The Evolution of Blade Manufacturing

Brian Glenn
Director, Rotor Blades
Clipper Windpower Technology, Inc.
TOPICS

• BLADE SIZE
• THE INDUSTRY
• DESIGN EVOLUTION
  – Materials
  – Processes
• COST
• FUTURE STUDIES
BLADE SIZE OVER TIME

- 50+ meter
- 34 meter
- 23 meter
- 20 meter
- 12 meter
- 9 meter
- 7.5 meter
- 5 meter

BLADE SIZE OVER TIME – cont’d

- Product life cycle is 3 to 6 years
- New development time is 1 to 2 years
- Tenfold size increase over 25 years (5 meter to 50 meter)
- The industry is maturing (i.e. aviation)
- Original blade length is now the maximum chord length of large blades
- Production methodology must evolve to accommodate large blades
50.5 Meter Blade
MYTH.....

Blade manufacturing is a GREAT business ! !

“Show me the Blade Millionaires”
<table>
<thead>
<tr>
<th>Industry</th>
<th>Casualties</th>
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</thead>
<tbody>
<tr>
<td>Alternegy</td>
<td>Rotorline</td>
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<tr>
<td>AeroDynamics</td>
<td>Polymarin</td>
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<tr>
<td>Kenetech</td>
<td>Stork</td>
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<tr>
<td>Bouma</td>
<td>Aerpac</td>
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<tr>
<td>AeroConstruct</td>
<td>WEG</td>
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<td>Gougeon Brothers</td>
<td>Howden</td>
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<tr>
<td>Century Design</td>
<td>Storm Master</td>
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<tr>
<td>Blue Max</td>
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<td>AWT</td>
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<td>Carter</td>
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<td>ATV</td>
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<td>Wind Master</td>
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</table>
Companies With Off-the-shelf Product

- LM
- NOI
Sub-Contract Manufacturers
(Will Build Your Blade)

MFG      TPI      TECSIS
A&R      ATV      LM
NOI

INDUSTRY - cont’d
INDUSTRY – cont’d

Wind Turbine Companies
(Manufacturing Their Own Blades)

Bonus
Vestas

Enercon
Nordex

GE Wind
Gamesa

Micon
Suzlon
DESIGN EVOLUTION – cont’d

• In the beginning, the turbine was designed around an “off the shelf” blade:
  – 90% of blades were out-sourced
  – Built in Western Europe and the U.S.

• Today, turbines are specifically designed...driven by loads, site conditions, control strategies, and COE targets:
  – 50% of blades are out-sourced
  – Built in Western Europe and U.S....and Brazil, India, & China

• In the future:
  – Majority of blades will be designed in-house
  – Built in low-cost countries
New Materials?

- Steel late 70s
- Aluminum late 70s
- Wood Epoxy late 70s
- Polyester E-Glass late 70s
- Epoxy E-Glass late 70s
- Epoxy Kevlar early 80s
- Epoxy S-Glass early 80s
- Epoxy Carbon early 80s
### Change in Cost over Time: 1984 – 2004 (Approximate)

<table>
<thead>
<tr>
<th>Material</th>
<th>Change</th>
<th>Cost</th>
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</thead>
<tbody>
<tr>
<td>E-Glass (Roving)</td>
<td>- 15%</td>
<td>$0.60 / lb</td>
</tr>
<tr>
<td>E-Glass (Stitched)</td>
<td>- 20%</td>
<td>$1.00 / lb</td>
</tr>
<tr>
<td>Carbon (Roving)</td>
<td>- 40%</td>
<td>$5.00 / lb</td>
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<tr>
<td>Polyester Resin</td>
<td>+20%</td>
<td>$0.80 / lb</td>
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<tr>
<td>Epoxy Resin</td>
<td>- 20%</td>
<td>$1.25 / lb</td>
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</tbody>
</table>
New Processes?

- Filament Winding: late 70s
- Wet Lay-up Vacuum Bagged: late 70s
- Wet Lay-up: late 70s
- Pultrusion: late 70s
- Pre-saturated Rovings: late 70s
- RTM: late 80s
- Pre-pregs: late 80s
- Infusion: mid 90s
Filament Winding
Dry Lay-up before infusion
Infusion (in process)
• Industry ramp up ramp down cycles favor automated lower labor hour processes
• Fiber waviness is a major driver
• Changing to Roving vs. Stitched UD saves 2.6% of blade cost; the same as a 20% labor reduction in a LCC
• Fiber sizings – binders need more study to enhance infusion
MYTH…..

BLADES ARE EXPENSIVE ! ! !
Blade Cost Per Pound

- Europe/US Polyester
- Kenetech Vinyl Ester
- US Epoxy In-house
- Europe Market Price
- Low Cost Country
- Nacelle Cost
Blade Cost Per kW

- 1978: $140
- 1983: $130
- 1988: $120
- 1993: $110
- 1998: $100
- 2003: $90

$US
BLADE WEIGHT (lbs) Per kW

- Stall Regulated
- Sub MW
- Multi MW
Cost Distribution Ex Works

US Built

- Direct Labor: 30%
- Materials: 50%
- Profit: 9%
- Overhead: 11%

Low Cost Country (LCC) 18% Less

- Direct Labor: 13%
- Materials: 66%
- Profit: 6%
- Overhead: 15%
Typical Cost Differences

- US Cost Distribution
- Low Cost Country

- Transportation
- Overhead
- Profit
- Direct
- Materials
COST – cont’d

• Overhead today is about the same in US vs. LCC
  – Opportunity for reduction in LCCs

• Labor cost reduction is limited
  – Advantageous to the US / Western Europe Model

• Material costs are at a very low level
  – Local supply helps LCC model
  – Risk of increase
  – Change from a stitched product to rovings; achieves large savings

• Transportation cost adder is the “wild card”

• Best opportunity for cost reduction is a longer uninterrupted product life cycle (steady state)
Aero
- Higher thickness to chord airfoils
- Design for load reduction; interact with loads group, structures, and control strategy

Process
- More consistent automated processes
- Better understanding of volume impact vs. plant size to blade cost.

Load Mitigation
- Feedback loops – control strategy – fiber brag – tower
- Predictive algorithm
- Smart blades – either structure or Aero