Automation Advancements in Wind Turbine Blade Production: A Review

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Abstract Wind turbine blade production involves intricate processes that require skilled labour, reliability and time. The automation of blade production processes in context with wind turbines aids to decreased cycle times and enhanced accuracy in the finished components. Automating the lay-up or material deposition process solely does not offer significant cost reductions, with rest of the processes remaining labour intensive. It is thus advantageous to establish a complete automated process chain for wind turbine blade production. This article enlists numerous automation methodologies which can be found suitable for a sequence of processes. The primary objective of this study lies in recognizing the advancements and the potential for automation in various operations associated with blade production. Besides helping to analyze the overall impact, this review shall assist researchers in realizing the challenging aspects of such self-driven processes as well.

Keywords Wind turbine · Blade production · Automation · Lay-up · Material deposition

1 Introduction

Harnessing energy from renewable resources has gained an increased attention over the recent decades. In specific terms, wind energy being one among the cleanest and environment friendly resources, the wind power sector has witnessed a rapid growth lately. With the requirement to tap more energy, the blades of wind turbines are being made larger and more efficient. On a standard basis, a utility scale wind turbine blade is found to have a length of 50 meters approximately, while there are blades measuring even beyond 70 meters in length [1]. With technological advancements, the efficiencies of harnessing energy from wind can be increased from 8% to even 50% [2].

The prime focus of blade manufacturers have been in cutting costs and cycle times for production of blade components, with no compromise to their performance and quality [3]. The urge to meet the foregoing needs is accomplished by automating a wide range of processes which are indulged in blade production. For instance, the fabric lay-up process for the Vacuum Assisted Resin Transfer Moulding (VARTM) is highly tedious and can be conveniently replaced by automating this manual process [1]. Similarly, continuous direct textile layup showcases an improved potential for cost reductions in comparison with currently used manual production processes [4]. It is worthwhile to note that automation techniques curb the proneness of workers to various health hazards during grinding or even finishing processes such as surface coating and painting [5]. Moreover, such techniques ensure improved quality control and reduce dimensional uncertainty, thereby leading to lower scrap rates during blade component production [6].

The generalized process chain for wind turbine blade production commences with the supply of raw materials, followed by handling processes that transfer the fed material in its unusable state. Material handling techniques further involve cutting, pick-up, positioning and lay-up, draping and fixation of material. Successively, primary manufacturing process such as vacuum infusion, prepreg or filament winding technology follows. This is accompanied by bonding and finishing techniques, which involve applying adhesives to blade halves and surface coating to mitigate the impact of natural factors respectively. The present paper is aimed to review the plausible methodologies of automation in blade production processes listed above. In addition, the article gives adequate focus to recognize the economic viability and draws attention to the challenges faced by the automation techniques.

2 Automation Processes in Blade Production

There are a wide number of techniques for automation, suitable for adoption in wind turbine blade production. In order to extract more energy from wind, blade profile plays a key role. Hence, its accuracy must be well assured [7], [8]. The methods for automation may broadly be categorized into processes accompanying supply along with handling of raw materials, primary manufacturing, assembly and finishing of blade components. These are reviewed in detail in the subsequent sections.

2.1 Supply and Handling of Materials

With advancements in materials, the technologies for supplying and handling raw materials to produce wind turbine blade components have drastically evolved. Polyurethane based materials are being incorporated for the sheets and preforms in order to produce blades with optimal strength to weight ratio [9]. A variety of flexible automated methods have been developed to adapt to such materials and their properties. The initial processes of feeding and cutting of fabric are in general, carried out using conveyors, automatic cutting tables carrying straight and round knife cutters [10]. A non-crimp fabric (NCF) roll with a standard width of around 1.27 meters is preferable for the automated process [11].

Fantoni et al. [12] put forward solutions for self-driven handling of materials by portraying different gripping devices. Based on the study, Bernoulli gripper is found to be relatively convenient as it operates based on airflow between the gripper and part, and is a contactless handling technique. Reinhart et al. [13] also conducted a study on flexible gripping methods and developed a technology which uses low vacuum suction principle with actuators for closing apertures on the perforated plate. Being suitable for limp materials, this technology is seen to remain advantageous over existing principles and can be widely used in the wind turbine blade production industry. Additionally, the Adaptive Robot End-effector (AEE) is a specialized technique which functions on hydro adhesive principle for the pick and place process using parallelogram kinematics and cryo grippers [14].

The prevailing methods of automating the lay-up process for blades include Automated Fibre Placement (AFP), Automated Tape Lay-up (ATL) and filament winding technologies. The intent of the lay-up process is to allow the fabric to take the shape of the blade mould through deforming and deposition, once picked and placed. The deposition rates for filament winding and ATL are reported to go up to 13 kg/hr and 90 kg/hr for complex parts respectively [1]. Specifically, ATL process is found convenient with a range of tool operations and may require just a quarter of the man hours needed. This has been verified for aerospace blade applications and may thus hold suitable for wind turbine blades [15]. It has been determined that a combination of ATL and AFP offers the added advantage of aiding in fibre orientations for the blade spar [6]. Sherwood et al. [16] and Siqi Zhu [1] described an automated lay-up concept of shifting which involves pre-forming the fabric based on mould shape and then depositing the fabric on to it. The study emphasized on the ability to manipulate NCF without causing any out of plane deformations.

It has been stated that automation of composite lay-up process requires sensing mechanism for gathering initial information, intelligent decision making capacity and efficient material handling system which can effectively perform operations [17]. Franke et al. [4] highlighted a continuous direct textile lay-up technique, named Automated Dry Material Placement (ADMP). It is determined to deposit textiles of 100 mm to 2000 mm width and 0.25 mm to 2.5 mm thick. Having proven to be effective in automating the production of aerospace parts, the technique finds analogous application in producing parts of wind turbine blades. Another suitable technique involved using Large Area Robot (LAR) to automate the lay-up for spar cap of wind turbine blade by using integrated positioning sensors. Line lasers may be equipped to monitor the position of the laid-up fabric [18].

The draping operation must ensure accurate fixing of NCF deposited on the blade mould. Automated draping avoids the risks associated with manual draping techniques in terms of time constraints and health hazards due to the fabrics being pre-impregnated with toxic epoxy resins. Potter [19] considered automating the draping process through vacuum forming technology, which later proved to be impractical for large parts due to economic reasons. In an effort to automate the process, the Institute of Integrated Product Development (IPD) developed a module comprising a draping head and vacuum grippers for gentle handling of NCF. The module is capable of reshaping and draping the fabric appropriately [20].

As draping is to be performed right after fabric deposition on to the mould, incorporating draping elements in the effector is recommended. Forster et al. [21] introduced a pixel- based draping and gripping unit which contain sensors for monitoring and controlling draping. The Danobat group incorporated a draping head to offer the required pressure surge against mould surface during the draping operation. To further enhance the adaptability of draping head to the complex mould contour, Direct Textile Placement (DTP) effector, a subproject of BladeMaker, was developed with a design that can vary the applied pressure to a certain limit [4].

Automation in fixation involves robotized spraying of hot melt adhesives and use of effectors for gel like adhesives. Fixation of NCF is much needed to prevent the material from slipping after it has been deposited using adhesives. The Institute for Integrated Product

Development (BIK) implemented a reproducible spray of adhesive using a gun coupled with the gantry robot system [4].

2.2 Manufacturing

Post et al. [22] conducted a study on the implementation of additive manufacturing in the wind energy sector and considered the Big Area Additive Manufacturing (BAAM) system (Fig. 1), developed by Cincinnati Incorporated. The system contains an extruder which is traversed by a gantry system and enables the extruder to move in all three axes, delivering 45 kg/hr of thermoplastic materials. This gantry system can achieve 5 m/s peak velocities and 1.64 m/s^2 accelerations with position accuracy of 0.05 mm. Moreover, Ingersoll Machine Tool Company is developing the Wide High Additive Manufacturing (WHAM) system (Fig. 2) with the ability to machine, print and coat. It is expected to start with a production rate at around 450 kg/hr and can be scaled higher. Implementing Internet of Things (IoT) in additive manufacturing will be a major contribution towards reduction of scrap during blade production, thus increasing the overall efficiency of the process chain.

Fig. 1 Big Area Additive Manufacturing (BAAM) [22]

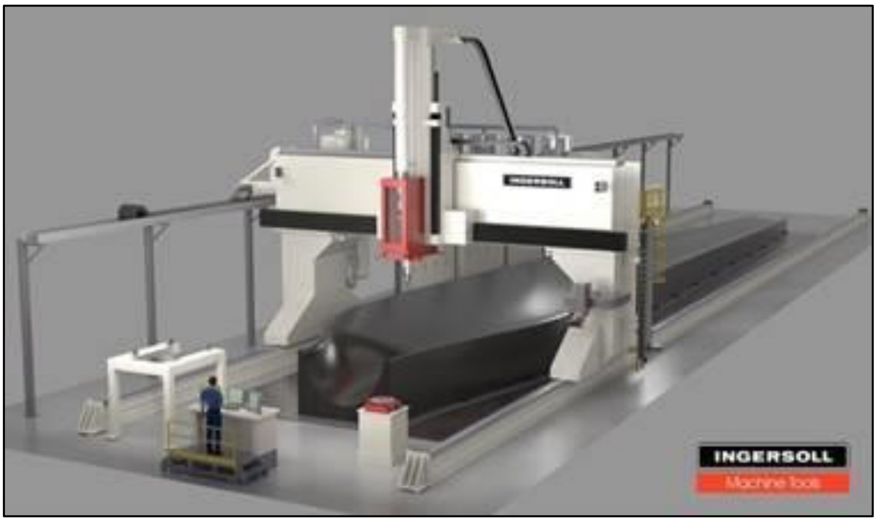

Fig. 2 Wide High Additive Manufacturing (WHAM) [22]

Dayton A. G. [23] presented a study dealing with the combination of automated preforming technologies and infusion processes which would avoid human intervention reduce cycle time and also prevent distortion of fibres. Oriented sprayed fiber preforms are considered suitable for the automated preform manufacturing for large wind turbines. The study covered various techniques of automated preform manufacturing for wind turbine blade structures and compared them using Analytic Hierarchy Process (AHP).

Richard Stewart [24] studied the applicability of Rapid Material Placement System (RMPS) (Fig. 3), a CNC controlled system containing multiple axes end effectors fitted onto a gantry. The system is capable of assisting the blade manufacturing process and can even perform operations like spraying and addition of adhesives on to the blade halves. It is reported that a dual gantry system, positioned next to each other takes only 2 hours to produce a 45 meter blade shell.

Another automation equipment, the Reaction Injection Moulding (RIM) machine is used to manufacture polyurethane wind turbine blades that lie in close proximity with wind power plants. The machine injects isocyanate and its reactive components into the mould. After compression and curing by radiation, the polyurethane blade is producible. Similarly, the Long Fibre Injection (LFI) machine injects both isocyanate, its reactive components along with long fibres which then compresses and cures, producing the polyurethane blade [25]. These machines curb difficulties associated with transportation of large blades as the entire process is performed in close proximity with the wind power plant.

Fig. 3 Rapid Material Placement System (RMPS) [24]

2.3 Assembly

For movements between assembly stations, the use of Automated Guided Vehicles (AGV) is advisable. AGV makes use of tracks for movement, allowing them to traverse along the whole location using signals detected by sensors embedded on them [5]. Kruger et al. [26] has very well described the man-machine cooperation in assembly lines. Various robotic assembly systems could prove to ease the transportation of blade components from one station to another. Moreover, integration of advanced machinery to form systems capable to carry out multiple operations leads to decreased number of assembly stations, avoiding balance delays.

Roberts et al. [27] patented a concept of joining blade components through improved methods which consumes lesser adhesives. The study suggested a method of printing and depositing 3D grid structures at the first joint area of the blade using CNC machine. This is followed by blade add-on components being placed onto the rotor blade; an adhesive is provided partially to fill the grid which secures the components to the blade. These grid structures are known to offer buckling resistance, assisting to reinforce the joint areas of the blade. The printed grid structures have tight gaps; hence, the usage of adhesives for bonding is limited in comparison with conventional blades. The latter makes use of excess bonding due to intricate profiles near joint areas, making the usage of printed grid structures preferable.

Mironov [28] solved the problem of limited accessibility of longitudinal movement of robots over the blade mould to spray gelcoat, place dry fibreglass and apply bonding adhesives to the blade halves prior to joining them. It suggested engaging a gantry over the moulds provided with a robot which can slide longitudinally over the blade halves using servo drive motors. After the application of adhesives, the halves are joined using turnover hinge devices which rotate one half over the fixed mould half with no hindrance to the gantry track. Interlocking the removable bridge sections and gantries is facilitated through a Programmable Logic Controller (PLC).

2.4 Finishing

The blade components produced through automated techniques are to be precisely finished. These may involve sanding, painting, surface coating, etc. The factors influencing finishing process and its associated costs are mainly the size of finished component and amount of finishing work to be performed [29]. Blade finishing which impact quality and productivity rates involves risks of manual tool and heavy machinery handling as well as exposure to hazardous blade materials such as GFRP and Epoxy resins. This poses a detrimental impact on the health of workers. Automating surface treatment and finishing of blades make various tedious operations relatively simple to be implemented. Moreover, it improves the quality of finish as robots are able to travel across entire blade length in a continuous manner, improving the blade quality in terms of resistance to weather, corrosion and mechanical stresses [5].

Liebherr Automation Systems carried out automated blade trimming and fibre layout techniques on a blade length of 60 meters. They implemented robotized polishing of blade surfaces, enabling large time and cost savings [30]. The complex blade contours make programming a robot difficult for trimming and sanding operations. EINA of Spain, managed to tackle the concern through a system capable of tracking changing contours and placing the sand tool normal to the blade surface at all times [31].

Tebulo Robotics, a Dutch firm, developed an Automatic Mobile Robot (AMR), capable of a 360^{o} rotation to follow and coat blade contours precisely by making use of the Externally Guided Motion (EGM) technology. The advanced technology imparts the capability to guide complex blade contours effortlessly with least programming needed for the robotic system. Besides, the AMR is suitable to be deployed for surface cleaning, precision polishing as well as non-destructive blade inspections. It is estimated to coat a 100 meter blade in 90 minutes [32]. The patented AccuFind technology developed by Dynamic Robotic Solutions (DRS) locates and processes the root end of blade and provides a self-driven solution for excess blade material to be identified and subsequently ground and sanded [33].

Table 1 summarizes various principles and techniques of automating different processes which are involved in the production of wind turbine blades. Further details regarding practices of various such advanced blade production technologies may be referred to using the tabular summary.

Table 1 Automation methods for various blade production processes

Process	Operation	Automation Method	Reference
Supply & Handling	Feeding & cutting	Conveyor	Vilumsone [10]
		Automatic cutting table	Vilumsone [10]
	Pick-up	Bernoulli gripper	Fantoni et al. [12]
		Low vacuum suction principle	Reinhart et al. [13]
		AEE	Kordi et al. [14]
	Position & lay-up	AFP	Siqi Zhu [1]
		ATL	Siqi Zhu [1]
		Filament winding	Siqi Zhu [1]
		Shifting	Sherwood et al. [16]
			Siqi Zhu [1]
		ADMP	Franke et al. [4]
		LAR	Franke et al. [4]
			Rolbiecki et al. [18]
	Draping	Vacuum forming technology	Potter K [19]
		DTP effector	Franke et al. [4]
	Fixation	Robotized sprayer	Franke et al. [4]
Manufacturing	Deposition,	BAAM	Post et al. [22]
	Infusion,	WHAM	Post et al. [22]
	Machining	RMPS	Richard Stewart [24]
Assembly	Transportation	AGV	Sainz JA [5]
	Bonding	3D printed grid structures	Roberts et al. [27]
		Gantry with robotized sprayer	Mironov G [28]
Finishing	Sanding	AccuFind technology	Abrams et al. [33]
	Painting & coating	AMR	Tebulo Robotics [32]

3 Economic Analysis

The primary objective of automating wind turbine blade manufacturing is to diminish the expenses of harnessing energy by reducing labour costs, production time, increasing reproducibility and volume of production. The predominant factors of analyzing the economic viability of blade production include cost of tooling, maintenance and labour, which are relatively high at low manufacturing levels [6]. Chen et al. [34] stated that the most efficient way to decrease the operation and maintenance cost of blade production is to find out the blade defects by reducing the cost of inspection and by automating the entire sequence of processes. Benjamin A. W. [35] developed a winding system which is automated. The system is capable of winding NCF plies around a mandrel at a low cost without affecting the quality when compared to other processes.

Murray et al. [36] presented a study owing the major contribution of production costs to materials and direct labour. The study depicted that 11.4% of material costs are from scrap materials. Based on these findings, incorporating an automated process chain in blade manufacturing may be considered to be a dominating step towards cost reduction by avoiding material wastage and ensuring tighter dimensional tolerances whilst manufacturing.

Schubel P. J. [6] adopted a Technical Cost Modelling (TCM) approach to contrast production costs of a 40 meter wind turbine blade shell set and spar using different manufacturing techniques. The comparison included six processes, namely hand lay-up prepreg, Vacuum Infusion (VI), Light Resin Transfer Moulding (LRTM), ATL, AFP and overlay braiding (Fig. 4 and Fig. 5). On comparing the automated fibre deposition strategies, i.e., ATL, AFP and braiding, it is found that braiding adds tremendous expenses and time due to its failure to put filaments along the length. It depicts a 21% expense surge over the manual techniques. In contrary, ATL and AFP appear to decrease fabricating costs by around 8%. ATL shows a decrement in expenses up to 4% over hand lay-up prepreg, being monetarily effective beyond production of 750 PPA. AFP is considered to have an added advantage of being more adaptable in comparison with ATL, making this technique more feasible.

Through automated preform techniques, blade manufacturers undergo reduced handwork costs, improved control over fibre orientation along with significant degree of consistency, helping to produce complex blade geometries with low misuse of crude materials, and reduced time for production [23].

Franke et al. [4] studied the reduction of manufacturing and labour costs in the lay-up process of the BladeMaker project. Gantry robots coupled with effectors incorporated within the automation system carried out the process of continuous direct material deposition. An investigation in context with the BladeMaker concluded cost savings of 17.3 % to 23.1 % by utilizing the automation arrangements and systems.

The literatures reviewed emphasize that the economic perks of automation technologies for wind turbine blade production are numerous. However, these tend to be largely reliant on the blade production volumes and the extent up to which the plant is automated. Expense reduction via partial automation of blade production may likely be compensated by a range of labour costs for rest of the processes.

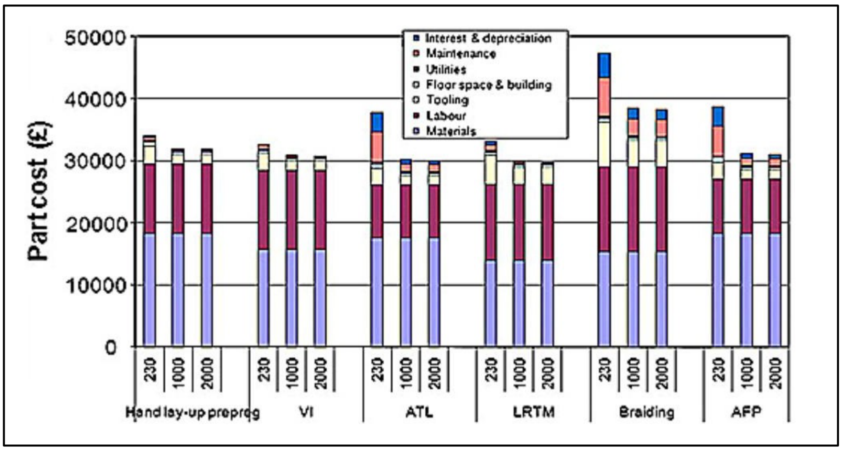

Fig. 4 Comparison of part costs for blade shell production via different processes [6]

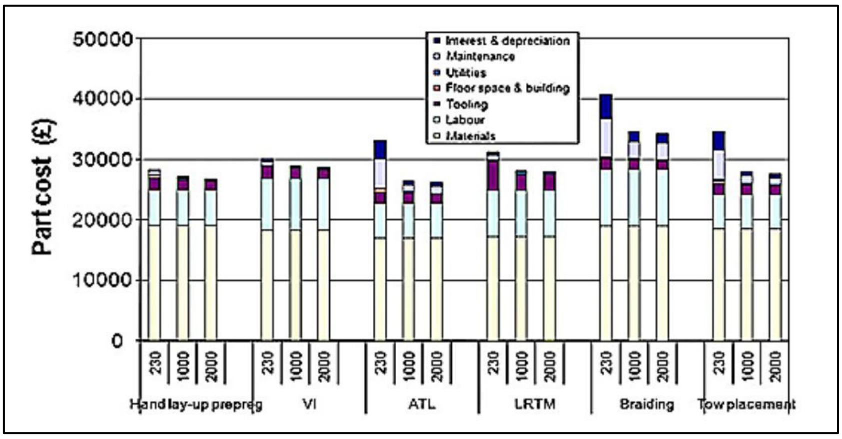

Fig. 5 Comparison of part costs for blade spar production via different processes [6]

4 Challenges

A key challenge faced during the automated feeding and cutting processes lies in establishing speeds of unwounded material roll and conveyor belt at par [37]. Manual processes are still being carried out handling and draping of dry fibers to manufacture prepreg, making it time consuming [38]. Manufacturing of wind turbine blades consists of geometric and time constraints, due to which automation techniques like AFP and filament winding principles become cumbersome to be carried out [1]. For instance, the curved profile of blade mould requires a handling unit with smaller width material roll for the automated layup process which would lead to an increased production time [4]. ATL and AFP face complexities to manufacture small parts like ribs, spars and blade corners [39]. Detection of small parts and contour details becomes inconvenient because of small course lengths [40].

With competencies to harness more energy from wind, the loads on wind turbines have been rising with the blade sizes [41]. The blades are to be designed light in weight, precisely manufactured to possess adequate strength and sustain heavy loads [1]. There is still scope for further research in developing concepts to restrain the extreme load conditions which the blades are subjected to, along with improvising the energy production [42]. Besides, there lie concerns in the transportation of bulky finished blade components. Peeters et al. [43] discussed the concept of segmented production of turbine blades, which not only offers convenience to 3D printing of blade components, but also eases transportation of large blades. However, this technique does face difficulties in resisting high loads. Furthermore, self-monitoring of wind turbine blades becomes difficult under such unfavourable conditions [44].

Recent advancements attributed toward Future Emerging Technologies (FET) appear superior over the need to automate blade production. FET such as Airborne Wind Energy (AWE) and offshore floating wind concepts are likely to be developed and put to practical use in the near future [45]. On account of reduced loads of these tethered systems, their operation could be relatively convenient with reduced capital expenses. It must be taken into account that difficulties associated with a weighted analysis and modelling between the convenience and costs of automation impede blade manufacturers from transforming into a completely automated process chain for blade component production.

5 Conclusion

A review on the automation advancements in blade production for wind turbines has been performed, highlighting the scope for technology-driven production plants in the wind power sector. This article enlists various automation techniques in a sequential process wise approach of producing wind turbine blades based on the survey of literature available.

As wind turbine blades continue to increase in their sizes, there is a need to develop advanced production techniques to boost production rates. There are countless automation techniques which suffice the demands of enhancing the efficacy of blade production. Different automated handling and manufacturing techniques discussed throughout the paper appear to ease the production process. Systems such as BAAM, WHAM and RMPS machines are developed to perform multiple operations such as assisting primary manufacturing along with machining and coating within itself. This could help cut down production time, with the number of stations being reduced. However, the hesitancy of blade manufacturers in adapting to a complete automated process chain is mainly attributed to an unconvincing comparison between beneficial and non-beneficial impacts of automation.

Though future emerging technologies are expected to replace tower based wind turbines over the coming years, adequate attention must be diverted to simplify the production of wind turbine blades through automation.

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