfoil coordinates were modified using the twist distribution from Section 3.5 before re-importing into SolidWorks. The final model included taper, twist and CFRP appearance, as shown in Figures 7 to 9.

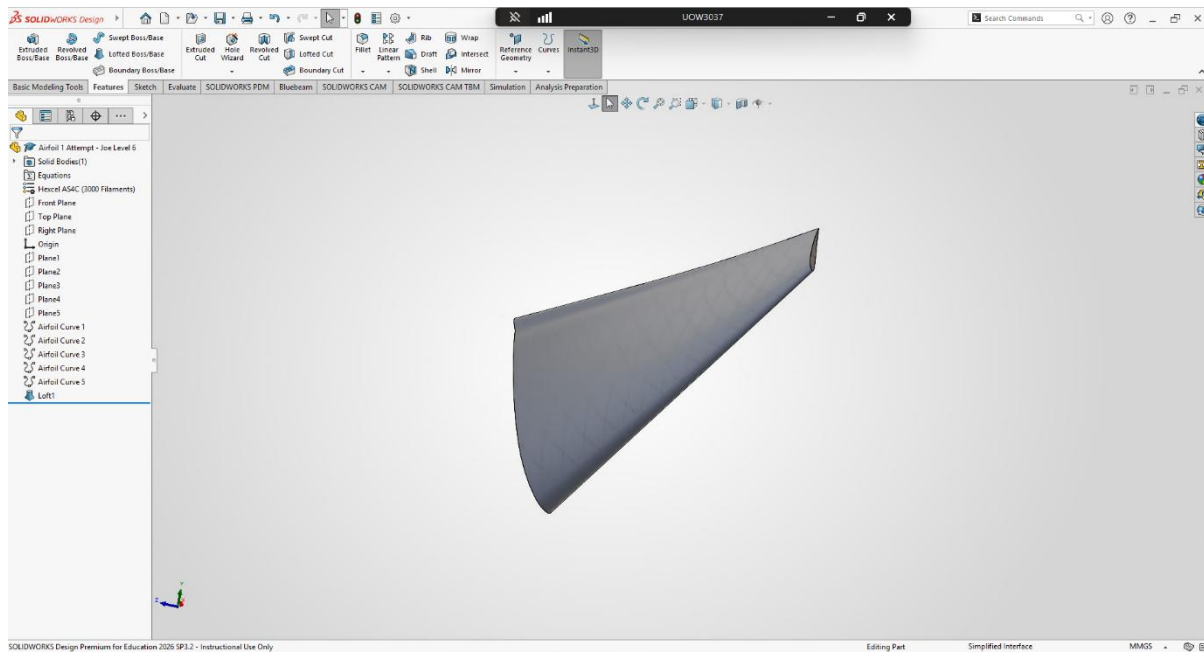


Figure 7: Final twisted SolidWorks blade model with CFRP material appearance (view 1).

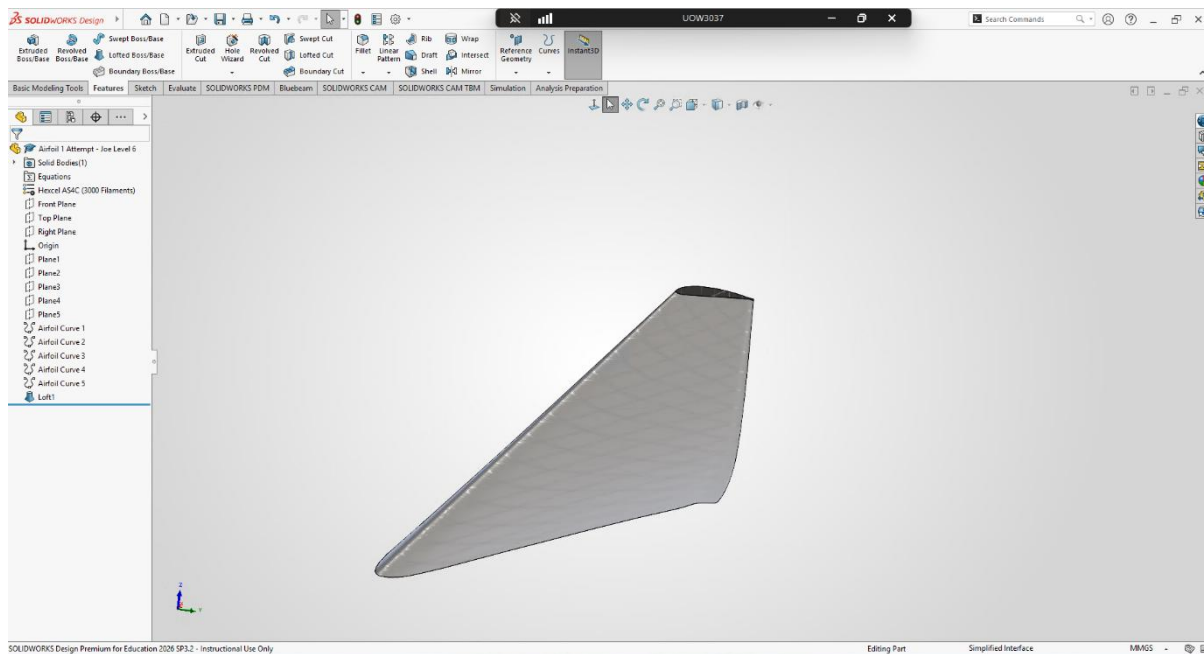


Figure 8: Final twisted SolidWorks blade model with CFRP material appearance (view 2).

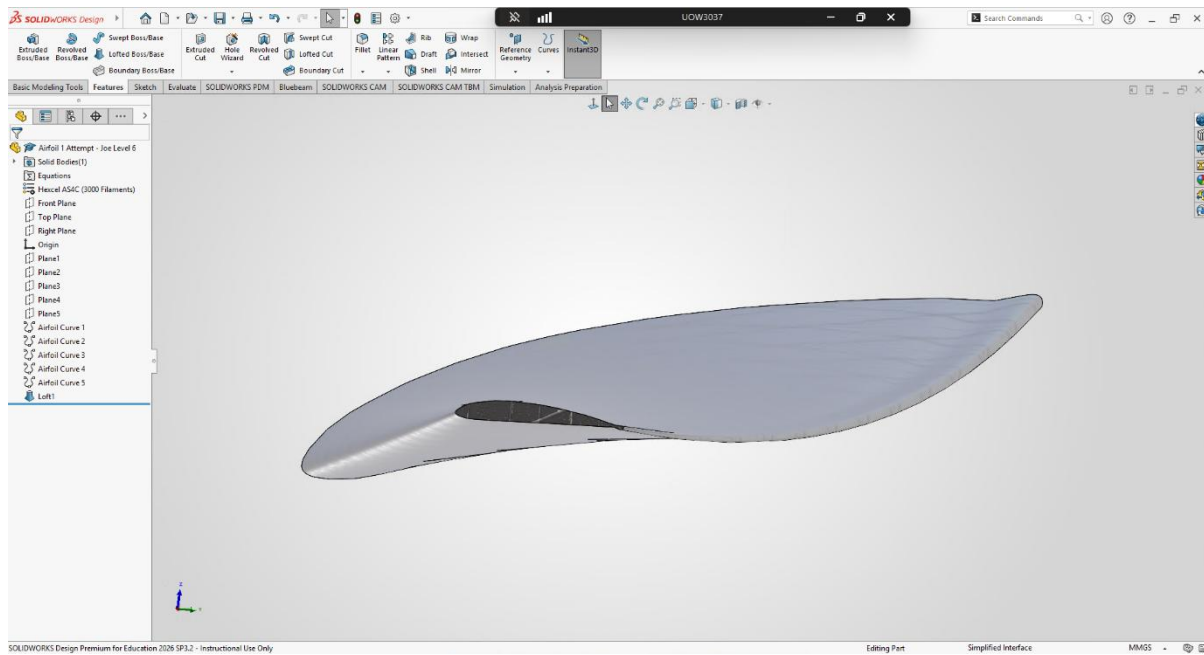


Figure 9: Final twisted SolidWorks blade model with CFRP material appearance (view 3).

6.3 Engineering drawing outputs

Engineering drawings were produced from the final SolidWorks model to present the blade as a technical component. The drawing includes isometric and orthographic views, overall design radius, modelled airfoil section length, chord taper and design notes linking the CAD model to the analytical calculations.

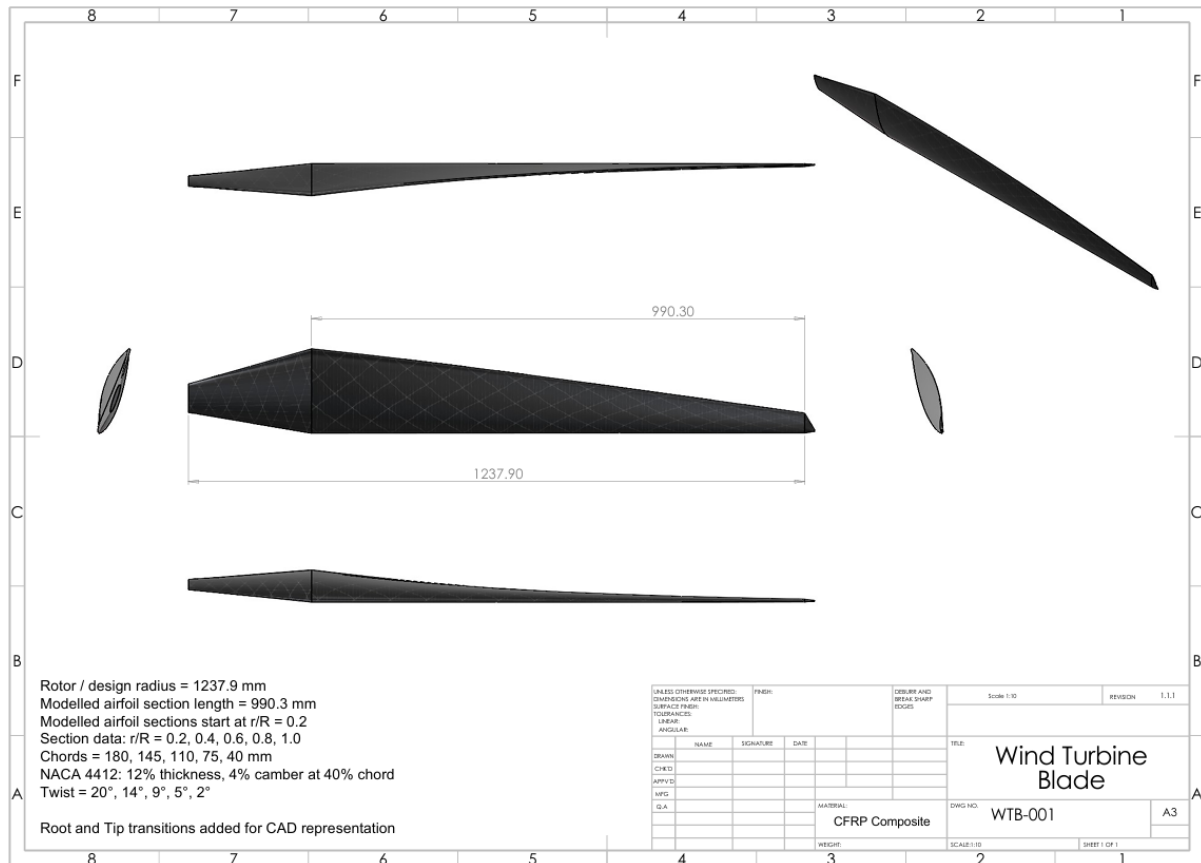


Figure 10: Engineering drawing of final wind turbine blade showing isometric and orthographic views, design radius, modelled airfoil section length, chord taper and CAD root/tip transitions.

The drawing provides the final link between the analytical calculations and the CAD model.

7 Discussion

The final design combines simplified aerodynamic calculations, material selection and CAD modelling to produce a tapered and twisted NACA 4412 blade using CFRP. It is suitable as a representative blade concept, although further optimisation would be required before manufacture or operational use.

7.1 Evaluation of final design

The blade geometry balances aerodynamic form, structural performance and manufacturability. Chord taper reduces mass and drag towards the tip while maintaining inner blade area for loading and support. Spanwise twist reflects the changing relative wind angle along the blade radius.

CFRP supports the design requirements through its low density, tensile strength, stiffness and fatigue resistance. This makes it more suitable for a lightweight rotating blade than aluminium 6061-T6, although GFRP remains a credible lower-impact alternative.

7.2 Design limitations

The main limitation is that the blade geometry was based on simplified aerodynamic assumptions rather than full BEM optimisation. The linear chord taper and finite tip chord were suitable for CAD modelling and manufacture, but they do not represent a fully optimised aerodynamic blade. Full BEM would require local tip-speed ratio, inflow angle, induction factor, angle of attack and iterative convergence at each radial section.

The lift and drag estimates used constant wind speed, lift and drag coefficients across all sections, although these vary with radius, Reynolds number, rotational speed and wind conditions. The CAD model also excluded detailed root fixing, blade reinforcement and finite element analysis, so structural performance was not fully

validated. A simplified bending load check is provided in Appendix F to support the mechanical assessment, although a full FEA was outside the project scope.

7.3 Recommendations for improvement

Further work should include full BEM optimisation, finite element analysis and a detailed root connection. Manufacturing development should refine vacuum-bagged CFRP costing, tooling, labour, curing and defect control. Environmental improvements could include GFRP, recyclable composite systems or lower-impact resins.

8 Conclusion

The blade design met the objective of developing a small-scale wind turbine blade for farmhouse demand. The calculated annual demand was 5290 kWh/year, giving an average required power of 603.88 W. Using the assumed wind conditions and power coefficient of 0.4, the required rotor radius was calculated as 1.24 m.

The final blade used a NACA 4412 airfoil with a tapered chord distribution and BEM-informed twist. CFRP was selected as the preferred material because it offered the strongest combination of low density, stiffness, tensile strength and fatigue resistance. Vacuum-bagged CFRP manufacture was identified as the most suitable production route for a small-scale blade.

The design remains limited by simplified aerodynamic assumptions, absence of full BEM optimisation and lack of FEA validation. Further work should therefore include full aerodynamic optimisation, structural simulation and a more detailed manufacturing cost assessment.

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Appendices

Appendix A – Wind Turbine Blade Design Calculations and Supporting Dataset

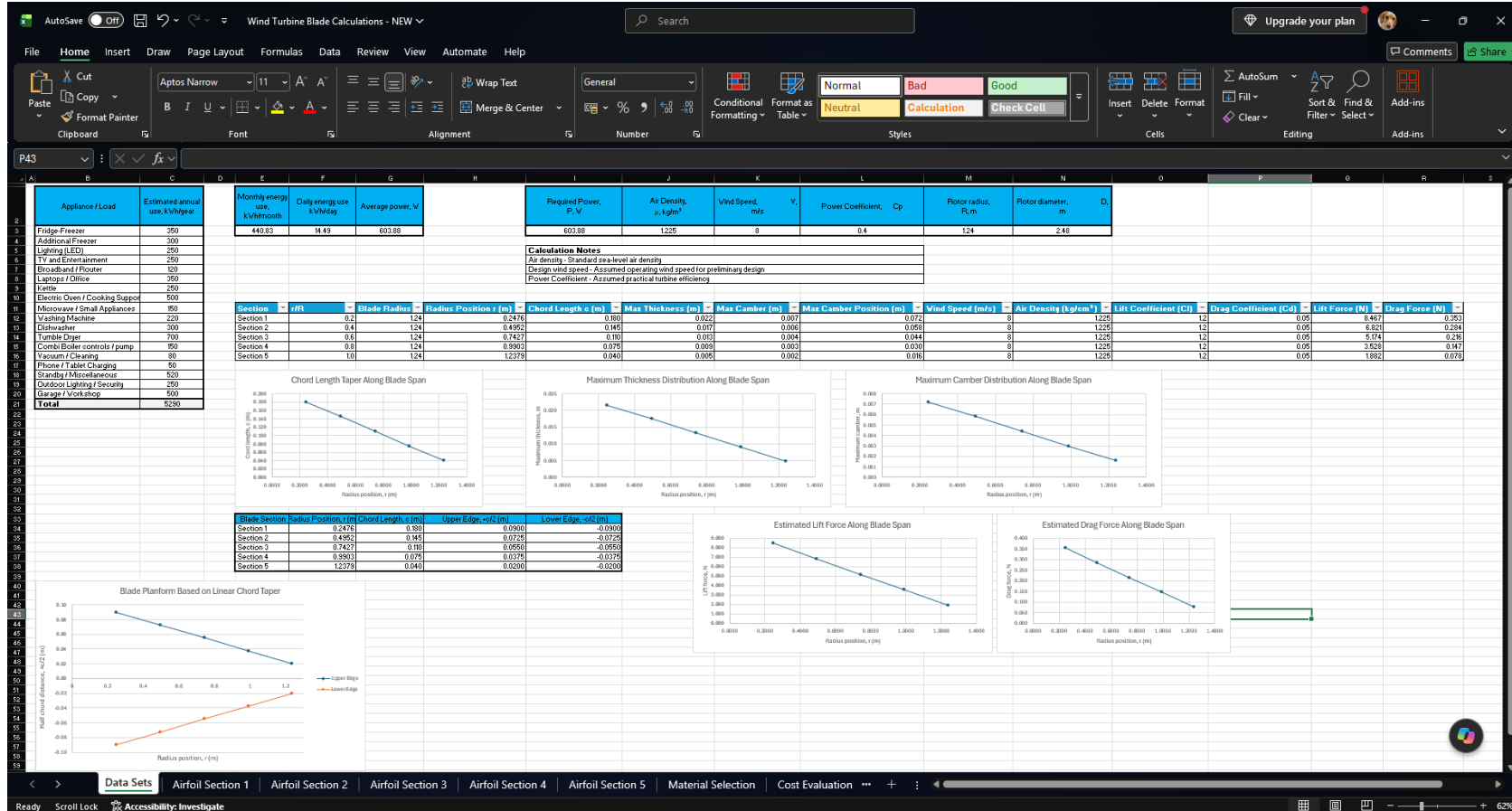


Figure 11: Wind turbine blade design calculations and supporting dataset.

Appendix B – NACA 4412 Airfoil Coordinate Data

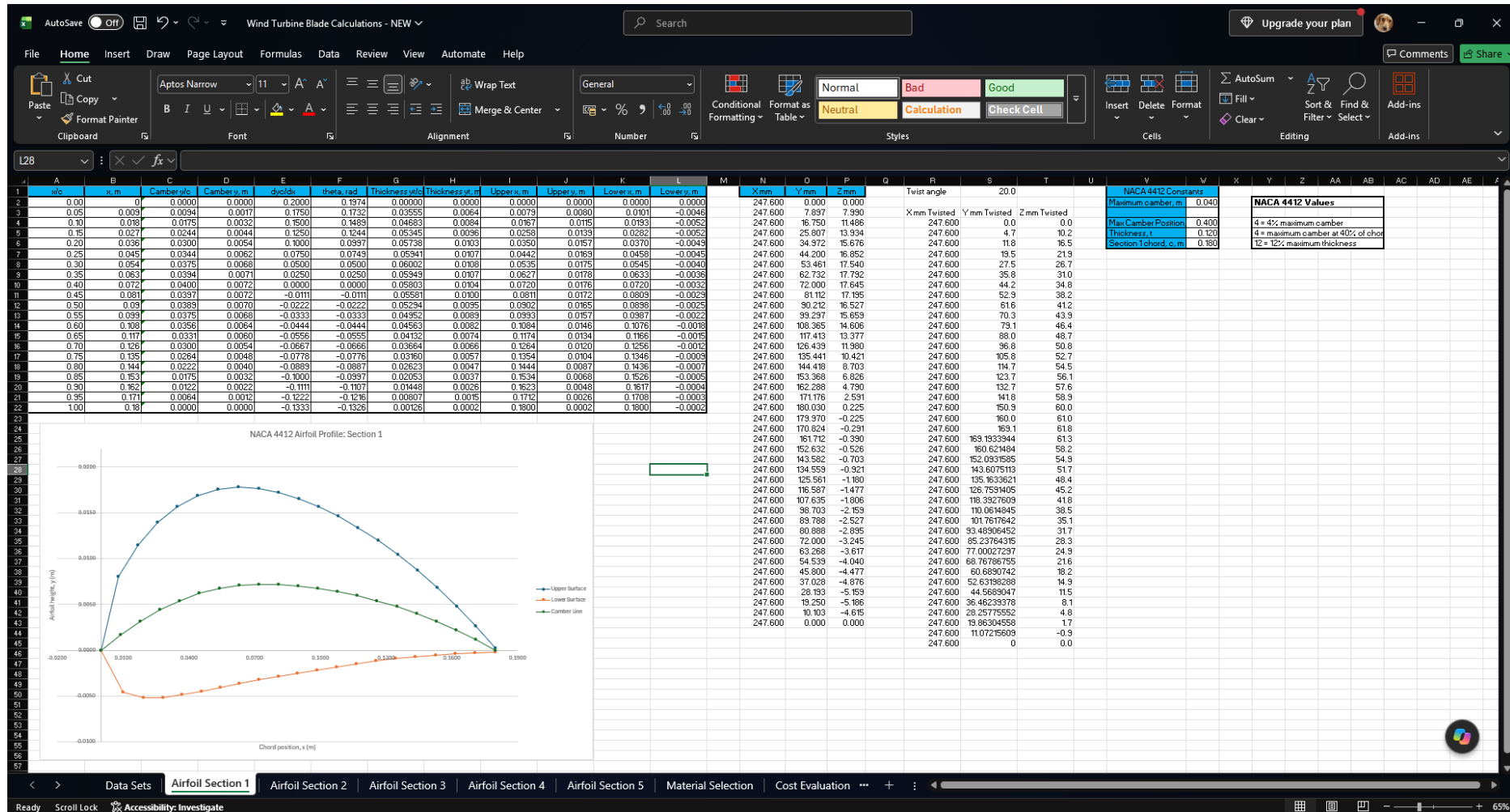
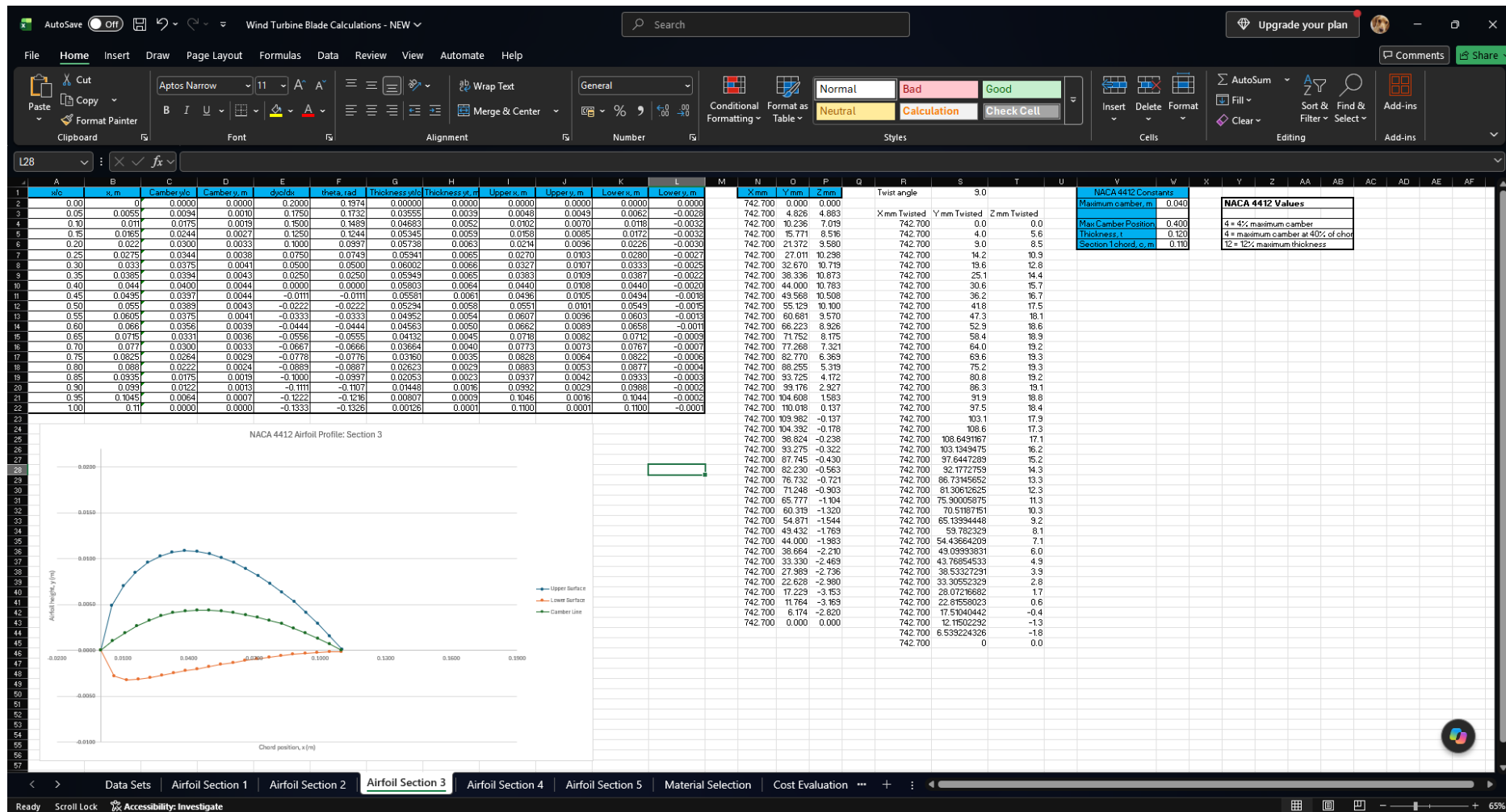


Figure 12: Excel worksheet showing NACA 4412 coordinate generation for blade section 1.





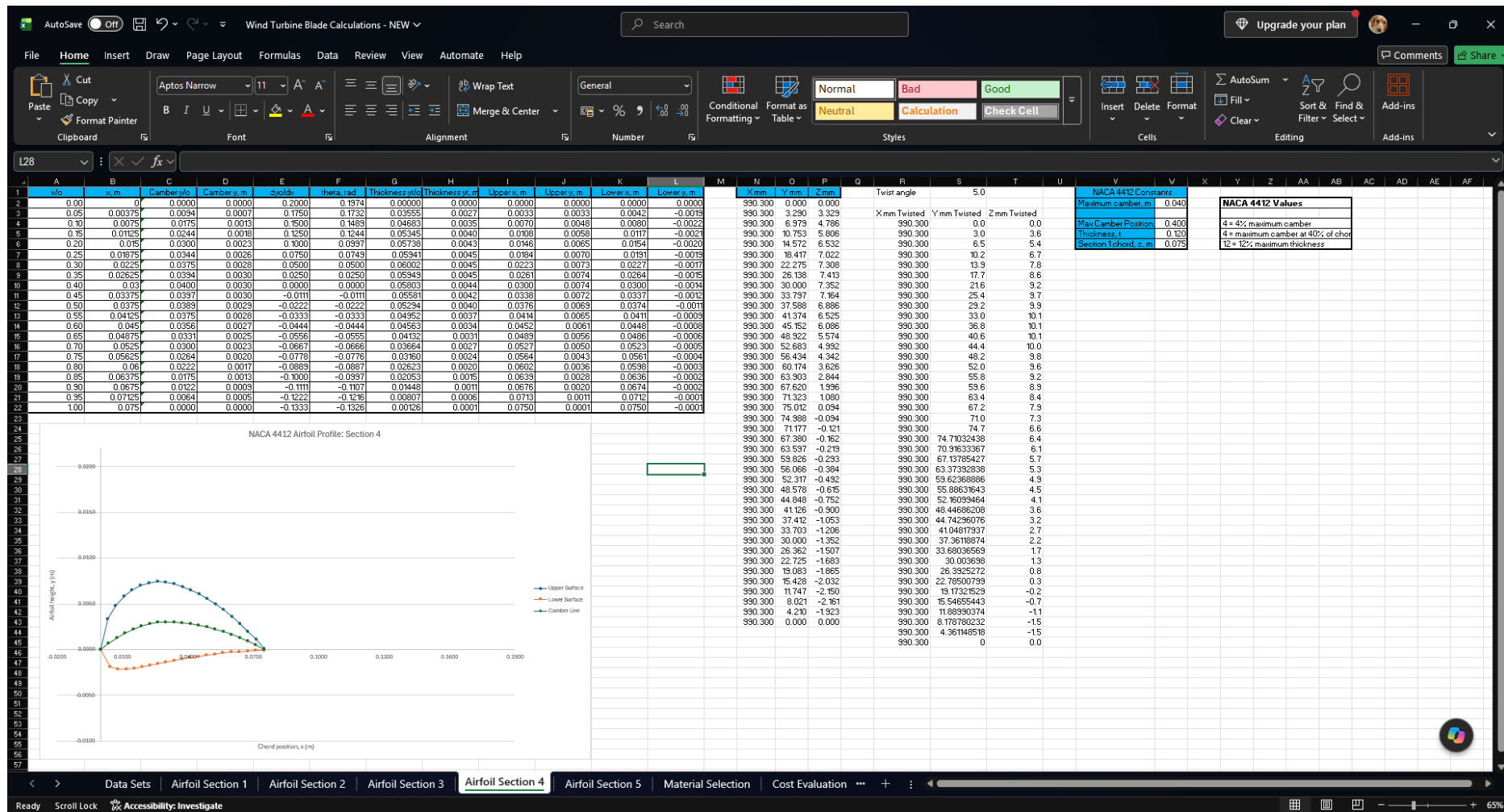


Figure 15: Excel worksheet showing NACA 4412 coordinate generation for blade section 4.



Appendix C – Granta EduPack Material Selection Evidence

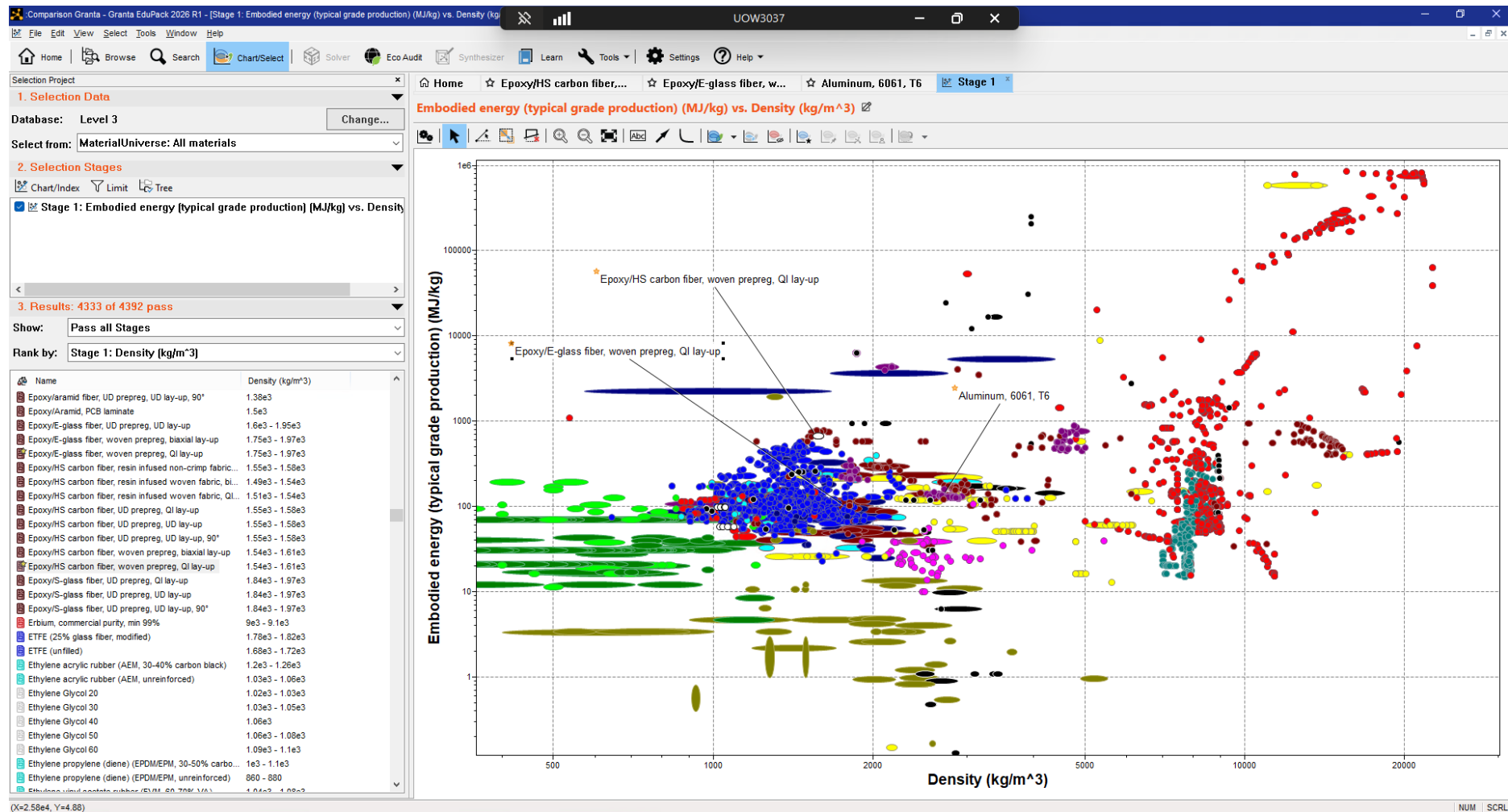


Figure 17: Granta EduPack embodied energy versus density chart used to compare the environmental burden and mass efficiency of GFRP, CFRP and aluminium 6061-T6.

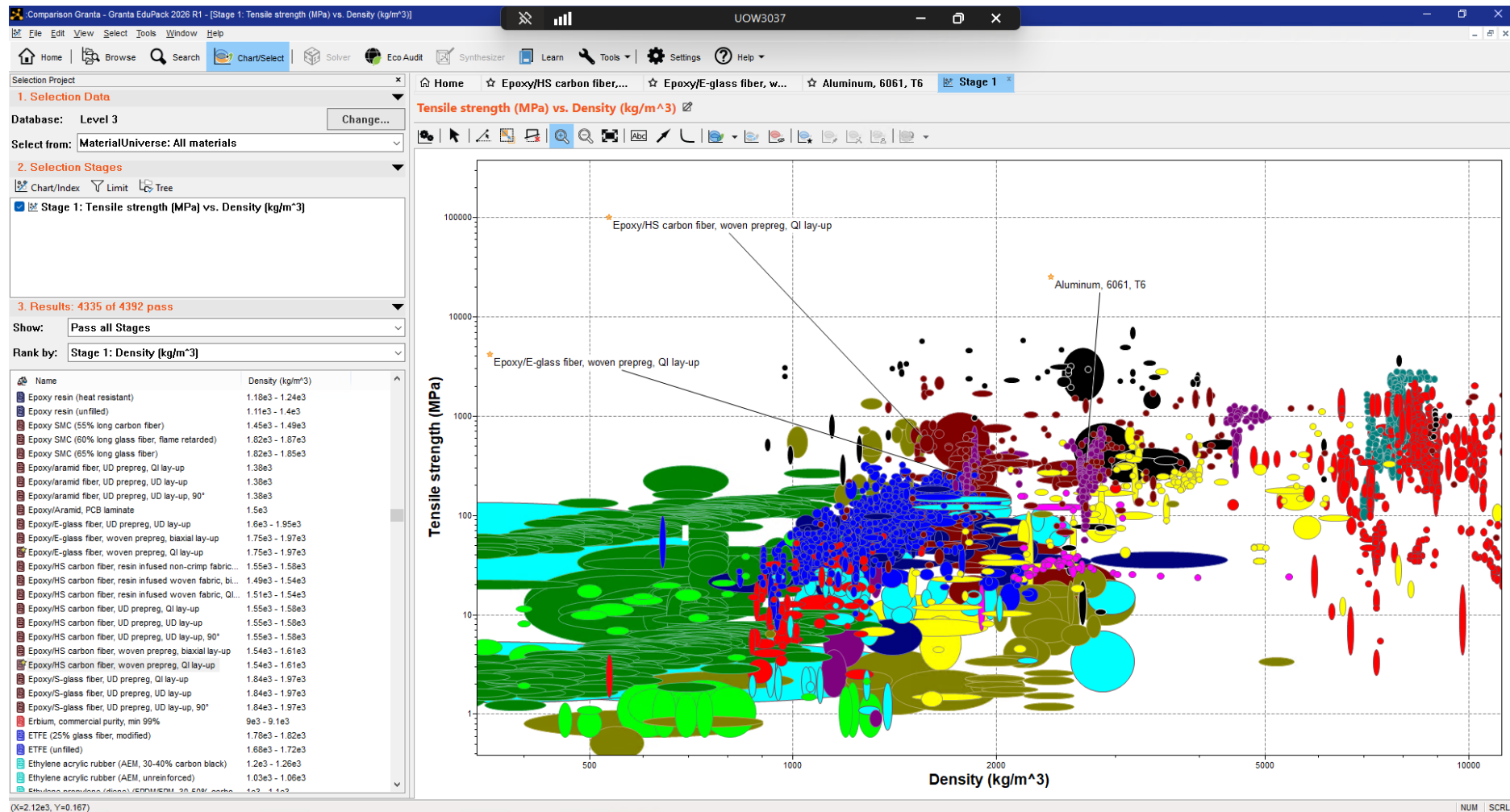


Figure 18: Granta EduPack tensile strength versus density chart used to compare strength-to-weight suitability of GFRP, CFRP and aluminium 6061-T6.

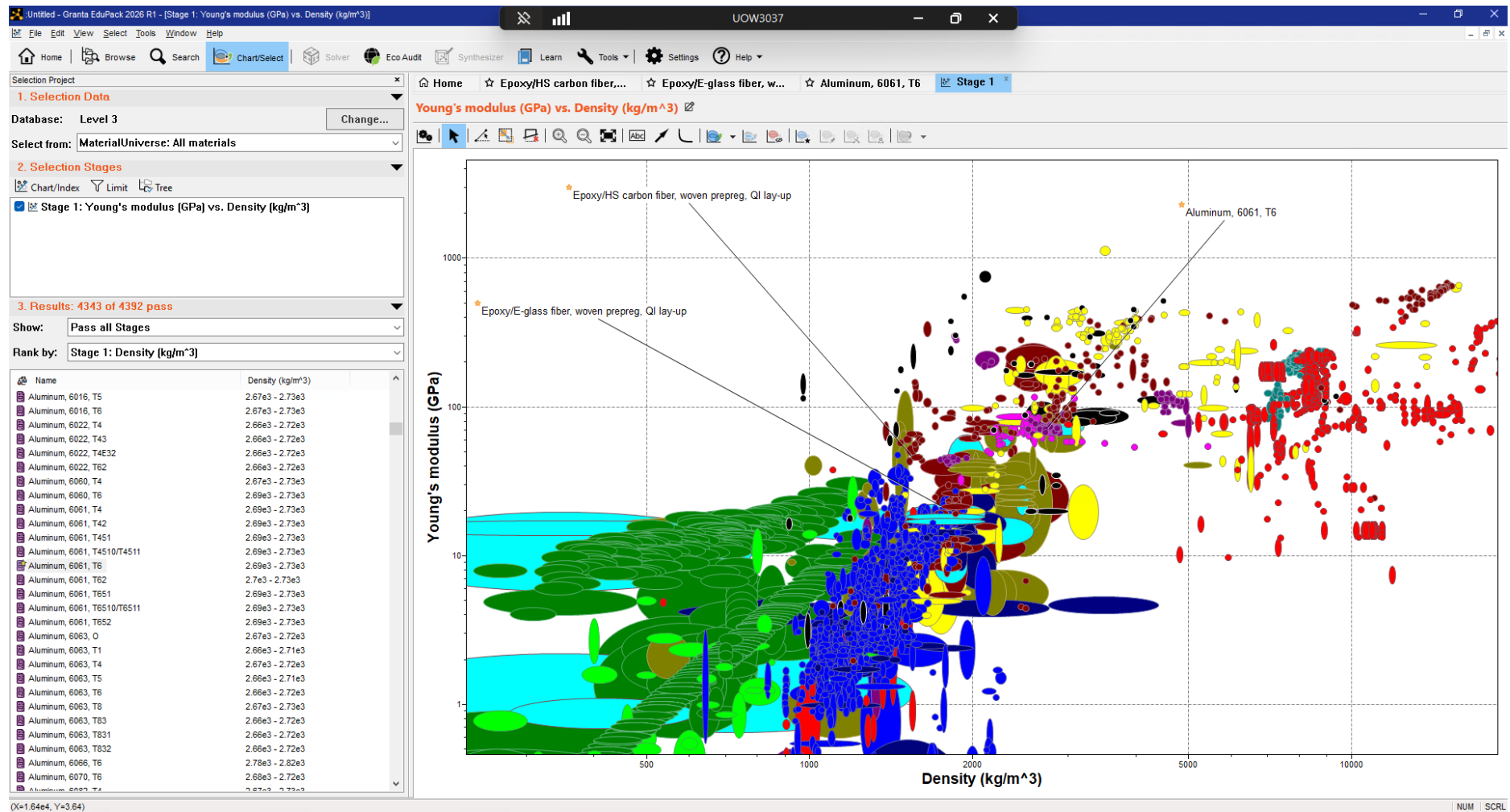


Figure 19: Granta EduPack Young's modulus versus density chart used to compare stiffness and density of GFRP, CFRP and aluminium 6061-T6.

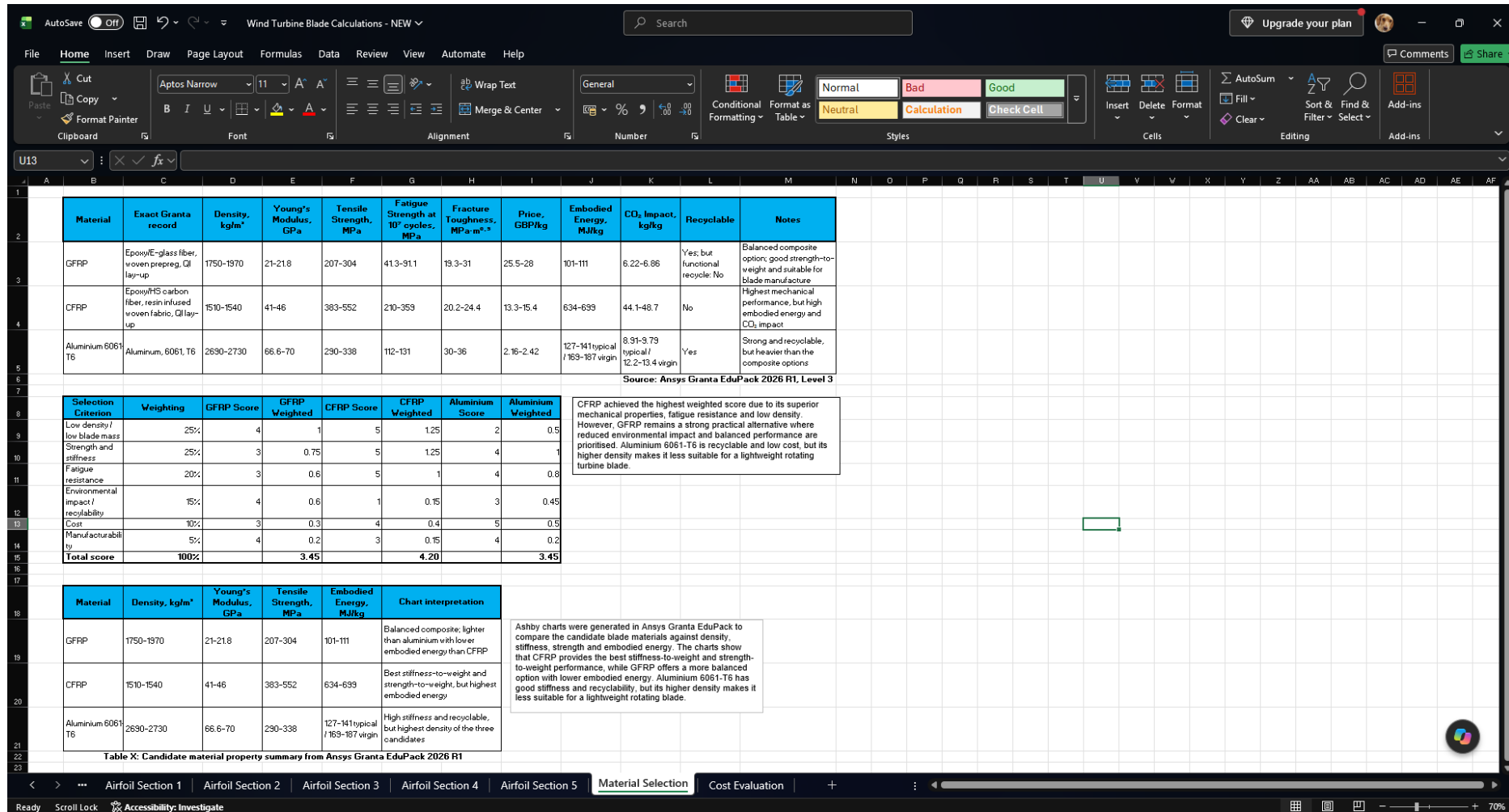


Figure 20: Excel material selection worksheet showing Granta EduPack material data and weighted decision matrix.

Appendix D – SolidWorks CAD Model and Engineering Drawing

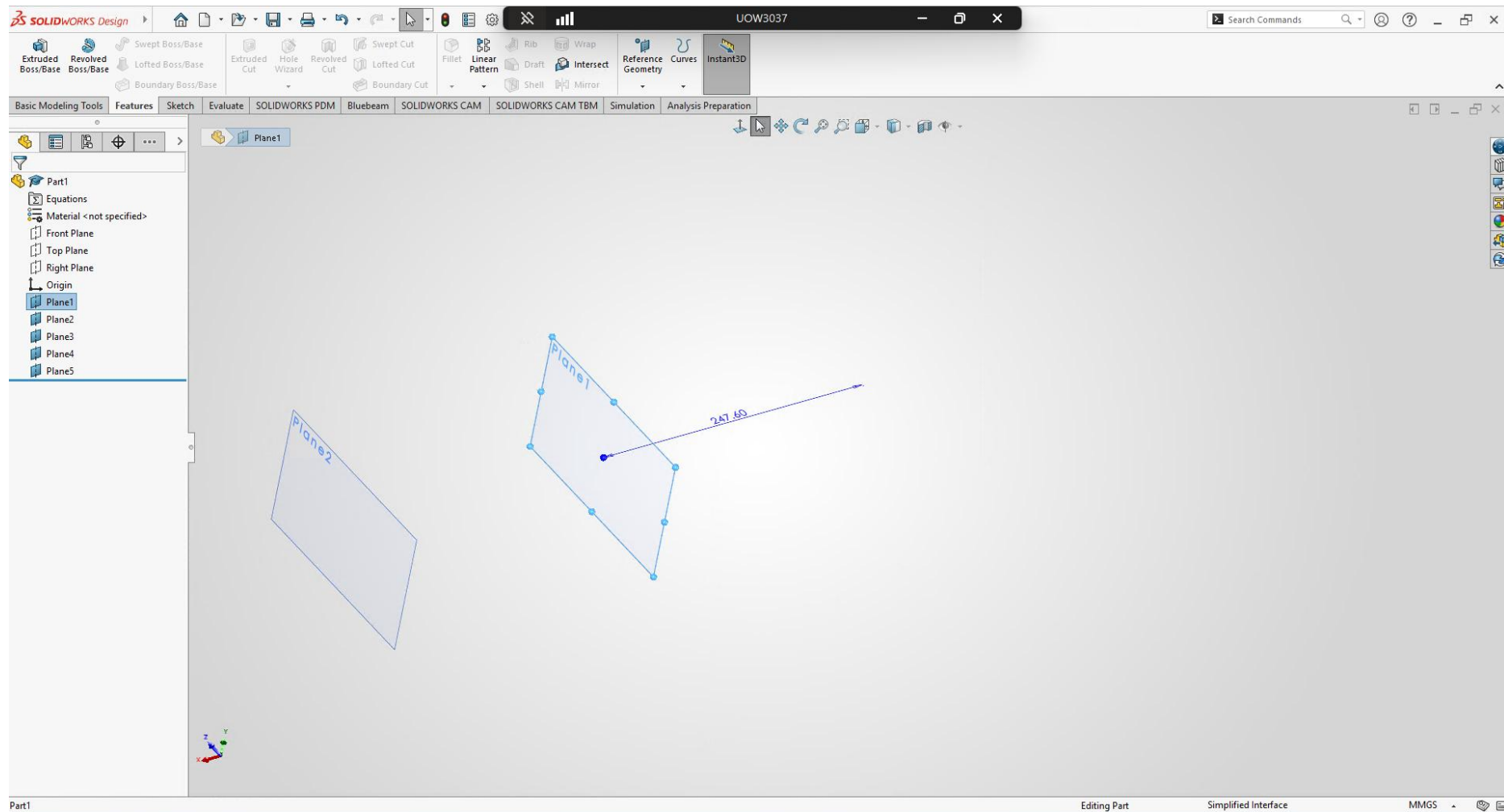


Figure 21: SolidWorks measurement of Plane 1 at 247.6 mm from the rotor centre.

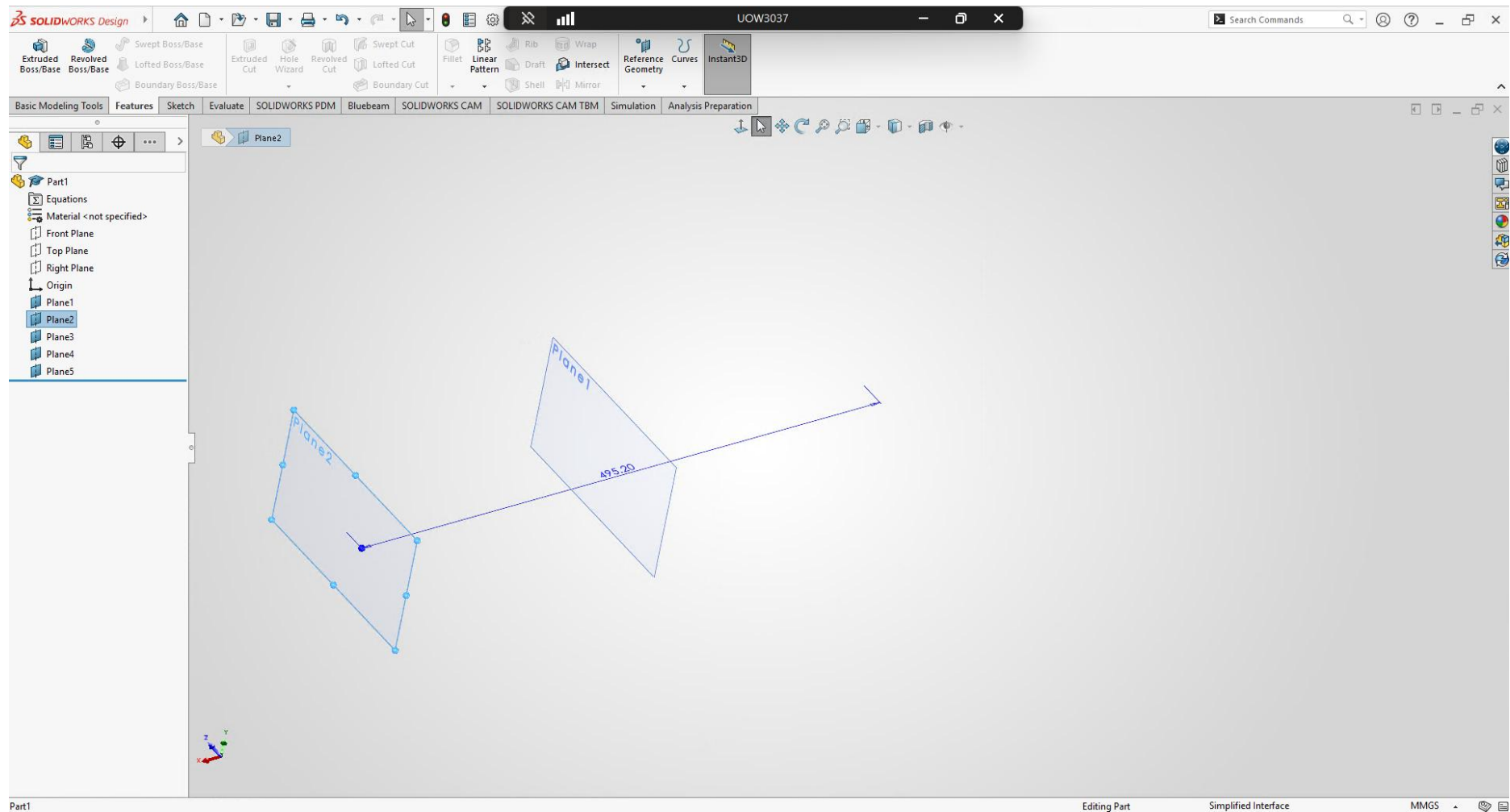


Figure 22: SolidWorks measurement of Plane 2 at 495.2 mm from the rotor centre.

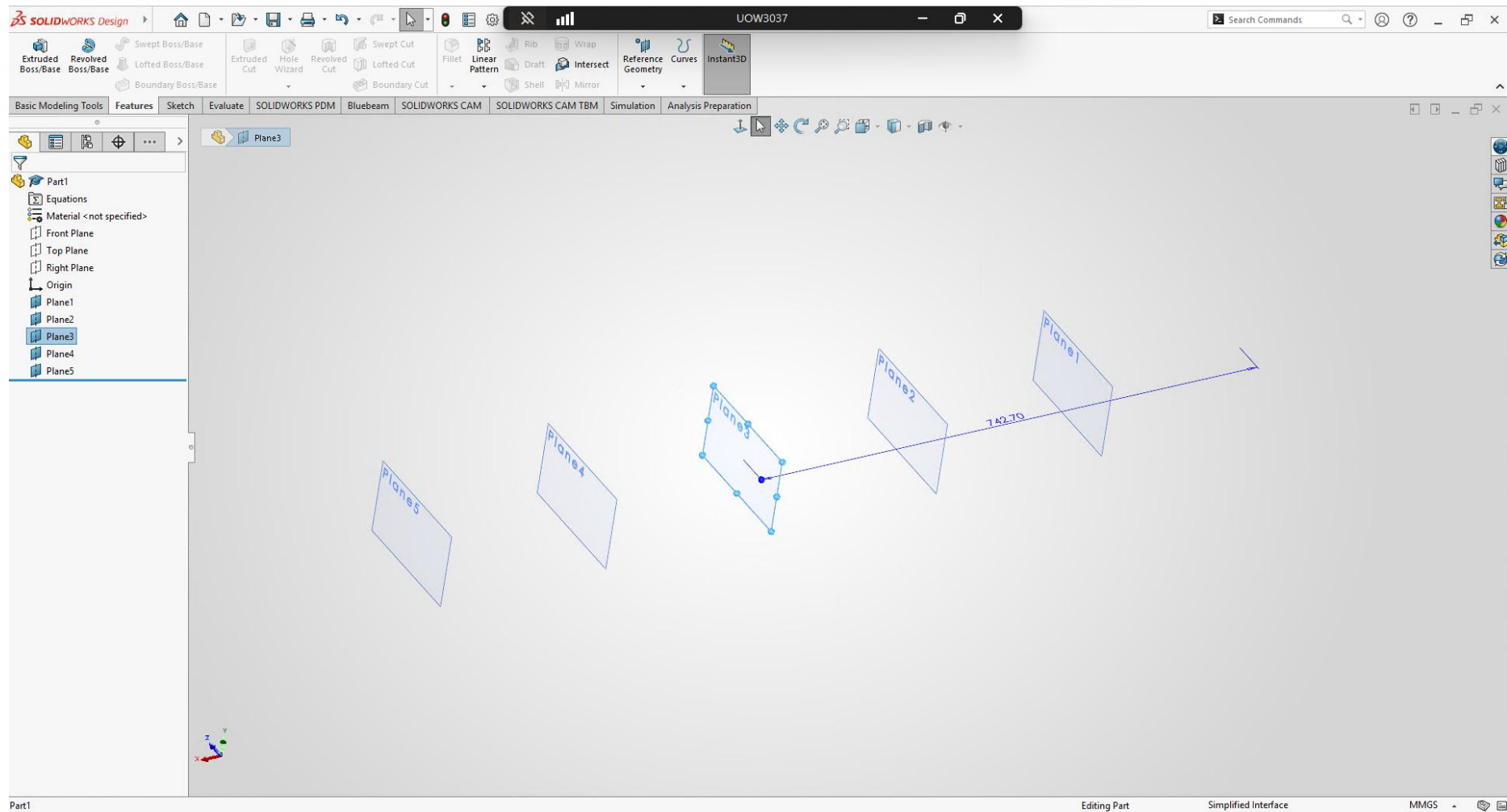


Figure 23: SolidWorks measurement of Plane 3 at 742.7 mm from the rotor centre.

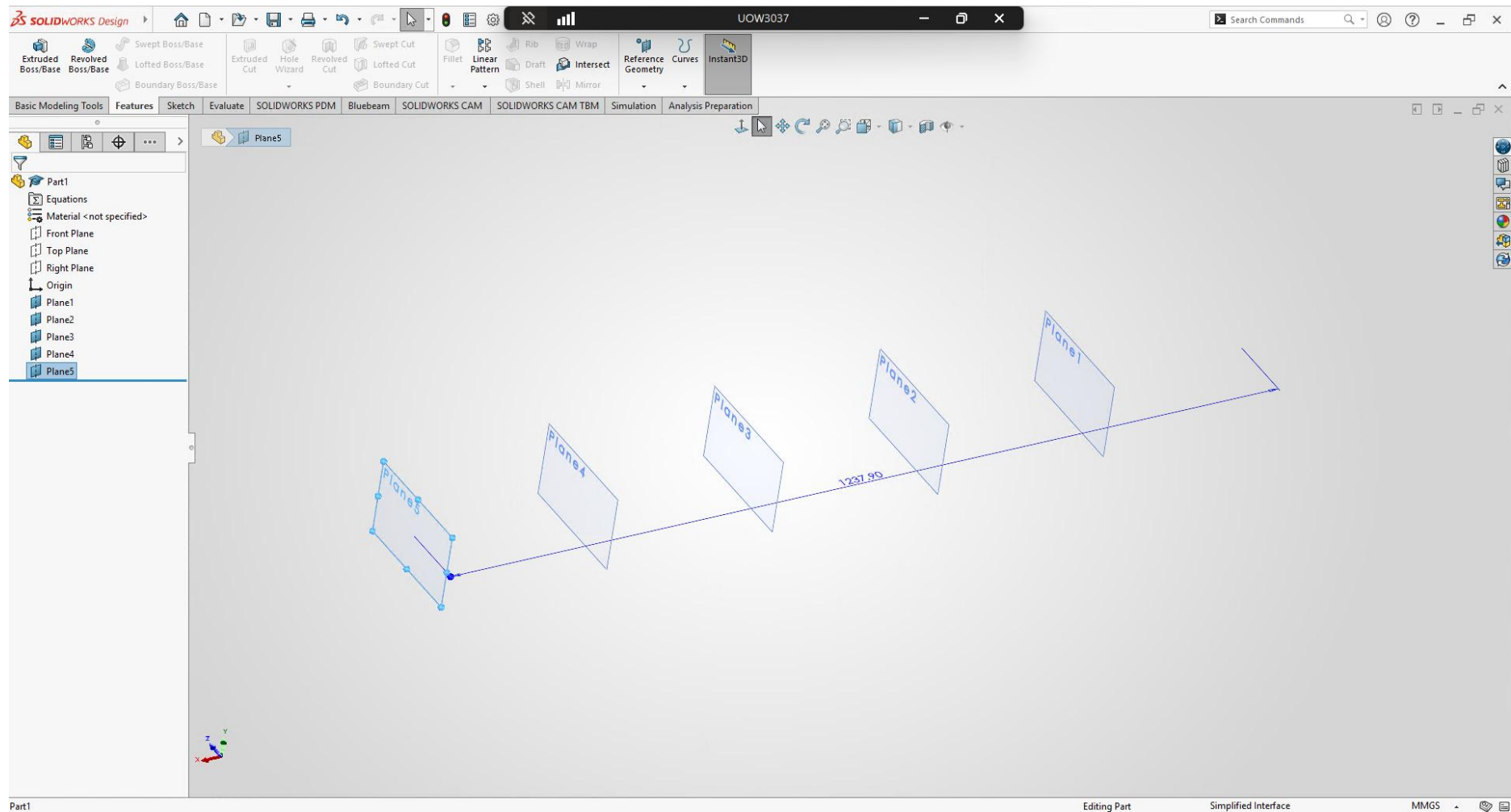


Figure 24: SolidWorks measurement of Plane 4 at 990.3 mm from the rotor centre.

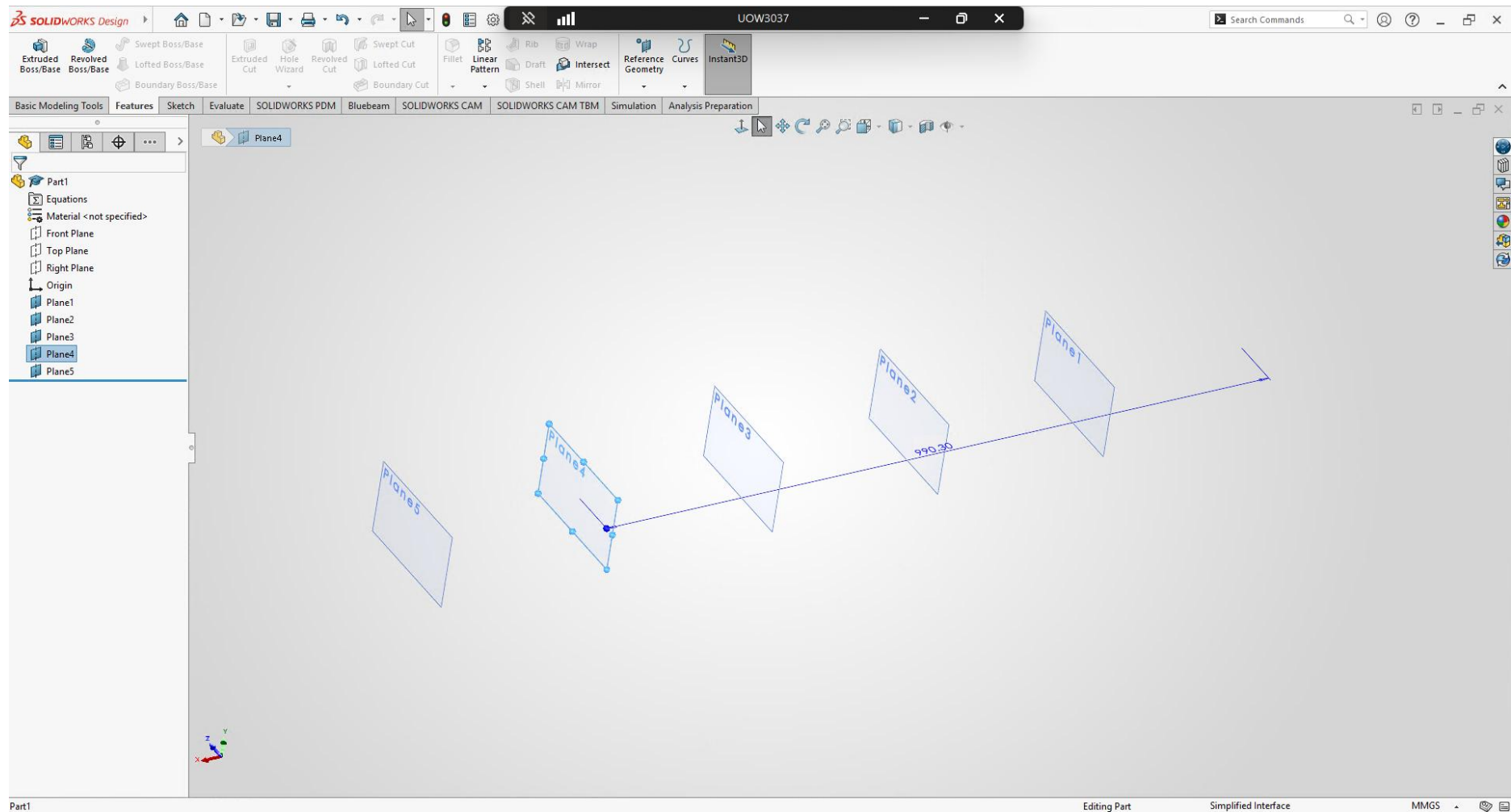


Figure 25: SolidWorks measurement of Plane 5 at 1237.9 mm from the rotor centre.

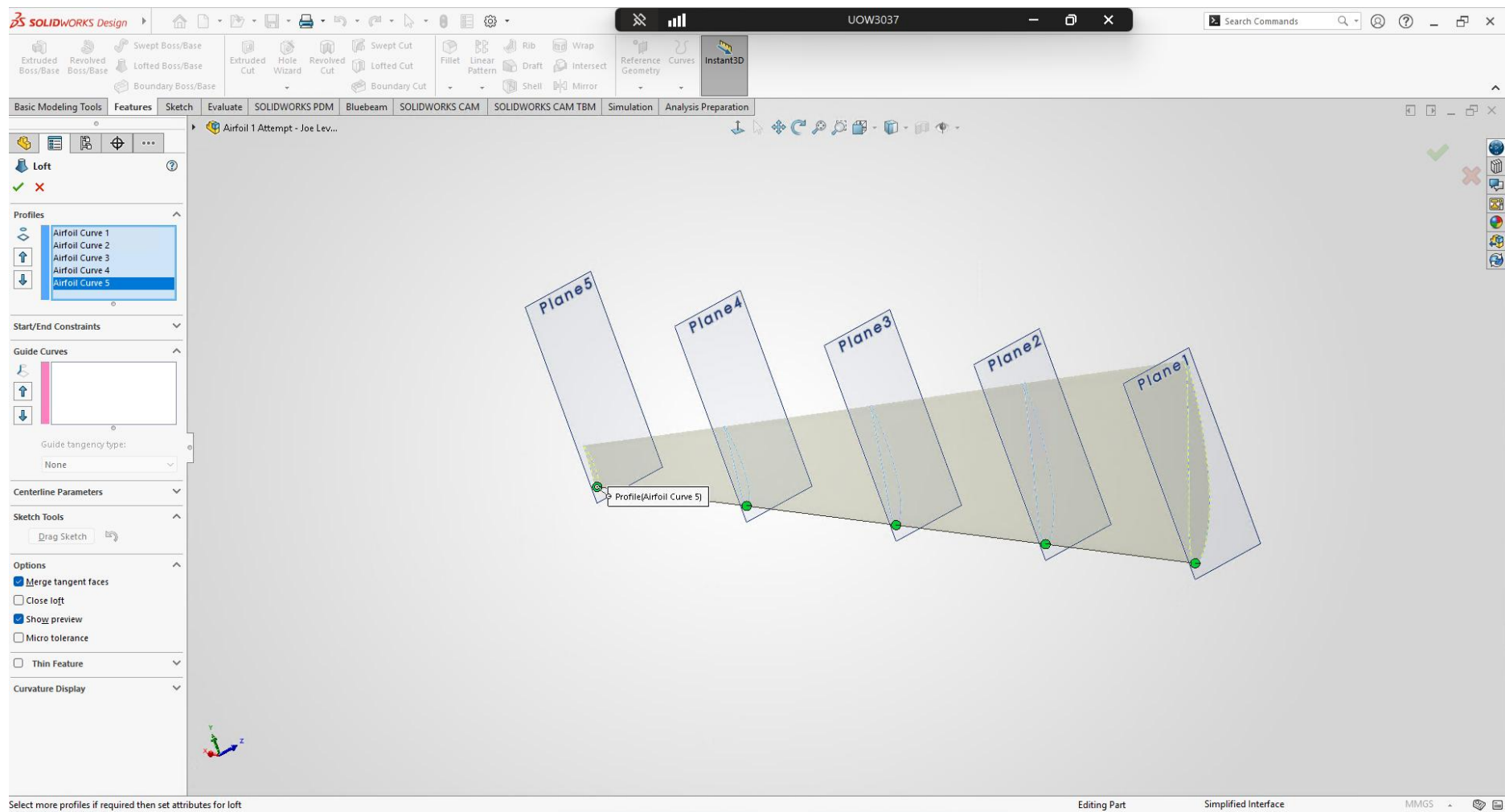


Figure 26: SolidWorks loft setup showing the five imported NACA 4412 airfoil curves selected as blade profiles.

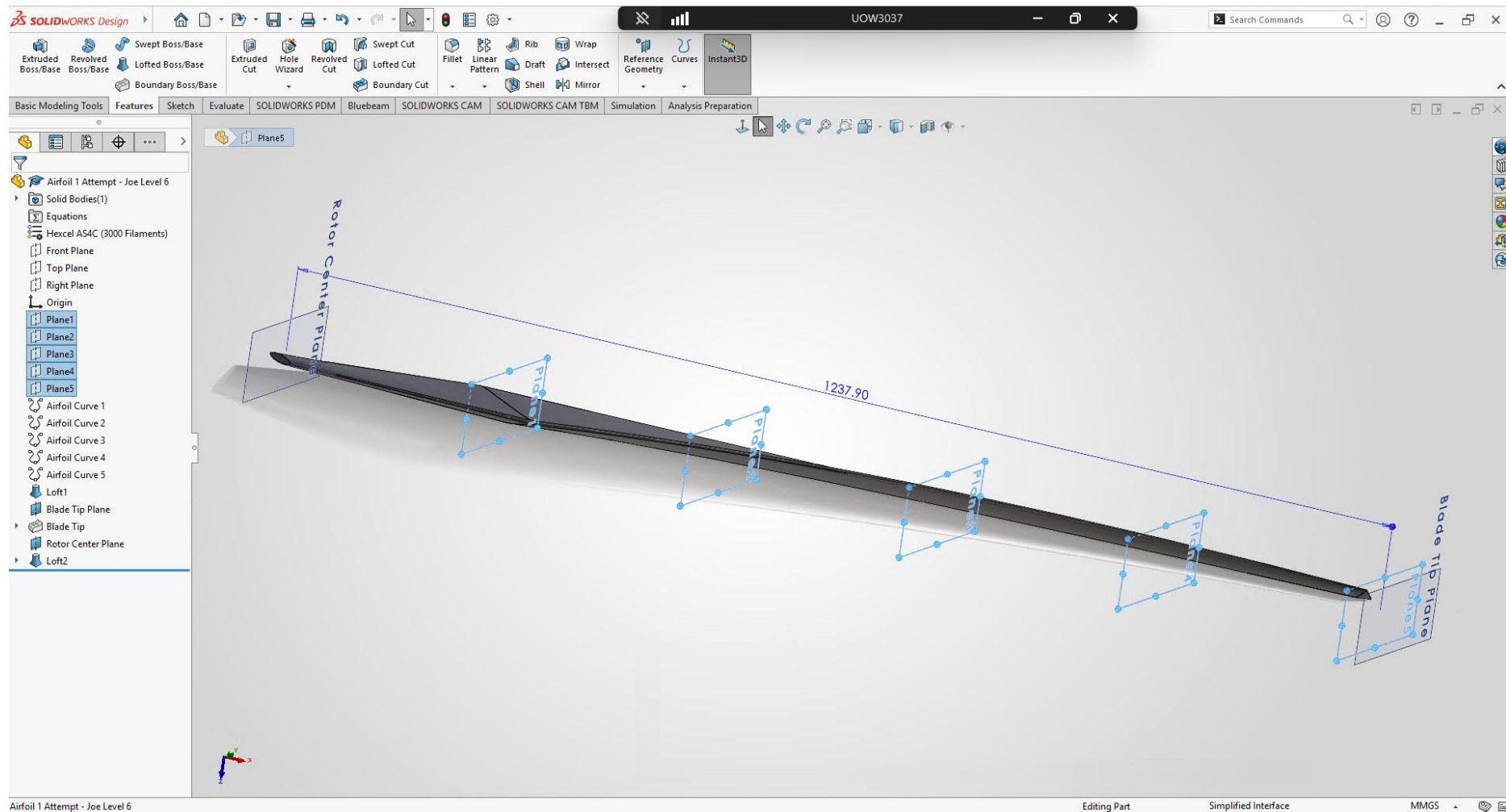


Figure 27: SolidWorks blade model showing the five reference planes, rotor centre plane, blade tip plane and overall design radius of 1237.90 mm.

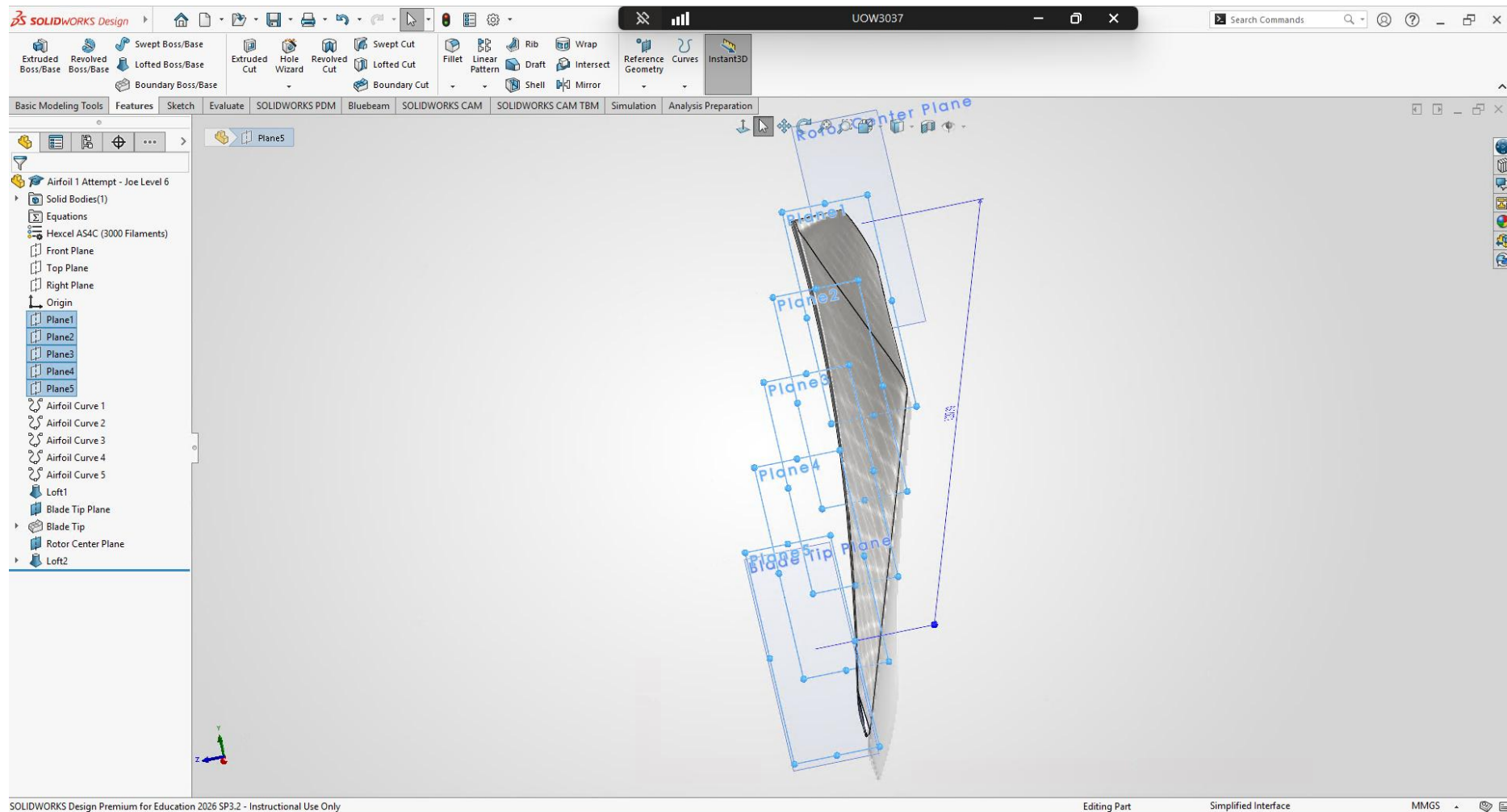


Figure 28: SolidWorks blade model showing spanwise twist and section orientation across the five reference planes.

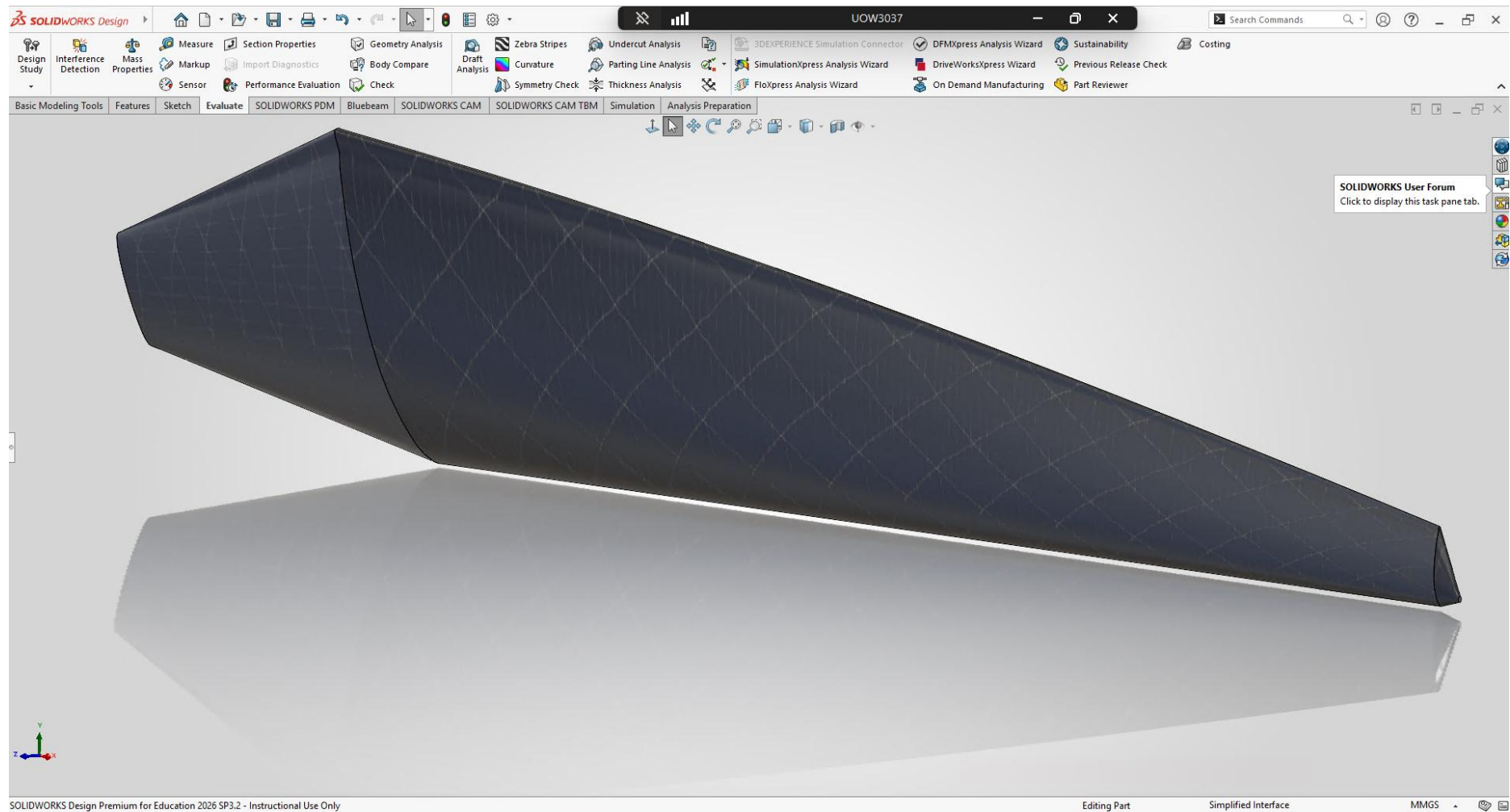


Figure 29: Final SolidWorks CFRP blade model showing tapered geometry, root transition and closed blade tip.

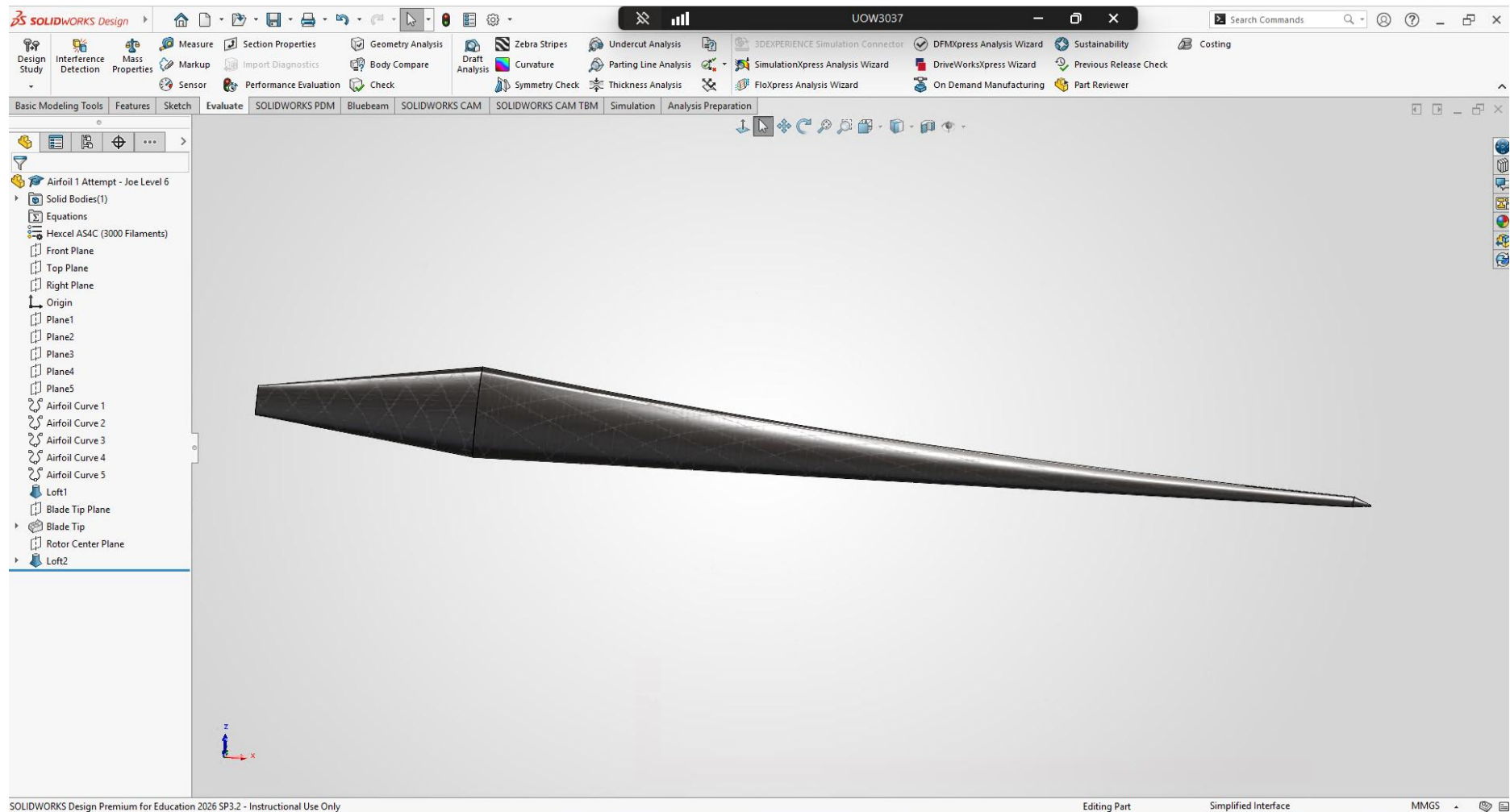


Figure 30: Final SolidWorks CFRP blade model showing tapered geometry, spanwise twist, root transition and closed blade tip.

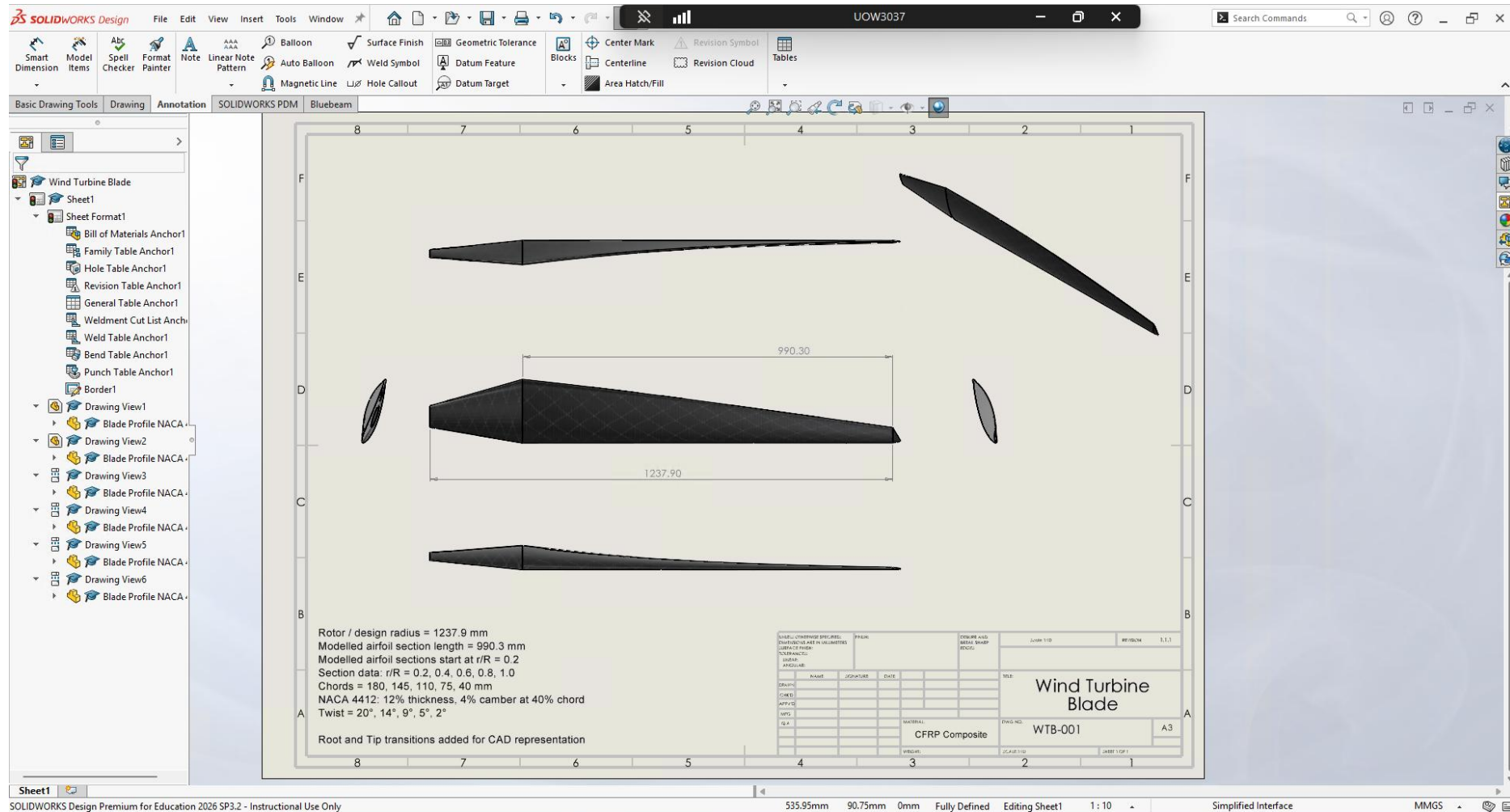


Figure 31: SolidWorks engineering drawing showing final blade views, design radius, modelled airfoil section length, chord taper and section data.

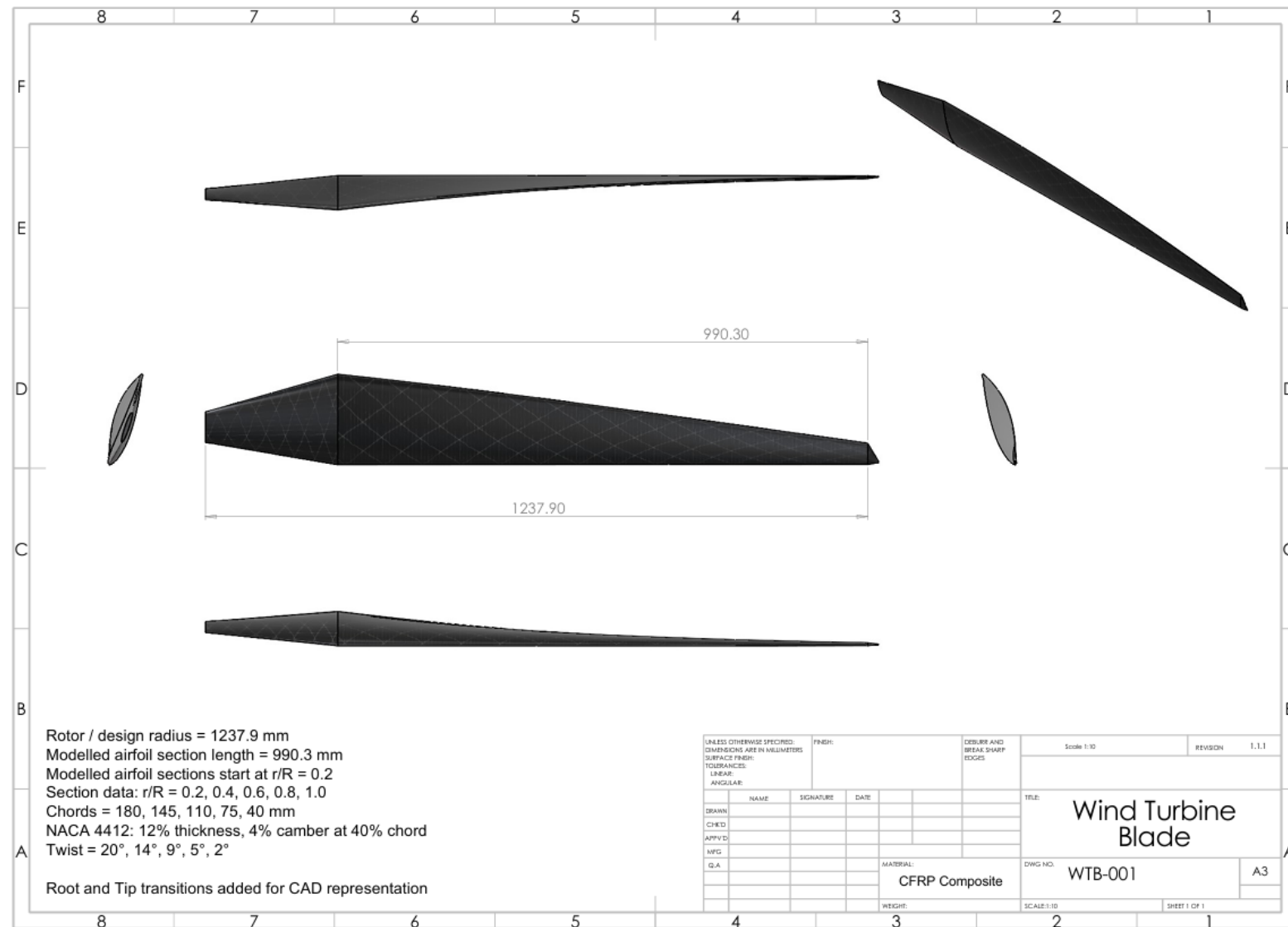


Figure 32: SolidWorks engineering drawing showing final blade views, design radius, modelled airfoil section length, chord taper, twist distribution and section data.

Appendix E – Cost Evaluation Spreadsheet

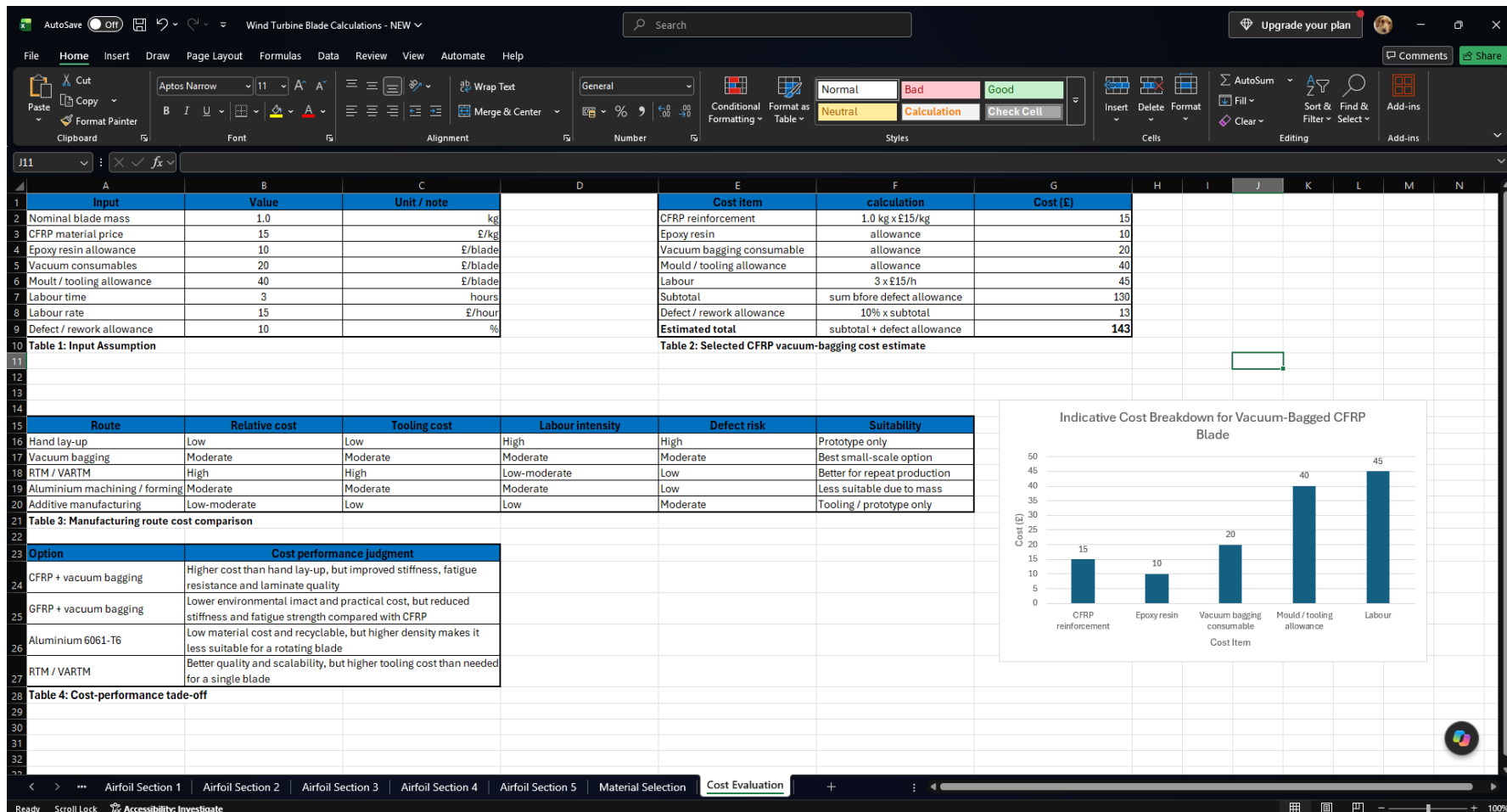


Figure 33: Excel cost evaluation worksheet showing input assumptions, vacuum-bagged CFRP blade cost estimate, manufacturing cost comparison, cost-performance trade-off and cost breakdown chart.

Appendix F – Simplified Structural Bending Load Check

	A	B	C	D	E	F	G	H
	Section	Radius position, r (m)	Lift force, L (N)	Moment contribution, L x r (N-m)				
1								
2	Section 1	0.2476	8.467	2.0964				
3	Section 2	0.4952	6.821	3.3778				
4	Section 3	0.7427	5.174	3.8427				
5	Section 4	0.9903	3.528	3.4938				
6	Section 5	1.2379	1.882	2.3297				
7	Total			15.1404				
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								

The simplified bending load check estimated a blade-root bending moment of 15.14 N-m using the calculated lift force at each radial section. This does not include dynamic loading, gust effects, centrifugal loading, laminate lay-up direction or full deformation analysis; therefore, finite element analysis would be required before manufacture.

Figure 34: Excel simplified bending load check using calculated blade section lift forces.