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## Article

# A Cost Model for 3D Woven Preforms

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**Abstract:** Lack of cost information is a barrier to acceptance of 3D woven preforms as reinforcements for composite materials, compared with 2D preforms. A parametric, resource-based technical cost model (TCM) was developed for 3D woven preforms based on a novel relationship equating manufacturing time and 3D preform complexity. Manufacturing time, and therefore cost, was found to scale with complexity for seventeen bespoke manufactured 3D preforms. Two sub-models were derived for a Weavebird loom and a Jacquard loom. For each loom, there was a strong correlation between preform complexity and manufacturing time. For a large, highly complex preform, the Jacquard loom is more efficient, so preform cost will be much lower than for the Weavebird. Provided production is continuous, learning, either by human agency or an autonomous loom control algorithm, can reduce preform cost for one or both looms to a commercially acceptable level. The TCM cost model framework could incorporate appropriate learning curves with digital twin/multi-variate analysis so that cost per preform of bespoke 3D woven fabrics for customised products with low production rates may be predicted with greater accuracy. A more accurate model could highlight resources such as tooling, labour and material for targeted cost reduction.

**Keywords:** 3D woven fabrics; preform; complexity; cost model; learning; Weavebird; Jacquard

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## 1. Introduction

3D woven composites have promising growth prospects in a wide range of markets [1,2]. They possess superior mechanical properties in some respects compared with conventional 2D preforms, for example a composite made from a non-crimp 0, 90 2D reinforcing fabric of interlacing orthogonal sets of warp and weft tows, with the warp tows at 0degrees running along the length of the weaving loom and the weft tows at 90degrees to the warp tows [3]. However, acceptance of 3D woven composites has been difficult in sectors such as aerospace which increasingly demand lower-cost materials with mechanical performance at least the same or greater than for 2D laminates. Table 1 compares a 0, 90 2D non-crimp fabric composite and a 3D woven composite.

At high production rates, for most manufacturing operations, material cost dominates other resources such as tooling, capital and labour, while tooling and labour costs dominate for bespoke manufacturing [4,5]. Dry 3D preforms are highly complex materials. There are two types of 3D woven preform: multi-axial and interlock. Interlock preforms are multi-layered fabrics produced by interlacing three sets of fibre tows in a specialised weaving machine. A general definition of a 3D warp interlock fabric was proposed to better describe the position of the various yarns located inside the 3D woven structure [6].

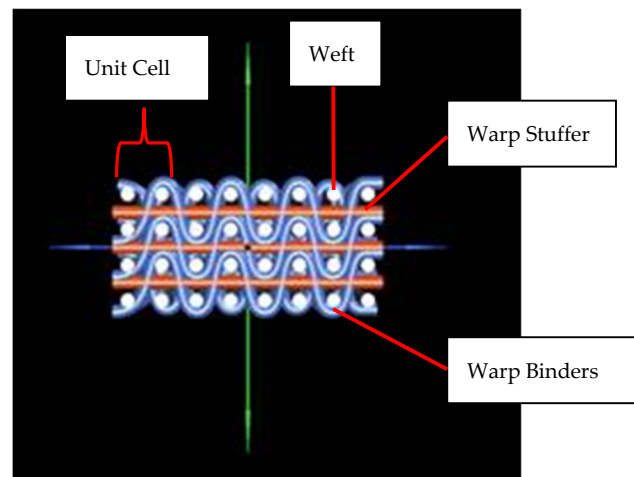
**Table 1.** Comparison of 2D and 3D woven composites.

	2D Woven Composite	3D Woven Composite
Fabric Manufacture	Conventional loom for weaving a fabric with interlacing tows in X and Y directions	Specialist loom for weaving a fabric with interlacing tows in X, Y and Z directions.
Fabric Structure	Warp tows run along the length of the weaving loom or X direction and weft tows run in the cross direction of the loom, or Y direction.	Warp, weft and binder tows run in X, Y and Z directions.
Properties	Higher in-plane-specific stiffness and strength. Lower delamination resistance. Lower out-of-plane stiffness and strength.	Lower in-plane-specific stiffness and strength. Higher delamination resistance due to z-binder. Higher out-of-plane stiffness and strength.

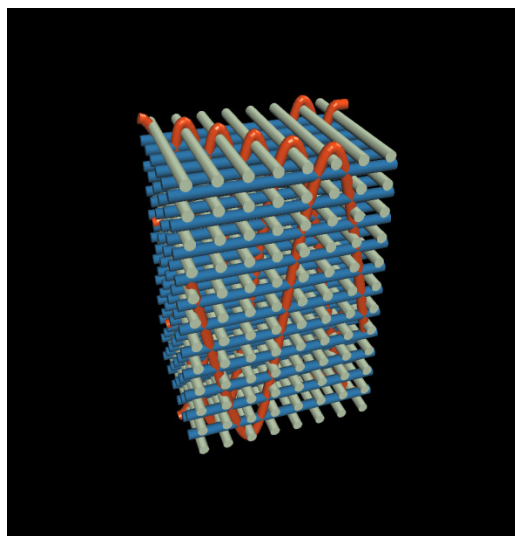
Alternate layers of warp and weft are placed in cross-layers at 0 degrees and 90 degrees, respectively, in the plane of multi-layered weave. The warp and weft layers are interlocked/interlaced by a third set of tows called binder tows. The binder tows are also called warp weavers because interlocking is generally achieved through warp tows [5,7]. Interlock preforms can be categorised as follows:

- a. Angle-interlock orthogonal composites: through-the-thickness interlock weave.
- b. Layer-to-layer interlock or multi-layer weave found in both orthogonal interlock and angle interlock weaves.

Examples of angle interlock layer-to-layer and orthogonal interlock architectures are shown in Figures 1 and 2.



**Figure 1.** Layer-to-layer weave architecture.



**Figure 2.** Orthogonal weave architecture.

Due to the inherent complexity of the preform manufacturing process, 3D woven textiles can be expensive [8]. Therefore, knowledge of fabric manufacturing cost is essential for devising strategies to reduce cost and enable successful competition with long-established 2D materials. However, while 3D preform commercial cost models are alluded to [9,10], they are not normally available in the public domain.

The aim of this study was to develop a model to estimate the cost of a hypothetical 3D preform. Data were derived from 17 bespoke 3D preforms manufactured on Weavebird and Jacquard weaving looms. A resource-based modelling approach [11] was developed that took account of the bespoke production of each preform. The model was based on the principles that cost is determined by resources such as material, tooling, labour and general overheads [4], and that manufacturing time, and therefore cost, increases with part complexity [12–14]. Data for resource inputs such as materials, equipment, labour and energy are approximate values for commercial sensitivity reasons. Technical cost modelling (TCM) was added as a further refinement in the form of a sub-model detailing how weaving equipment, labour and energy costs scale with part features such as part shape and complexity.

Manufacturing cost is not simply the addition of cost elements. How they interact with each other is a function of learning, which can be either by human agency (for example, the combination of textile designer and production operative) or an autonomous machine control algorithm. The study included a description of how preform manufacturing cost can be reduced once a certain level of learning is attained. For future work, research into digital twin and/or multi-variate analysis for enhanced learning is proposed as a strategy for reducing the manufacture cost of bespoke preforms made singly or in small batches.

Two cost models were developed, one for a Weavebird loom (centre closed dobby shedding mechanism) and another for a Jacquard loom (mechanised production of patterned textiles). In both cases, there was a high correlation, measured by correlation coefficient  $r^2$ , between manufacturing time and preform complexity for preforms woven on each loom. Constants derived from time–preform complexity curves for both looms were input to the model to estimate and compare the cost of a large bespoke 3D preform to be woven on both looms. Weave tooling and labour accounted for approximately 80% of preform cost for the bespoke preform. The Jacquard loom is more automated and hence much more cost effective for large preforms compared to the Weavebird. Learning through experience will significantly reduce manufacturing weave time and cost per preform.

### 1.1. Literature Review

There are a wide variety of cost models for composite parts by market sector. Huber [11] proposed three categories for cost modelling of aerospace composites: analogous, parametric, and bottom-up cost estimation. Two possible cost estimation scenarios exist:

- Some historic cost data/experience exists for a top-down cost estimation.
- Design and process knowledge for a bottom-up, detailed cost calculation.

Essentially, all models are either one of these scenarios or a combination of them. This generalisation applies equally to cost models in other sectors such as automotive, marine and construction. The proprietary nature of fundamental data and equations leave most developed models unusable for third parties.

#### 1.1.1. Manufacturing Cost Models

Esawi [4] provided a comprehensive summary of manufacturing cost model approaches. The required output of a model will depend on the context. In competitive bidding, the model must deliver a precise, absolute cost as an error of a few percent can make the difference between profit and loss. When predicting the approximate part cost where historical data aren't readily available, for example in the early stages of design, a cost accurate to within a factor of two is acceptable

Function-costing or parametric methods extrapolate the cost of a part that is a variant of an existing family for which historic cost data already exist. In this case, two conditions must be met. The part must be a member of a closely related family. Secondly, the family must have many members with established historical cost data. Similar empirical or cost scaling methods can be used for part costing which are based on correlations using historical data for estimating the manufacturing cost of a part with given features. The cost of a new part having certain features made by a given process can be estimated by analysing cost correlations between previous parts with these features against their size, shape and complexity and then locating the new part in this cost field. Activity-based costing methods calculate and sum the cost of each unit operation involved in the manufacture of a part. However, a large amount of pre-existing input data are required.

Resource-based modelling accounts for materials, energy, equipment and infrastructure capital, time, and information resources required for part manufacture. The method is approximate as values for these inputs are often unknown. TCM is a further refinement of resource modelling and includes sub-models for how equipment, tooling cost, and production rate scale with part features such as part mass, size and complexity. Costs can be approximate and are isolated, giving TCM flexibility, scalability and adaptability. As more data become available, detail can be added to the model to improve predictive power [4].

For TCM calculations based on established data and discussions with experts, Esawi [4] assumed a complexity factor varying from 1 (minimum complexity) to 5 (maximum complexity), with a value of 2 assumed for an average complexity factor in calculations of tooling cost, capital cost and production rate for injection moulding, extrusion and casting operations. For these operations, tooling cost, capital cost and production rate scale with part mass and complexity. Tooling and capital vary non-linearly, with exponents for mass and complexity varying between 0 and 1, implying an economy of scale with increasing part mass and complexity. Production rate decreases with increase in mass and complexity, so values of exponents for mass and complexity are negative for injection moulding, extrusion, and casting operations.

Hagnell and Akermo [15] describe a TCM for a generic aeronautical wing in which costs scale with part features for a given production method. An integrated top-down and bottom-up approach was employed, depending on available cost data. For a generic aeronautical wing, hand layup is normally the most cost-effective method of those studied for annual volumes of less than 150 structures per year. For higher production volumes, automatic tape layup (ATL) followed by hot drape forming (HDF) are the most cost-effective

choices. For all production methods, cost per part fell as production rates increased until material cost dominated at a minimum production rate.

Gutowski et al. [16] derived a series of cost equations incorporating variables and constants to estimate composite part manufacturing costs for an aircraft structure. The estimated results fit well with the Advanced Composite Cost Estimating Manual (AC-CEM) model [11]. However, the system does not account for quality inspection processes. Verrey et al. [17] studied two resin transfer moulding (RTM) processes for automotive body-in-white (BIW) structures. An epoxy system was compared with a novel reactive polyamide 12 (PA12) via characterisation of reaction kinetics and the production of carbon thermoplastic (TP) fibre floor pan quadrant demonstrators incorporating typical geometrical features. Parametric TCM tools were used to compare the two RTM variants for full floor-pan production at volumes of 12,500–60,000 parts per year. TCM offered flexibility together with easy manipulation of processing and economic factors for sensitivity studies. A 22% increase in cost occurred for the standard TP-RTM cycle versus the epoxy system. In-mould cycle time was dominated by thermal cycling of the tool which was required to reduce component temperature below  $T_g$  before demoulding the thermoplastic part. A study of alternative strategies showed that a reduction in non-crimp fabric scrap gave major cost savings. Cost per part reduced with increase in production volume, with carbon non-crimp fibre (NCF) material cost accounting for 66% of part cost at a minimum production volume of 60,000 parts per year. At this volume, carbon fibre becomes economic at a maximum price of €10/kg compared with glass fibre and steel.

Schubel [18] employed TCM to compare the cost of making a 40m wind turbine blade by handlayup, prepreg, vacuum infusion and resin transfer moulding with automated manufacturing techniques such as automated tape laying (ATL), automated fibre placement (AFP) and overlay braiding. ATL and AFP reduced manufacturing costs by up to 8% despite the high capital costs of automated equipment. Part size, production volume, material cost and tooling cost were accounted for. Cost centres were isolated and clearly indicated the dominance of materials and labour. For the manufacture of a large wind turbine blade, material deposition in the tool is only one of a string of labour-intensive processes. A holistic automated blade manufacturing approach is required to see true labour saving benefits.

3D woven fabrics are promising materials for growing market sectors, e.g., wind turbine blades for renewable energy generation [10]. However, high cost is still a major obstacle for uptake of high-performance materials such as carbon fibre. Ennis et al. [19] assessed the commercial viability of cost-competitive carbon fibre composites specifically suited for the unique loading conditions experienced by wind turbine blades. The wind industry is cost driven while carbon fibre materials have been developed for the performance-driven aerospace industry. Carbon fibre has known benefits for reducing wind turbine blade mass due to significantly improved stiffness, strength and fatigue resistance per unit mass compared to fibreglass. Novel carbon fibre reinforcements derived from the textile industry, and characterised using a validated material cost model and mechanical testing, were studied as potentially more optimal materials for wind turbine blades.

A novel heavy tow textile carbon fibre was compared [19] with commercial carbon fibre and fibreglass materials in representative land-based and offshore reference wind turbine blade models. Some advantages of carbon fibre spar caps are observed in reduced blade mass and improved fatigue life. The heavy tow textile carbon fibre has improved cost performance over the baseline carbon fibre and performed similarly to commercial carbon fibre in wind turbine blade design at a significantly reduced cost. The novel carbon fibre was observed to outperform fibreglass when comparing material cost estimates for spar caps optimised to satisfy design constraints. The study outlined a route for broader carbon fibre usage by the wind industry to enable larger rotors that capture more energy at a lower cost. Heavy tow textile carbon fibre cost is estimated at €9.46/kg for an annual production volume of 2400 tonnes per year, reducing by 43% to €6.88/kg for an increased annual production volume of 6000 tonnes per year.

Fibre-reinforced composites play a key role in automotive applications because of their high strength to weight and stiffness to weight ratios compared with metals [20]. An integrated assessment of the durability, reliability and affordability of these materials is critical for facilitating their inclusion in new designs. A method to develop this assessment is described for fabricating sheet moulding compound (SMC) parts, together with the concept of Preform Insert Assembly for improved affordability in composite part manufacture.

A computer-aided material selection tool was developed for selecting the most suitable carbon fibre-reinforced composite configuration for aircraft structures [21]. The procedure is based on technical, economic and environmental performance objectives for a given design, in a multi-disciplinary and multi-objective optimisation scenario.

Carbon-fibre-based composite manufacturing processes have been considered for automotive body panel applications [22]. A full-scale front wing-fender component was produced using two composite manufacturing processes, a semi-impregnated (semi-preg) system and a novel directed fibre preforming-resin transfer moulding process. Both processes were compared with an existing stamped steel component for mechanical properties, weight saving and cost, using a TCM procedure. Mechanical testing demonstrated that the carbon fibre composite solutions provided 40–50% weight saving for an equivalent bending stiffness compared to steel panels and greatly improved dent resistance. For the part studied, carbon fibre semi-preg systems offered the lowest-cost process at approximately 500 parts/annum and directed fibre preforming technologies were cheaper, between 500 and 9000 parts/annum. The steel component was seen to be more cost effective at volumes above 9000 parts/annum.

A study was conducted to estimate the manufacture cost of a simple component in a number of different composite materials and by different manufacturing routes [23]. The materials and routes selected span the range of composites appropriate from general engineering to aerospace applications. A simple methodology is introduced for a comparison on the basis of cost-performance efficiency. It is demonstrated that more economic solutions may often be realised by the choice of 'expensive' carbon rather than 'cheaper' E-glass as the reinforcing fibre.

The majority of 3D woven preforms currently commercially available are formed by a 2D weaving process to build a preform with fibres oriented in three dimensions. Multiple insertion 3D differs from traditional weaving and involves 3D fabric formation with each process cycle, i.e., multi-layers at one time. The successful development and application of 3D woven composites will depend on an accurate understanding of the cost drivers in the manufacturing process. The costs associated with textile preforming are not as straightforward. A cost model was developed for multiple insertion 3D weaving [24] focusing on the effects of fabric design, fabric size (thickness and width) and fibresize (linear density) on setup cost, running production cost and conversion cost.

Despite the limited number of commercial 3D preform weave technologies, the design window for this class of materials is very broad. Even for one 3D weaving technology, and restricting fibre inputs to selected standard carbon and glass tows, design flexibility is still almost limitless. Process modelling, cost modelling, and performance modelling must all be applied to the design in terms of material, preform and performance in the final application so that development cycle times can be reduced. A concurrent engineering approach is described [25] for designing 3D woven fabrics that accounts for manufacturing and performance in addition to cost. A case study was presented to demonstrate that relatively minor design changes can result in very different performance and costs.

The cost-effective manufacture of carbon fibre-reinforced parts in high-wage economies is a major research goal for industry. An initiative is described [26] to develop a software tool for cost prediction in the early design stage to assist optimum process selection and highlight potential cost reductions.

While advanced composites can significantly reduce aircraft structural weight compared to conventional metal structures, the aerospace industry was reluctant to introduce

them to new aircraft. The US Air Force Composites Affordability Initiative [27] found that the key to affordability in composites was to reduce assembly costs through the integration and bonding of parts. A partnership between various aerospace companies, the US Air Force Research Laboratory, and the US Office of Naval Research, was created to develop the materials and technologies required to fly large integrated and bonded structures. A multi-disciplinary approach was highlighted: maturation of materials and processes, an understanding of the structural behaviour of bonded joints, and quality assurance and non-destructive testing to ensure joints remain bonded throughout an aircraft's service life. The result was that technologies for large integrated and bonded composite structures were successfully developed across the fixed and rotary wing industrial base.

A design framework for cost analysis of a wind turbine blade made of variable stiffness composite laminates was outlined [28], consisting of design optimisation, time-variant reliability analysis, structural performance analysis, and life-cycle cost evaluation phases. Design optimisation will maximise stiffness via the material properties of the fibre-reinforced composites and correct orientation of the composite plies. Different volume constraints of carbon fibre-reinforced polymer (CFRP) are imposed on composite laminates in the load-carrying component. Structural performance and service lifetime of the blade designs were estimated based on a time-variant reliability assessment, which was evaluated using an out-crossing asymptotic method. Wind speed and material properties are considered as the random parameters during the reliability assessment. Maintenance cost of the various designs was determined by combining the estimated structural performance with an analytical method. The final designs are selected according to their cost-effectiveness using different discount rates and undiscounted costs.

#### 1.1.2. Complexity, Organisational Learning

Organisational Learning is defined as a conscious attempt by organisations to improve productivity, effectiveness and innovation in complex economic and technological market conditions. Learning enables quicker and more effective responses to a complex and dynamic environment. Increasing complexity requires greater learning [29–32]. 3D woven preform manufacture is a highly complex process with numerous steps carried out in a required sequence for successful manufacture [5]. If there is a delay in completing a given step, the time required to complete the overall preform will increase thereby increasing preform cost.

Wright [33] observed that as aircraft production increased, the cost in terms of direct labour hours fell. For a new component which has not been manufactured before, the learning required and therefore the cost to make the part will initially be high. As more units are made, there is a steep drop in direct labour hours per part until the rate of decrease in direct labour hours per part becomes smaller.

Klenow [34] and Baloff [35] reviewed various studies investigating learning by doing for a single defined production process across a variety of industrial sectors that showed estimates for a learning rate of approximately 20%, which is the rate at which productivity rises with a doubling of cumulative output. Lee [36] summarised learning rates from the literature by manufacturing sector and activity. Even in one overall activity, in this case manufacturing, learning rates will vary considerably by individual sector. Yelle [37] and Argotte and Epple [38], observed that productivity rose across a variety of industries through a process of learning by doing.

A key assumption with learning in a manufacturing context is that production be continuous so that learning is reinforced and cost decreases. However, production may be discontinuous, leading to unlearning or forgetting [39]. Another assumption is the use of Wright's learning curve model [33] to estimate the cumulative number of preforms produced, based on the estimated time to make one preform and an assumed learning rate. The model yields production times equal to zero [40] after a high number of repetitions, which is impossible. Furthermore, it does not account for workers' prior experience [41], nor the influence of machinery in the learning process [42].



### 1.1.3. Jacquard and Dobby Looms

The cost model is based on the cost structure for 3D preform manufacture, which is split between loom setup and weaving (Section 3.3). In a Jacquard loom, Figure 3, harness cords extend down from a control head. Each harness cord is connected to one, two or sometimes four warp yarns which can be moved individually, allowing for weaving of much more intricate, complex and longer length 3D fabrics [43]. In the setup phase, fibre is wound onto bobbins. PTFE tubes glued to an eyeboard will prevent movement of tubing through the eyes and provides fibre tension. The bobbins with wound fibre are then mounted onto creels followed by fibre being thread through the tubing. Fabric is woven in a similar fashion to that described for a Weavebird except that each fibre is individually controlled by the Jacquard head.

The Weavebird([www.weavebird.com](http://www.weavebird.com)), Figure 4, is a doobby loom. In setup, warp yarns are taken from a beam mounted on the back of the Weavebird loom and fed through the eyeboard. The eyeboard controls the warp ends as they enter eyelets on heddles sitting on loom shafts. The eyeboard houses PTFE tubing which protects the fibre and provides tension during the weaving process. The heddles are in a sequence determined by the required architecture. The heddles sit inside shafts or frames, which can lift the warp threads up or down, one warp thread for each heddle. During weaving, each time a group of heddles is lifted, a “shed” is created. The shed is the opening between the lifted and stationary warp threads. The weft is held in a shuttle or rapier, which passes the weft through the shed to the other side. The shed then closes, and a different set of heddles will be lifted, creating a new shed, effectively completing the interlacement of warp and weft.

The warp ends are then threaded through the reed, a long, comb-like instrument that keeps the warp at the correct width and density and helps pack or beat the weft down into place. Beat up is the motion of weaving that compacts the weft/stuffer yarns with a consistent force ensuring an even density in the fabric. The woven fabric is wound on the take-up beam on the front of the loom until the warp on the back beam runs out.

Gurkan [7] notes that while doobby mechanisms work together with harnesses, there are harness cords for each warp yarn in a Jacquard loom. Therefore, the capability of Jacquard looms to make highly complex patterns is the highest among shedding mechanisms such as doobby, crank or cam. Stewart [43] observed that the main difference between a doobby and a Jacquard loom is how the warp yarns are moved up and down to form gaps or sheds through which the weft yarns are drawn by a shuttle to form the weave pattern. In the case of a doobby loom, the warp yarns can only be controlled in groups moved by harnesses attached to shafts or frames. When a harness goes up or down, all attached warp yarns move with the harness. As the loom can only hold a certain number of harnesses, this means that there is a limit on weave complexity. Dobby looms are best used for making simple geometric patterns and short fabric lengths because of harness limitations.



**Figure 3.** Jacquard loom.



Figure 4. Weavebirdloom.

## 2. Methodology and Experimental

### 2.1. Methodology

Data for this study came from 17 bespoke 3D woven preforms manufactured by a Northern Ireland-based company. A resource-based modelling approach was developed that took account of the bespoke production of each preform utilising the principles that cost is determined by resources such as material, capital, tooling, energy and labour (MCTEL), and that cost increases with part complexity. Data for MCTEL resource inputs were supplied as approximate values for commercial sensitivity reasons. TCM was added as a further refinement and included a sub-model for how weaving equipment, labour and energy costs scale with part features such as part shape and complexity.

Dedicated costing for one-off and batch manufacturing

The cost of a 3D fabric preform is the sum of certain cost resources (Equation(1)):

$$\text{Cost} = \text{Material} + \text{Tooling Cost} + \text{Labour} + \text{Overheads} \quad (1)$$

There are two possible production scenarios. In a one-off production scenario, a single bespoke part with unique features will be manufactured in a defined time followed by manufacturing another bespoke part with a different set of unique features in a different time. In batch production, a given amount of identical parts are manufactured in equal times.

#### 2.1.1. Costing Methodology for Batch Manufacturing

In batch manufacturing, cost resources for a set of identical parts are defined as follows.

Material

Material cost for one part of mass  $m$  (Equation (2)):

$$C_1 = mC_m/(1 - f) \quad (2)$$

where  $C_m$  is the cost per unit mass of material,  $m$  is mass of material, and  $f$  is the scrap rate.

Dedicated Tooling Cost

Dedicated tooling cost  $C_t$  for a production run of a part is wholly assigned to the production run of that part. For a production rate of  $n_r$  parts, this cost is written off against  $n_r$  and is  $C_t/n_r$ . Tool life  $n_t$  is the number of parts that a tooling set can make before it must be replaced. Each time tooling is replaced, there is a step up in the total cost to be spread over the whole batch. This extra cost is captured by a smoothing factor  $(1 + n_r/n_t)$  which is multiplied by the tooling cost (Equation (3)):

$$C_2 = C_t/n_r (1 + n_r/n_t) \quad (3)$$

### Capital Cost

Capital cost  $C_c$  is for equipment used to make different parts and associated infrastructure such as land and buildings. Capital cost is converted into an overhead by a capital write-off time,  $t_{wo}$ . The resulting quantity,  $C_c/t_{wo}$  is cost per unit time provided equipment and infrastructure are used continuously.  $C_c/t_{wo}$  is divided by a load factor  $L$ , the fraction of time for which the equipment is productive. The contribution of capital to cost per unit is cost per unit time divided by the production rate  $n_r$  to give cost per part (Equation (4)):

$$C_3 = 1/n_r (C_c/Lt_{wo}) \tag{4}$$

### Labour and Utilities

Overhead  $C_{oh}$  is labour, energy, R&D and administration. Dividing by production rate  $n_r$  (Equation (5)):

$$C_4 = C_{oh}/n_r \tag{5}$$

Therefore, the total manufacturing cost per part  $C_{mc}$  is the sum of  $C_1$  to  $C_4$ , or (Equation (6)):

$$C_{mc} = \frac{mC_m}{(1-f)} + \frac{C_t}{n} \left(1 + \frac{n_r}{n_t}\right) + \frac{1}{n_r} \left(\frac{C_c}{Lt_{wo}} + C_{oh}\right) \tag{6}$$

Note: Equations (1)–(6) are taken from “Materials: Engineering, Science, Processing & Design” [44].

### 2.1.2. Cost Methodology for One-Off 3D Woven Preform Manufacturing

Cost resources for a unique 3D woven preform are defined as follows.

#### Material Cost

The material cost for one 3D woven preform of mass  $m$  is  $mC_m$ , and is multiplied by  $1/(1-f)$  where  $f$  is the scrap fraction.

$$C_{material} = \frac{mC_m}{(1-f)}$$

#### Tooling Cost

Tooling or capital cost  $C_t$  is the cost of the weaving loom, creels, bobbins and associated weaving equipment. This cost is not dedicated to a given preform as the loom can weave different preforms of varying fibre architectures. Data for other capital costs such as land and buildings were not provided. Tooling cost is converted into an annual overhead by dividing by a capital write-off time,  $t_{wo}$ , (e.g., 5 years) over which it is recovered. The resulting quantity,  $C_t/t_{wo}$  is the annual cost.

$$C_{tooling} = \frac{C_t}{t_{wo}}$$

A unique preform will be manufactured in a defined time which will be different from the time required for another preform. If the annual production time is  $T$  hours and the time taken to make a preform is  $t_i$ , the proportion of the annual production time for this preform is

$$t_i/T$$

Therefore, the proportion of the annual tooling cost assigned to this preform (Equation (7)) is:

$$C_{tooling} = \frac{t_i}{T} \left(\frac{C_t}{t_{wo}}\right) \tag{7}$$

#### Labour Cost

Labour is the sum of annual salary costs of a weave manager, technician, and other staff costs:

$$C_{\text{salaries}} = \sum C_{\text{total annual salaries}}$$

The proportion of the annual labour cost assigned to this preform (Equation (8)) is:

$$C_{\text{salaries}} = \frac{t_i}{T} \sum C_{\text{total annual salaries}} \tag{8}$$

General Overhead Cost

Finally, general overhead cost is the sum of energy, building rental and administration costs (Equation (9)):

$$C_{\text{overhead}} = \sum C_{\text{general annual overhead}} \tag{9}$$

The proportion of the annual overhead cost assigned to this preform (Equation (10)) is:

$$C_{\text{overhead}} = \frac{t_i}{T} \sum C_{\text{general annual overhead}} \tag{10}$$

A smoothing factor would be included for a dedicated production run of the same preform. In this study, individual preforms were manufactured on a one-off basis so that a smoothing factor would be required to account for the replacement cost of the weave machine after several production runs for each preform. To simplify the analysis, a smoothing factor for each preform was not included as only one preform was manufactured at a time.

Therefore, the total manufacturing cost  $C_{p_i}$  for a unique preform  $p_i$  is the sum of each cost resource:

$$C_{p_i} = \frac{mC_m}{(1-f)} + \frac{t_i}{T} \frac{C_t}{Lt_{wo}} + \frac{t_i}{T} \sum C_{\text{total salaries}} + \frac{t_i}{T} \sum C_{\text{general overheads}}$$

Simplifying:

$$C_{p_i} = \frac{mC_m}{(1-f)} + \frac{t_i}{T} \left( \frac{C_t}{Lt_{wo}} + \sum C_{\text{total salaries}} + \sum C_{\text{general overhead}} \right) \tag{11}$$

2.1.3. Relationship between Manufacturing Time and Preform Complexity

Preform cost will scale with part complexity [12–14]. Time can be a surrogate for cost, so preform complexity will scale with preform manufacturing time. Therefore, for a range of preforms of increasing complexity, manufacturing time,  $t$  will increase with increasing preform complexity,  $R$ :

$$t \propto R$$

Time  $t_i$  is the manufacturing time for the simplest 3D woven preform, called the baseline preform, and complexity  $R_b$  is the baseline preform complexity. If  $t_i$  for a preform  $p_i$  is expressed relative to  $t_b$  for the simplest preform and  $R_i$  is expressed relative to  $R_b$ , then:

$$\frac{t_i}{t_b} = m \left( \frac{R_i}{R_b} \right)^n \tag{12}$$

where  $m$  is a constant of proportionality and  $n$  is a power factor index assuming a non-linear relationship between  $t$  and  $R$ . As preform complexity  $R_i$  increases, the time taken  $t_i$  to make  $R_i$  increases compared to a baseline preform  $R_b$  with time  $t_b$ .  $t_i/t_b$  is the relative manufacturing time factor for a preform  $p_i$  and  $R_i/R_b$  is the relative feature factor for a preform  $p_i$ .

2.1.4. Feature Factor: Quantifying Preform Complexity

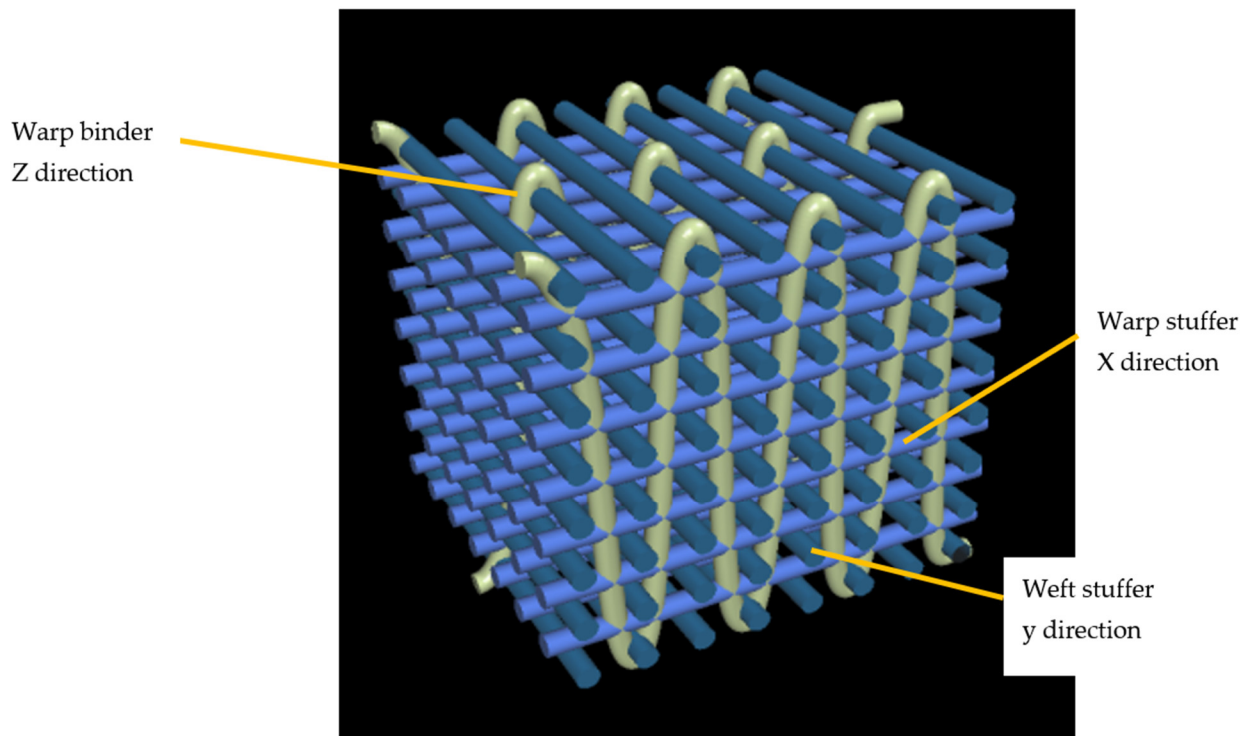
Fagade et al. [12–14] define part complexity in terms of features such as the number of holes, corners, and dimensions. In this study, complexity is a function of the number of fibre tows (warp and weft) in a preform, and preform shape:

**Warp Stuffer**—Total number of warp stuffers along the preform width

**Weft Filler**—Total number of fillers along the preform length

**Warp Binder**—Total number of through-thickness binders along the width

plus additional sub - featurer such as the number of holes. For example, a typical 3D preform has a fibre architecture as shown (Figure 5).



**Figure 5.** Unit cell, orthogonal 3D woven architecture:7 warp layers, 8 weft layers, 28 fibre ends per unit cell, and 5 warp binder ends.

For given preform  $p_i$ , the feature factor is assumed to be a function of two overarching preform features which together make up the preform complexity  $R_i$ : the total number of warp stuffers, weft fillers and warp binders  $A_i$ , and sub-features such as holes and the sum of preform structural elements  $\sum SE_i$  which is a measure of the preform shape(Equation (13)):

$$R_i = \sum (A_i + \text{sub - features}) \left( \sum SE_i \right) \tag{13}$$

The simplest structural element is assumed to be a flat profile, Figure 6, and is numbered as 1. Therefore, the number of structural elements reduces to 1 and the baseline complexity simplifies to:

$$R_b = \sum(A_b) \left( \sum SE_i \right) \text{ or } R_b = \sum(A_b) \tag{14}$$

The cross-sectional preform shape is determined by the number of structural elements. A T- piece is assumed as 3 flat profiles as shown in Figure 7, therefore the shape is given the number 3.

A pi section (Figure 8) will have 5 structural elements as it has 5 flat profiles each of number 1. If the pi preform has 700 fibre tows (the total number of warp stuffer, weft filler and warp binder tows), and has no holes or corners, the complexity is:

$$R_b = (700)(5) = 35,000$$

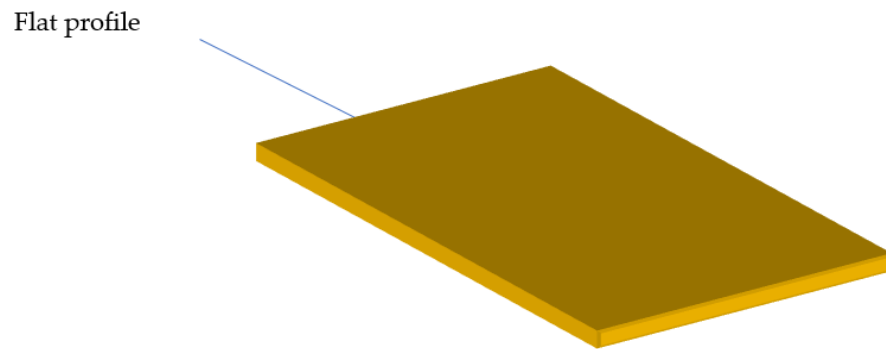


Figure 6. Baseline structural element.

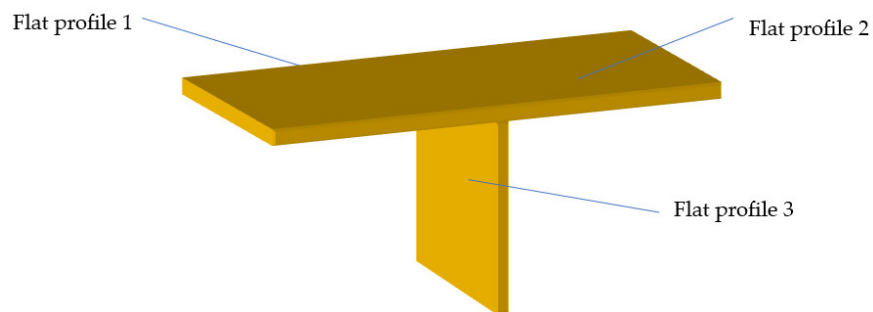


Figure 7. T section, 3 structural elements.

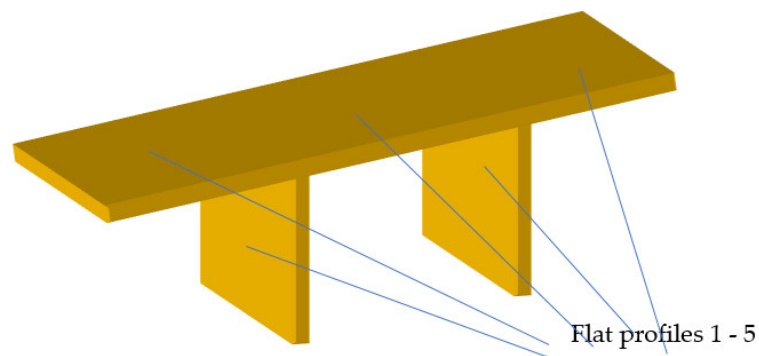


Figure 8. Pi section, 5 structural elements.

### 2.1.5. Estimating the Cost of a New 3D Woven Preform

For a new preform not yet manufactured and whose manufacturing time,  $t_i$  is unknown, the cost can be estimated as follows. Rearranging Equation (12), time  $t_i$  to weave a given preform  $p_i$  is:

$$t_i = m \left( \frac{R_i}{R_B} \right)^n t_b \tag{15}$$

Substituting for  $t_i$  in Equation (11), the cost of the preform is:

$$C_{p_i} = \frac{m C_m}{(1-f)} + m \left( \frac{R_i}{R_B} \right)^n \frac{t_B}{T} \left( \frac{C_t}{L t_{wo}} + \sum C_{total\ salaries} + \sum C_{general\ overhead} \right) \tag{16}$$

If  $t_i$  and  $R_i$  are known for a range of 3D preforms, together with  $t_b$  and  $R_B$  for a baseline preform, the feature factor coefficient  $m$  and power factor  $n$  can be found by

plotting  $t_i/t_b$  against  $R_i/R_B$  (Figure 9). Therefore, the cost of a new preform can be estimated. Alternatively, the cost of a new preform can be estimated from Equation (11).

Equation (16) is the basis of the Excel resource technical cost model, a series of linked spreadsheets each named for a given resource, e.g., preform fabric material, capital tooling cost, and general overhead.

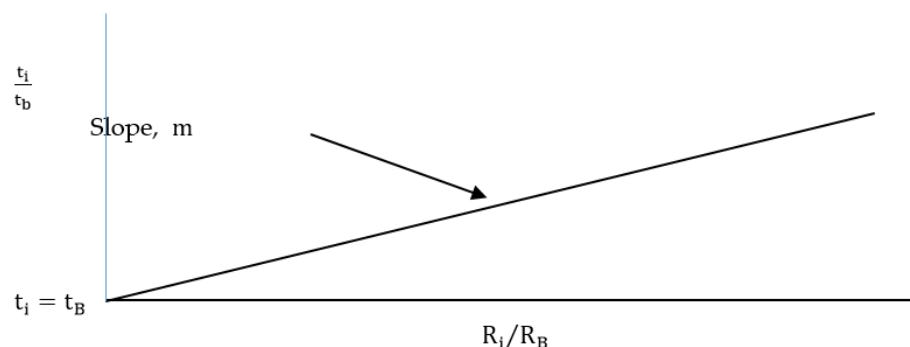


Figure 9. Manufacturing time against preform complexity.

2.2. Experimental: 3D Woven Preform Manufacturing

Seventeen unique preforms were manufactured on either a Jacquard or Weavebird loom, with a variety of architectures ranging from single layer, layerto layer and orthogonal (Tables 2 and 3). Nine preforms were woven on the Weavebird, a detailed example of which is an orthogonal T-piece profile with an architecture of 7 warp, 8 weft and 1 warp binder tows per cm (Figure 5). The fibre type for each preform is included in Tables 2 and 3. Binder or Z tows run over the top weft tow then orthogonally through warp and weft layers which are orthogonal to each other. The binder warp comes out at the bottom then runs under the lowest weft and back up to the top of the preform to repeat the sequence. Warp tows run in the loom machine direction, so are counted across the fabric width. Weft tows run at right angles to warp tows, so are counted along the fabric length.

Table 2. Preforms woven on Jacquard loom.

Preform	Fibre Type	Weave Machine	Architecture	Manufacturing Time (Hours)	$R_i/R_b$	$t_i/t_b$
3	E-Glass HYBON 2002	Jacquard	Orthogonal flat profile	252	137	28.0
9	Carbon T 700 50C	Jacquard	Layer to layer flat profile	58	2.00	6.44
10	Carbon T 700 50C	Jacquard	Orthogonal flat profile	108	5.48	12
12	Carbon T 700 50C	Jacquard	Orthogonal T-piece profile	77	3.53	8.56
13	Carbon T 700 50C	Jacquard	Orthogonal T-piece profile	116	11.25	12.89
14	Carbon T 700 50C	Jacquard	Orthogonal T-piece profile	154	14.92	17.11
15	Carbon T 700 50C	Jacquard	Orthogonal flat profile	73	2.33	8.11
16	Carbon T 700 50C	Jacquard	Orthogonal flat profile	130	5.65	14.44



**Table 3.** Preforms woven on Weavebirdloom.

Preform	Fibre Type	Weave Machine	Architecture	Manufacturing Time (Hours)	R <sub>i</sub> /R <sub>b</sub>	t <sub>i</sub> /t <sub>b</sub>
1	Carbon T 700GC	Weavebird	Single layer flat profile	9	1.0	1.0
2	Carbon T 700GC	Weavebird	Layer to layer flat profile	130	9.75	14.44
4	Carbon T 700GC	Weavebird	Orthogonal T-piece profile	99	11.5	11.0
5	E-Glass HYBON 2002	Weavebird	Orthogonal T-piece profile	49	5.18	5.44
6	E-Glass HYBON 2002	Weavebird	Orthogonal T-piece profile	43	5.50	4.78
7	E-Glass HYBON 2002	Weavebird	Layer to layer flat profile	35	6.80	3.89
8	E-Glass HYBON 2002	Weavebird	Layer to layer flat profile	92	10.42	10.22
11	Carbon T 700 50C	Weavebird	Orthogonal T-piece profile	79	3.79	8.77
17	Carbon T700 50C	Weavebird	Orthogonal T-piece profile	82	9.57	9.11

Table 4 records design and fabric processing step times using Preform 4 as an example, the sum of which is the total manufacturing time. The preform was designed on the Scotweave CAD package and then transferred to the Proweave software package on the loom, which instructs the loom to weave the preform fabric according to the design architecture. The total manufacturing time (loom setup and weaving) was itemised as follows (Table 4).

**Table 4.** Preform 4 setup and weave manufacturing times.

Stage	Loom Setup, Design and Weave	Time Required (h)
1	Winding of bobbins	16
2	Bobbins insertion on creel	8
3	Tubing preparation time, 315 tubes	24
4	Passing 315 carbon tows through PTFE Tubing and loom	24
5	Weave time	3
6	Design on Scotweave	24
Total Manufacturing Time:		99

### 3. Results

Each preform is unique in terms of complexity. In this study, the key metric for complexity is the product of the total number of fibre tows or warp stuffers, weft fillers and warp binders, any sub-features such as holes and the sum of preform structural elements  $\sum SE_i$ , which is a measure of the preform shape. Complexity is expressed by Equation (13).

Each preform complexity and manufacturing time is compared to a baseline preform complexity and manufacturing time, and expressed as the relative feature factor  $R_i/R_b$  and relative manufacturing time factor  $t_i/t_b$ , respectively. Tables 2 and 3 summarise preforms woven on the Jacquard and Weavebird looms, respectively.



3.1. Calculation of  $t_i/t_b$  and  $R_i/R_b$

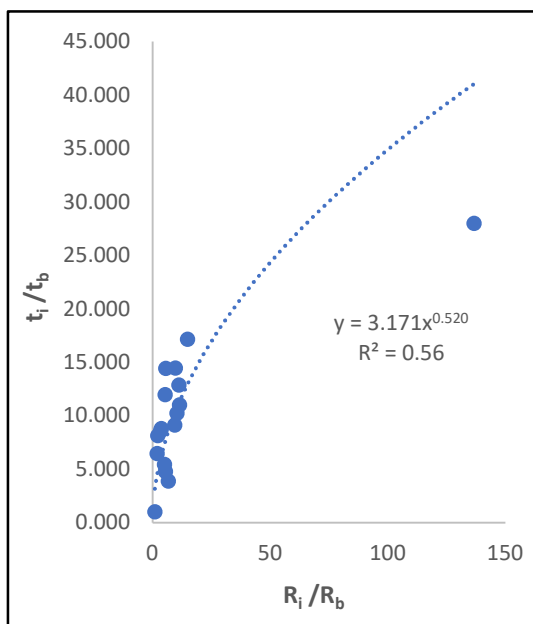
The baseline fabric is the simplest in terms of woven architecture compared with the other fabrics and has the shortest manufacturing time  $t_b$ .  $R_b$  is complexity of Preform 1, (Equation (14)).

As the baseline is a single simple flat profile,  $\sum SE_b$  is equal to 1,  $A_b$  is 360, the total number of fibre tows. As  $R_i$  is the same as  $R_b$  for Preform 1,  $R_i/R_b$  for Preform 1 is 1. Manufacturing time  $t_i$  for Preform 1 is 9 h. As  $t_i$  is the same as  $t_b$  for Preform 1,  $t_i/t_b$  for Preform 1 is 1. Values of  $t_i/t_b$  and  $R_i/R_b$  were found as follows for Preform 4, which is a fabric woven in the shape of a T-piece. A T-piece is assumed to be treated as 3 flat profiles (Figure 7), therefore the shape is given the number 3 or 3 structural elements. For Preform 4, the total number of fibre tows is 1380. Therefore, complexity  $R_4$  for Preform 4 is:  $R_4 = (1380)(3) = 4140$  so  $R_4/R_b$  is  $4140/360 = 11.5$  (Table 3).  $t_4$  for Preform 4 is 99 h, while  $t_b$  is 9 h. Therefore,  $t_4/t_b$  is  $99/9 = 11$ .

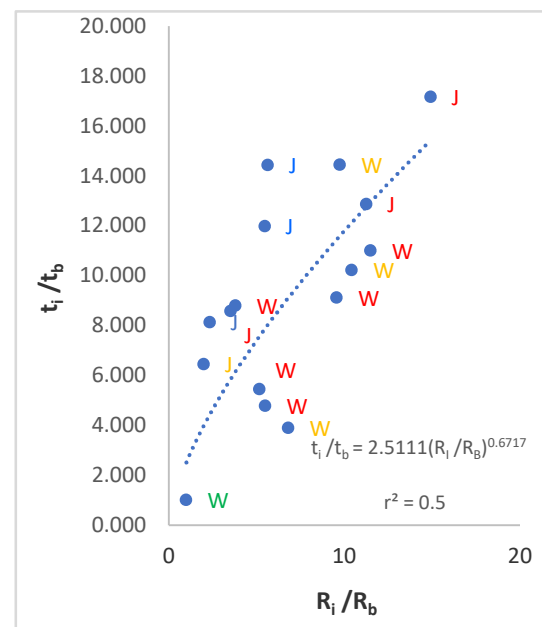
Values of  $t_i/t_b$  and  $R_i/R_b$  for the remaining profiles were calculated by the model, summarised in Tables 2 and 3 and plotted (Figure 10a–c) to validate Equation (12).

3.2. Data Analysis by Loom Type and Preform Architecture

Nine preforms were made on the Weavebird loom, and eight on the Jacquard loom. Figure 10a has 17 data points, one for each 3D woven preform, and shows a trend of increasing manufacturing time with increasing preform complexity. Each preform varies in complexity and architecture in terms of the number of weft and warp tows, preform shape and whether orthogonal or layer to layer. Figure 10a includes Preform 3 which took 252 hours to produce a profile 20 m in length. The complexity value for Preform 3 was 36,901, the product of the total number of fibre tows (36,901) and one structural element as it is a flat profile with no extra features such as T sections. Production times for the remaining preforms ranged from 9 to 130 hours. Correlation coefficient  $r^2$  is 0.56.



(a)



(b)

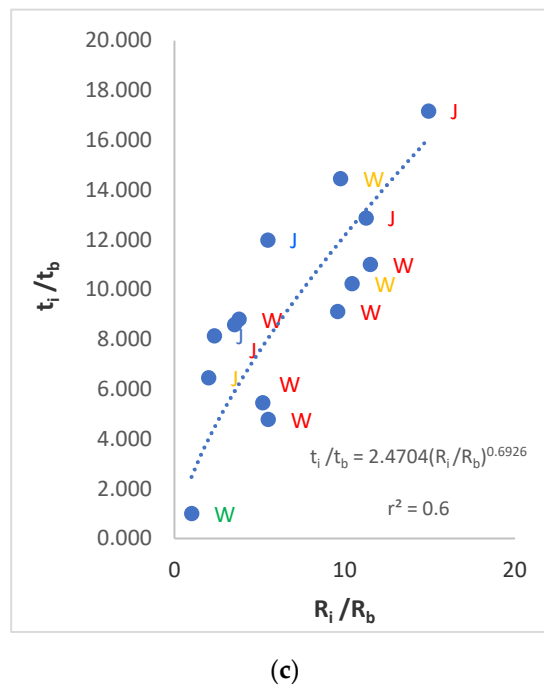
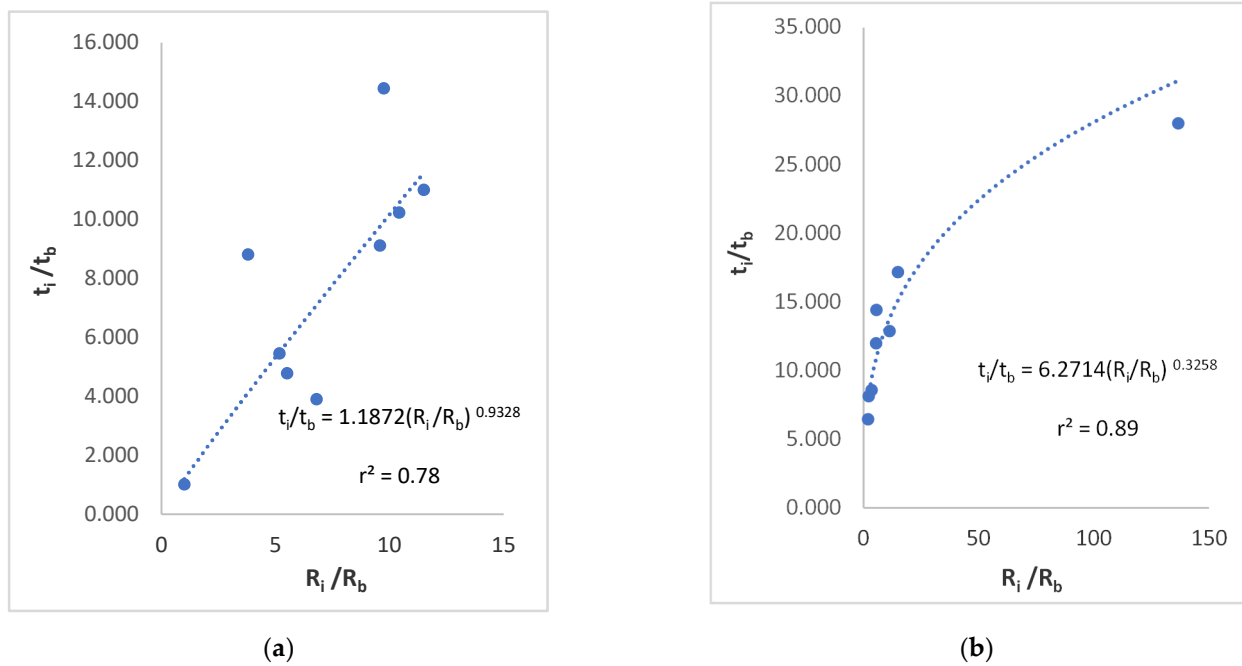


Figure 10. The(a) 17 preforms, (b) 16 preforms, and (c) 14 preforms.

In Figure 10b, Preform3 has been removed. Correlation coefficient  $r^2$  is 0.51. Correlation between two variables will either be “weak” [45] or “well related”[46], depending on sector context. For example, correlation between two variables may be judged either “weak” in a manufacturing [45] context or “well related” in a public sector context [46]. Two outliers in Figure 10b are due to Preforms 7 and 16. If these are removed, Figure 10c for 14 profiles gives a significantly improved trend of increasing  $t_i/t_b$  with  $R_i/R_B$ , with  $r^2 = 0.62$  compared with 0.51. Figure 10b,c show a tendency for preforms to separate out by loom type, with Jacquard preforms tending to group above the trendline and Weavebird preforms grouping below. Figure 11a is a plot of nine preforms from the Weavebird loom. Figure 11b is a plot of eight preforms from the Jacquard loom. Tables 2 (Jacquard) and 3 (Weavebird) include the weave architecture for each preform.

Figure 11b indicates a strong correlation between manufacturing time and preform complexity for the Jacquard preforms as shown by correlation coefficient  $r^2 = 0.89$ , while Figure 11a shows a moderately strong correlation with  $r^2 = 0.78$  for nine Weavebird preforms. Additionally, Figure 11b shows a pronounced tendency for manufacturing time to level off with increasing preform complexity, i.e., the rate of change of  $t_i/t_b$  decreases with increasing complexity,  $R_i/R_B$ . For both Jacquard and Weavebird preforms, Tables 2 and 3 indicate that the relationship between  $t_i/t_b$  and  $R_i/R_B$  is independent of preform architecture.



**Figure 11.** (a) The nine preforms, Weavebirdloom. (b) The eight preforms, Jacquard loom.

3.3. Preform Cost Modelling for a Commercial Quote

The cost of a preform estimated by a local manufacturer was compared with the model-estimated preform cost. A Republic of Ireland-based manufacturer of resin transfer moulded 3D woven composites buys 3D fabrics from a US supplier, and requested a quote from the local manufacturer. Fabric profile data supplied by the ROI 3D woven composite manufacturer is shown in Table 5. The cost structure in 3D preform manufacturing is split between the proportion of costs due to loom setup and weaving, so Table 5 details the total number of warp and weft tows in the setup and weave phases. For example, fabric width is 1270mm (both setup and weave). The number of warp layers is 3. The number of warp tows is 280/m, so the total number of warp tows in the preform will be  $1.27 \times 280 \times 3 = 1067$  tows. The preform length to be woven is 454m. The number of weft tows is 190/m and the number of weft layers is 4, so the total number of weft tows in the woven preform will be  $190 \times 454 \times 4 = 345,040$  tows. The total number of tows, warp and weft, in the woven preform is  $1067 + 345,040 = 346,107$  tows.

**Table 5.** Hypothetical 3D woven preform fabric.

<b>Fabric Materials</b>	
100% E-glass	
Fibre content: warp stuffer: 98%, Weft filler, warp binder: 2%	
Material cost, E-glass: £1/kg	
Warp tow: Setup and Weave	
Warp tows/cm/layer: 2.8	
Warp tows/cm/layer/total: $2.8 \times 127 = 356$	
Number of warp layers in preform: 3	
Total number of warp tows in preform, set andweave = $356 \times 3 = 1068$	
Warp andWeft: Setup	Warp andWeft: Weave
Setup length (cm): 2000	Length (cm): 45,400
Width (cm): 127	Width (cm): 127
Weft tows/cm/layer: 1.9	Weft tows/cm/layer: 1.9
Number of preform weft layers: 4	Number of preform weft layers: 4

Weft tows/cm/layer/total: $1.9 \times 2000 = 3800$	Weft tows/cm/layer/total: $1.9 \times 45,400 = 86,260$
Weft tows, preform setup: $3800 \times 3 = 15,200$	Weft tows, weave: $86,260 \times 4 = 345,040$
Total number of tows: $1068+15,200 = 16,267$	Total number of tows: $1067+345,040 = 346,107$
Material Cost	
Setup fabric area (m <sup>2</sup> ): $1.27 \times 20 = 25.4$	Weave fabric area (m <sup>2</sup> ): $1.27 \times 454.27 = 577$
Areal weight (g/m <sup>2</sup> ): 5200	Areal weight (g/m <sup>2</sup> ): 5200
Weight of woven fabric (kg): $5.2 \times 25.4 = 132$	Weight of woven fabric (kg): $5.2 \times 577 = 3000$
Cost: $\text{£}1/\text{kg} \times 132 = \text{£}132$	Cost: $\text{£}1/\text{kg} \times 3000 = \text{£}3000$
Total Material Cost: $3000 + 132 = \text{£}3132$	

Using constants  $y$  and  $m$  from Figure 10c (14 Jacquard and Weavebird preforms), Figure 11a (9 Weavebird preforms) and Figure 11b (8 Jacquard preforms), manufacturing costs for the new preforms were estimated and compared for each set of constants. These plots were chosen as they have the highest correlation between manufacturing time and preform complexity as shown by correlation coefficient  $r^2$ .

Manufacturing cost based on constants derived from 14 preforms

The following equation was derived from Model—estimated data (Figure 10c):

$$\frac{t_i}{t_b} = 2.4704 \left(\frac{R_i}{R_b}\right)^{0.6926}$$

where  $y$  is  $\frac{t_i}{t_b}$  and  $x$  is  $\left(\frac{R_i}{R_b}\right)$ .

Feature Factor Calculation

Fabric manufacturing cost was estimated from Equation (16), which includes the relative feature factor since  $t_i$  for the fabric is unknown, with the feature factor is given by Equation (12).

Resource Cost Example: Proportion of Tooling Cost for Quoted 3D Fabric

The cost structure in 3D fabric manufacturing is split between the proportion of costs due to the loom setup and costs due to weaving. These costs are labour, capital and overheads. In the setup phase, 20m of warp and weft tows will be woven while in the weave phase, 454m will be woven. Two feature factors for complexity were calculated, one for setup, the other for weaving. The proportion of the capital tooling cost for setup and weaving is found from:

$$\text{Proportion of capital tooling cost} = 2.4704 \left(\frac{R_i}{R_b}\right)^{0.6926} \frac{t_B}{T} \frac{C_t}{0.7t_{wo}}$$

where  $t_{wo}$  is the write-off time for capital equipment, 5 years, and  $C_t$  is capital tooling cost.

A load factor of 0.7 is assumed for the Jacquard loom on which the fabric would be woven.

Fabric complexity is a function of the total number of fibre tows and sub-features, e.g., holes, in the fabric and the shape of the fabric or number of structural elements (Equation (13)):

$$R_i = \left(\sum A_i + \text{sub - features}\right) \left(\sum SE_i\right)$$

where  $A_i$  is the total number of fibre tows and  $\sum SE_i$  is the number of structural elements. This fabric is a flat profile with no sub-features, so  $\sum SE_i = 1$  and

$$R_i = \left(\sum A_i\right)$$

Setup Feature Factor:

Fabric complexity  $R_i = 16,267$  tows or 16k (Table 5). Baseline complexity  $R_B = 360$  tows.

Therefore  $\frac{R_i}{R_b} = 16,000/360 = 45$

Weave Feature Factor

Fabric complexity  $I = 346,107$  tows (Table 5). Baseline complexity  $R_b = 360$  tows, so

$$\frac{R_i}{R_b} = 346,107/360 = 962$$

The company runs one shift per day, so total annual production time is 1840 h based on 8 h per day at 5 days per week for 46 weeks per year. The baseline setup time  $t_b$  is 9 h, which was the total time over two days, and the baseline weave time is 1 h, so  $t_b/T$  is  $8/1840 = 0.004348$  for the baseline setup time and  $1/1840 = 0.000543$  for the baseline weave time. The capital cost amortised over 5 years is £200,000/5. From Figure 10c,  $m$  is 2.4704 and  $n$  is 0.6926. A key variable is load factor  $L$  or machine utilisation. A load factor of 70% was agreed with the manufacturer. Using these values and approximate cost data for tooling, labour and overheads (Table 6), the proportion of annual capital tooling cost  $C_{\text{tooling}}$  was calculated by the model for both setup and weave phases:

Loom setup: tooling cost =  $24,704 \times 45 \cdot 2^{0.5209} \times 0.00435 \times 200,000/5 \times 0.7 = \text{£}8595$

Weaving: tooling cost =  $24,704 \times 962^{0.5209} \times 0.000543 \times 200,000/5 \times 0.7 = \text{£}8934$

Proportion of capital tooling cost, setup and weave =  $\text{£}8595 + \text{£}8934 = \text{£}17529$

In the same way, the proportion of labour and overhead costs for setup and weaving was calculated and summed to give an overall manufacturing cost of £46,736 for the fabric at a width of 127cm and a total length of 454m (Table 7). Using the same methodology, costs were estimated with constants derived from 8 Jacquard and 9 Weavebird preforms, as shown in Tables 8 and 9.

**Table 6.** 3D preform resource costs.

Resource	Cost (£)
Material, 3132kg, E-glass at £1/kg	3132
Labour, £30,000 for two operatives	60,000
Capital Tooling	
Jacquard loom	70,000
Four creels:	80,000
Bobbins:	20,000
Feed/Transport:	10,000
Other items:	20,000
Total	200,000
Overheads	25,000

**Table 7.** Estimated cost of 3D woven fabric, 14 preforms.

Cost Element	Loom Setup	Weaving	Total	%
Capital Tooling (£)	8595	8934	17529	37.5
Labour (£)	9025	9381	18406	39.4
Overheads (£)	3760	3909	7669	16.4
3D woven fabric material (£)			3132	6.7
Total Cost (£)			46,736	100

**Table 8.** Estimated cost of 3D woven fabric, eight Jacquard preforms.

Cost Element	Loom Setup	Weaving	Total	%
Capital Tooling (£)	5393	1826	7218	34.2
Labour (£)	5662	1917	7579	35.9
Overheads (£)	2359	799	3158	15.0
3D woven fabric material (£)			3132	14.9
Total Cost (£)			21,087	100

**Table 9.** Estimated Cost of 3D woven fabric, nine Weavebird preforms.

Cost Element	Loom Setup	Weaving	Total	%
Capital Tooling (£)	10317	22355	32671	38.4
Labour (£)	10833	23472	34301	40.3
Overheads (£)	4514	9780	14924	17.6
3D woven fabric material (£)			3132	3.7
Total Cost (£)			85,028	100

Table 10 shows the variation in quoted preform cost with values of constants n and m. Data for n and m from Figures 10c and 11a,b gave cost estimates of £46,736, £85,028 and £21,087, respectively. The biggest cost contributors are Labour and Tooling. The lowest value of exponent n is 0.3258 as all eight preforms in this case were made on the Jacquard, while n = 0.9328 when nine preforms were woven on the Weavebird. Figure 12 shows a steep rise in manufacturing cost for the quoted 3D fabric as weave manufacturing conditions change from those on the more efficient Jacquard to the less efficient Weavebird and complexity exponent n approaches 1, i.e., linearity.

**Table 10.** Quoted preform cost: cost breakdown (%) and total cost.

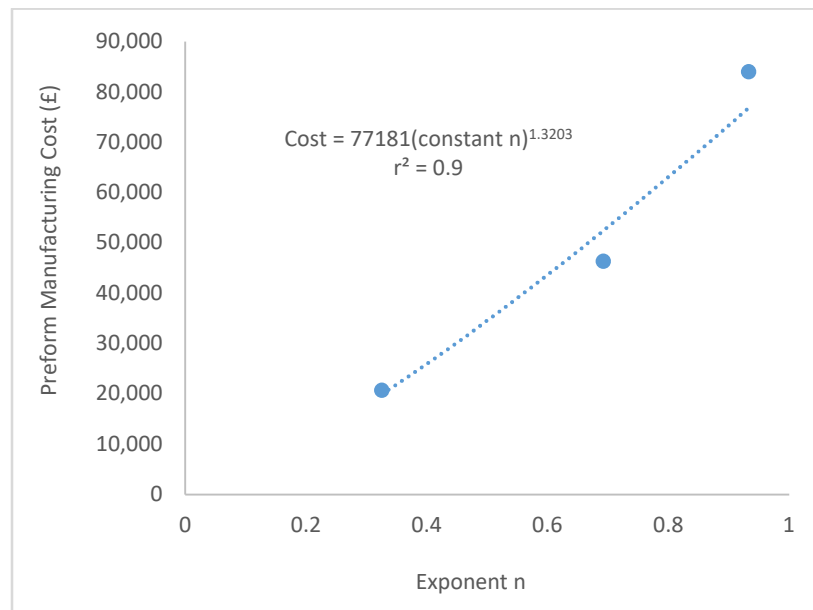
Number of Preforms	n	m	Cost Breakdown (%)				Cost (£)
			Tooling	Labour	Overhead	Material	
8 J	0.3258	6.2714	34.2	35.9	15.0	14.9	21,087
14 J and W	0.6926	2.4707	37.5	39.4	16.4	6.7	46,736
9 W	0.9328	1.1872	38.4	40.3	17.6	3.7	85,028

J = Jacquard; W = Weavebird.

The relationship between preform manufacturing cost  $C_i$  and exponent n (Figure 12) as a measure of decreasing loom efficiency from Jacquard to Weavebird as n approaches 1 is:

$$C_i = 77181n^{1.3203} \tag{17}$$

Although sample size is 3,  $r^2 = 0.90$ , implying a very strong correlation between preform manufacturing cost and complexity exponent n. More preform manufacturing data are needed to fully validate this relationship and show whether the curve intercepts the y-axis or goes through the origin.



**Figure 12.** Manufacturing cost vs. complexity exponent.

**4. Discussion**

*4.1. Correlation of Preform Manufacturing Time and Complexity*

Production of 17 individual preforms of varying fibre architecture and shape started in June 2017 and finished in June 2019. No data for other profiles were available, so costs (capital, labour and overheads), profile complexity and time data for the 17 preforms were employed to develop a resource-based TCM to enable estimation of manufacturing cost for a new bespoke preform yet to be made. The working hypothesis is that preform production time, and therefore cost, scales with preform complexity. Increasingly accurate estimation of preform manufacturing cost is possible as more data become available [5].

Figure 10b shows a clear distinction between preforms manufactured on the Jacquard and Weavebird looms, with seven of the eight Jacquard preforms either on or above the trendline and seven of the nine Weavebird preforms below the line. In Figure 10c, which showed the same trend by loom, two outliers were removed resulting in an  $r^2$  value of 0.62, indicating either a moderate or strong correlation between manufacturing time and complexity [46]. Although sample sizes were below 12, Figure 11a,b show strong and very strong correlations [45], 0.78 and 0.89, for nine and eight preforms made on the Weavebird and Jacquard looms, respectively (Table 11). The lower values of  $r^2$  and greater scatter of data observed in Figure 10a–c can be explained by the presence of both Jacquard and Weavebird data points on the same plots. For a sample size comparison, Fingersh et al. [47] used sample sizes varying from 6 to 13 when determining  $r^2$  for the dependence of wind turbine tower mass on blade swept area and blade hub height.

**Table 11.** Correlation coefficient and number of preforms by loom.

Number of Preforms	Correlation Coefficient $r^2$ , $\frac{t_i}{t_b}$ vs. $\frac{R_i}{R_b}$
17 Jacquard and Weavebird	0.56
16 Jacquard and Weavebird	0.51
14 Jacquard and Weavebird	0.62
8 preforms woven on Jacquard	0.89
9 preforms woven on Weavebird	0.78

Significant variation across all 17 preforms was present according to profile shape and weave architecture. The Weavebird is suitable for weaving short length profiles while the Jacquard is suitable for longer preforms such as Preform 3, Table 2. The preforms were a variety of flat and T-section shapes with weave architecture varying from single layer, layer to layer and orthogonal. All 17 preforms were woven for the first time with loom setup issues such as fibre clumping, contact with loom framework and fibre breakage causing significant time delays. The time recorded for each preform included these time delays (Tables 2 and 3, pp. 16 and 17). In Section 4.3, a reduction in manufacturing time as learning increases is discussed in detail (Equation (24), p.29, Table 12, p.26).

Jacquard looms can make long complex fabrics much more efficiently than dobbie looms, e.g., the hypothetical fabric (454 m). This is shown clearly in Figure 11b for eight Jacquard preforms, in which manufacturing time increases at a decreasing rate with complexity and length, i.e., the loom becomes more efficient at weaving longer, more complex fabrics. Conversely, where all the preforms were made on a Weavebird loom, manufacturing time increases almost linearly with complexity, Figure 11a, and weaving efficiency does not increase with preform complexity.

#### 4.2. Costing of the Hypothetical 3D Woven Preform

For nine Weavebird preforms, constants from Figure 11a gave a cost of £85,028, while for eight Jacquard preforms, constants from Figure 11b gave a preform cost of £21,087. Therefore, a less efficient Weavebird will give a much higher manufacturing cost for a large, complex preform compared to the cost when woven on a more efficient Jacquard. Values of complexity exponent  $n$  between 0 and 1 in Equation (12) for the feature factor imply an economy of scale for 3D woven preform manufacturing with increasing preform complexity:

$$\frac{t_i}{t_b} = m \left( \frac{R_i}{R_B} \right)^n \tag{12}$$

$$0 < n < 1$$

Esawi [4] found a similar relationship for injection moulding, extrusion and casting operations in which tooling cost and capital cost scale with complexity exponents  $y_t$  and  $y_c$ , respectively. Values for  $y_t$  and  $y_c$  vary between 0 and 1, implying greater economy of scale as tooling and capital equipment, for example a plastics injection press, become more complex:

$$0 < y_t < 1, 0 < y_c < 1$$

The analysis for preforms woven on the Jacquard and Weavebird looms indicates that as manufacturing conditions change from the more efficient Jacquard to the less efficient Weavebird, as indicated by the increasing value of complexity exponent  $n$ , economy of scale will decrease and manufacturing cost increase for a large, complex preform (Table 10, Figure 12). In conclusion, Jacquard costs alone should be used to estimate costs for a large, complex preform intended to be made on the Jacquard loom. Therefore, £21,087 for the commercial preform is judged the most accurate estimate. Assuming a non-linear relationship between manufacturing time and complexity based on the available data and observed correlation coefficient for Jacquard and Weavebird manufactured preforms (Table 11), two feature factor sub-models are proposed for 3D preform weaving, one for the Jacquard and one for the Weavebird:

Jacquard feature factor: Weavebird feature factor:

$$\frac{t_i}{t_b} = 6.2714 \left( \frac{R_i}{R_b} \right)^{0.3258} \tag{18}$$

$$\frac{t_i}{t_b} = 1.1872 \left( \frac{R_i}{R_b} \right)^{0.9328} \tag{19}$$



which in turn leads to two cost models for preform manufacturing cost,  $C_i$ :

Jacquard cost model

$$C_i = \frac{mC_m}{(1-f)} + 6.27 \left(\frac{R_i}{R_b}\right)^{0.3258} \frac{t_b}{T} \left(\frac{C_t}{Lt_{wo}} + \sum C_{\text{total salaries}} + \sum C_{\text{general overheads}}\right) \quad (20)$$

Weavebirdcost model

$$C_i = \frac{mC_m}{(1-f)} + 1.19 \left(\frac{R_i}{R_b}\right)^{0.9328} \frac{t_b}{T} \left(\frac{C_t}{Lt_{wo}} + \sum C_{\text{total salaries}} + \sum C_{\text{general overheads}}\right) \quad (21)$$

The cost estimate of £21,087 is approximately three times that for the same preform supplied by a US manufacturer, or £7500. The lower cost may be due to a higher production rate coupled with a more efficient loom leading to lower preform cost and greater experience from embedded learning.

#### 4.3. Cost Reduction by Learning

Organisational Learning is defined as a conscious attempt by organisations to improve productivity, effectiveness and innovation in complex economic and technological market conditions. Learning enables quicker and more effective responses to a complex and dynamic environment. The greater the complexity, the greater the need for learning [29–32]. 3D woven preform manufacture is a highly complex process with numerous step-carried out in a required sequence for successful manufacture. If there is a delay in completing a given step, the time required to complete the overall preform will increase thereby increasing preform cost. In this study, 17 preforms were made for the first time with no previous 3D preform manufacturing experience. Wright [33] observed that as aircraft production increased, the cost in terms of direct labour hours fell as shown in Figure 13, which is a learning curve (LC).

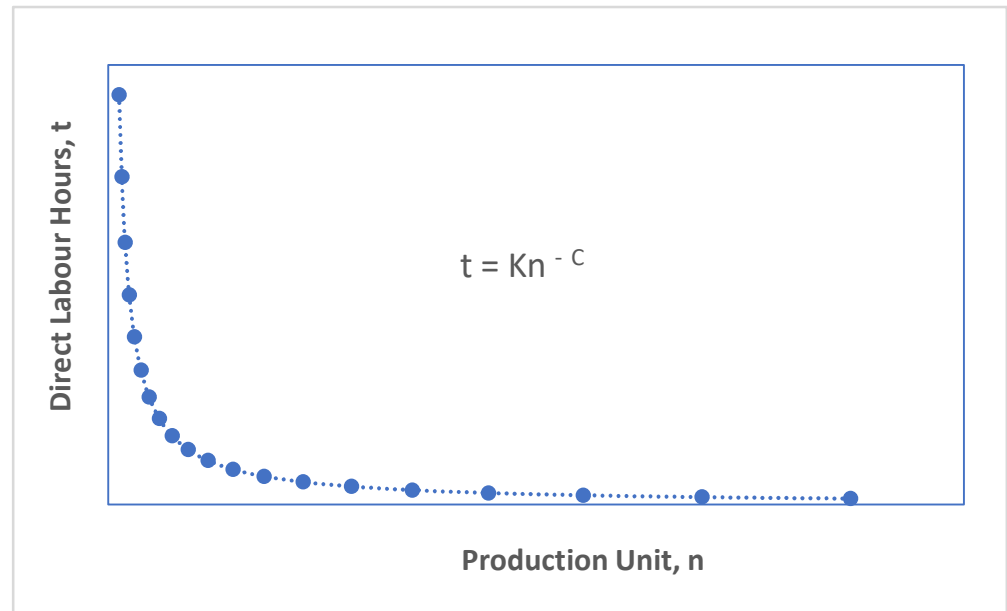


Figure 13. General relationship, component cost and production volume.

In general, learning curves (LC) can be described by Equation (22) [33]:

$$y = C_1 x^b \quad (22)$$

where  $y$  is the average time (or cost) per unit required to produce  $x$  units;

$C_1$  is the time (cost) to produce the first unit;

parameter  $b$  ( $-1 < b < 0$ ), the slope of the LC, which describes the worker's learning rate.

For a new component not previously manufactured, the learning required and therefore the cost to make the part will initially be high as shown by the start of the slope on the left of Figure 11. As more units are made, there is a steep drop in labour hours per part until the rate of decrease in direct labour hours per part becomes smaller.

Klenow [34] reviewed various studies investigating learning by doing for a single defined production process across a variety of industrial sectors, observing estimates of approximately 20% for the learning rate. Baloff [35], and Garg and Milliman [48] showed that 20% is the rate at which productivity rises with a doubling of cumulative output. Lee [36] summarised learning rates by manufacturing sector and activity (Table 12) and showed that even in one overall activity, in this case industrial manufacturing, learning rates will vary considerably by individual sector. In several studies, Yelle [37] and Argotte and Epple [38], observed that productivity rose across a variety of industries through a process of learning by doing.

**Table 12.** Representative learning rates by industrial sector.

<b>Sector Representative Learning Rates</b>	
Aerospace	15%
Shipbuilding	15%–20%
Machine Tools (new models)	15%–20%
Electronics (repetitive)	5%–10%
Electrical Wiring (repetitive)	15%–25%
Machining	5%–10%
75% Manual Assembly + 25% Machining	20%
50% Manual Assembly + 50% Machining	15%
25% Manual Assembly + 75% Machining	10%
Punch Press	5%–10%
Raw Materials	5%–7%
Purchased Parts	12%–15%
Welding (repetitive)	10%

In preform manufacture, direct labour hours are associated with activities such as bobbin winding and insertion, tube preparation time, loom maintenance and operation, and stoppage time due to issues encountered during weaving, e.g., damage to carbon and glass fibres from contact with the loom framework. Manufacturing time in this study is the time taken to complete these activities. With increased preform production, manufacturing time  $t_i$  and manufacturing cost should decrease with increased learning. The estimated manufacturing time  $t_i$  for one preform is found from Equation (12),

$$\frac{t_i}{t_b} = m \left( \frac{R_i}{R_b} \right)^n$$

from which

$$t_i = m \left( \frac{R_i}{R_b} \right)^n t_b$$

3D fabric manufacturing cost is split between the proportion of costs due to loom setup and costs due to weaving, therefore there are two manufacturing times for a given preform:  $t_{i\text{ weave}}$  and  $t_{i\text{ setup}}$ . The estimated cost of the commercial preform was £21,087 (Table 10) for weaving on the Jacquard loom. The company has no experience of making this preform. Setup time and weave time  $t_b$  for the baseline preform was 8 and 1 h, respectively. Using values for constants  $m$  and  $n$  (Table 10), the estimated setup and weave times for the hypothetical preform are:

$$\text{Setup time: } t_{i\text{ setup}} = 6.2714(45.19)^{0.3258} 8 = 174 \text{ h}$$

Weave time:  $t_{i\text{weave}} = 6.2714(962)^{0.3258} 1 = 59 \text{ h}$

Total manufacturing time:  $t_{i\text{setup}} + It_{i\text{weave}} = 174 + 59 = 233 \text{ h}$

No data were publicly available for 3D preform learning rates. The total estimated manufacturing time is 233 h. Setup time is the manual labour time involved in activities such as bobbin winding, bobbin placement on the creel and taking fibre tow onto the loom. The setup time is 174/233 or 74.7% while the weave or machine time is 25.3%. From Table 12, a learning rate of 20%, in which manufacturing time decreases by 20% for each doubling of cumulative production, corresponds to a manufacturing activity in which manual operations are 75% and machine time is 25% of total activity. Since manual setup time (74.7%) and weave time (25.3%) are closest to 75% manual assembly and 25% machining, 20% was the assumed learning rate for the new preform. Based on this rate, a learning curve (Figure 14) and an equation (Equation (23)) was derived by the model from Equation (22), to estimate a competitive manufacturing cost for the new preform.

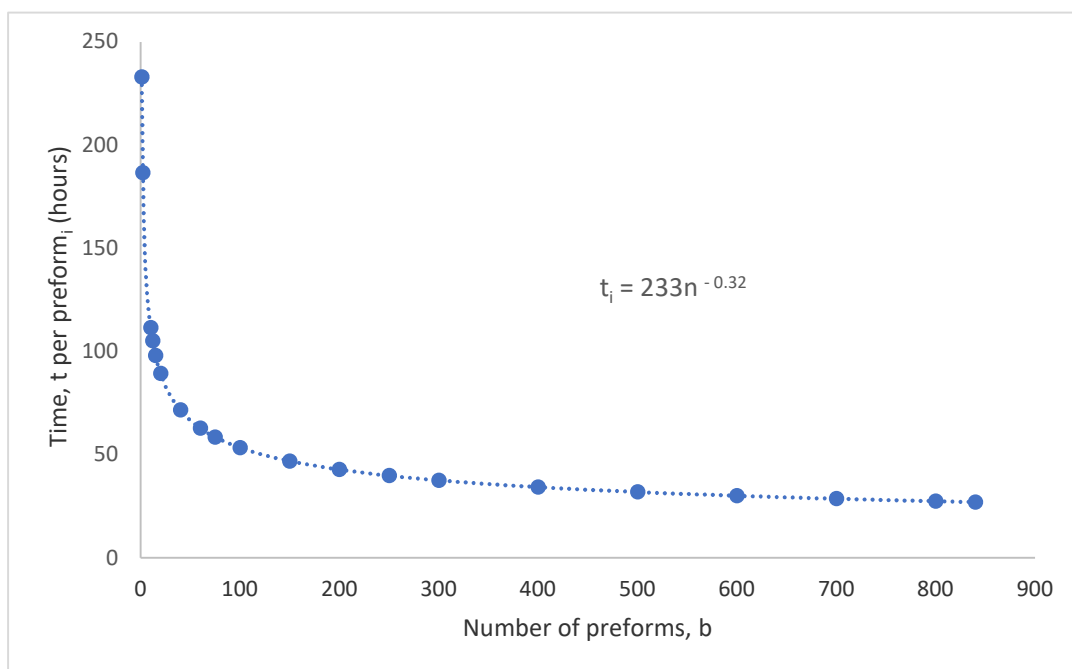


Figure 14. Learning curve for commercial preform i.

$$t_i = 233b^{-0.32} \tag{23}$$

where  $t_i$  = preform manufacturing time;  $b$  = number of preforms.

The model estimated a manufacturing time  $t_i$  of 98 h per preform after a cumulative production of 15 preforms. Therefore, setup time and weave time will have decreased with increased cumulative production. Insertion of this value for  $t_i$  in Equation (11) together with resource costs for tooling, salaries, overhead, write-off time (Table 6) and load factor 0.7 gave an estimated cost of £8002, approximately one third of the first-time preform cost of £21,087 and in line with the US supplier’s cost of £7500. More manufacturing data will be required to clarify learning rates for 3D woven preforms to fully validate Equation (23) and provide a more accurate estimate of preform cost.

$$C_{pi} = \frac{mC_m}{(1-f)} + \frac{t_i}{T} \left( \frac{C_t}{Lt_{wo}} + \sum C_{\text{total salaries}} + \sum C_{\text{general overhead}} \right) \tag{11}$$

$$= 3132 + \frac{98}{1840} \left( \frac{200,000}{0.7 \times 5} + 60000 + 25000 \right) = \text{£}8002$$

Various issues were encountered during first-time preform manufacture:

- Fibre catching on the edges of the bobbin.

- Fibres splitting at the tensioning bars.
- Weight of bobbins causing tension problems.
- Damage to carbon and glass fibres due to contact with loom framework.
- Crossing fibres forming balls of carbon at the heddles.
- Weft insertion forming fibre clumps and splitting.

These issues accounted for the observed manufacturing times for each preform (Tables 2–4) due to low embedded learning and first-time preform manufacture. A key assumption underlying this analysis is that the commercial preform will be continuously manufactured so that unlearning or forgetting [49], due to discontinuous production is avoided. Another assumption is the use of Wright’s learning curve model [33] to estimate the cumulative number of preforms produced from the estimated time to make one preform and an assumed learning rate. The model yields production times equal to zero [40] after a high number of repetitions, which is impossible. Furthermore, it does not account for workers’ prior experience [41], nor the influence of machinery in the learning process [42]. However, workers’ prior experience does not apply in this case as all seventeen preforms were made for the first time, while no data exist for the influence of weaving loom machinery on learning. Finally, Wright’s model has been used successfully in various manufacturing sectors [41]. Therefore, the choice of this LC model is justified.

Irwin and Klernow [50] pointed out that productivity growth from learning by doing diminishes as experience accumulates with a technology. Even though learning by doing is largely specific for a given technology, a review of the literature showed that this same pattern holds for a wide variety of industries. An alternative visual representation of learning is a plot which shows learning increasing as a function of decreasing manufacturing time against the number of manufactured preforms. This relationship can be expressed as:

$$\text{Learning} = \left[1 - \left(\frac{t_i}{T}\right)\right] = n^c \tag{24}$$

Figure 15 represents Equation (24) using the same learning rate of 20% and a manufacturing time of 233 h for initial manufacture of the commercial preform.

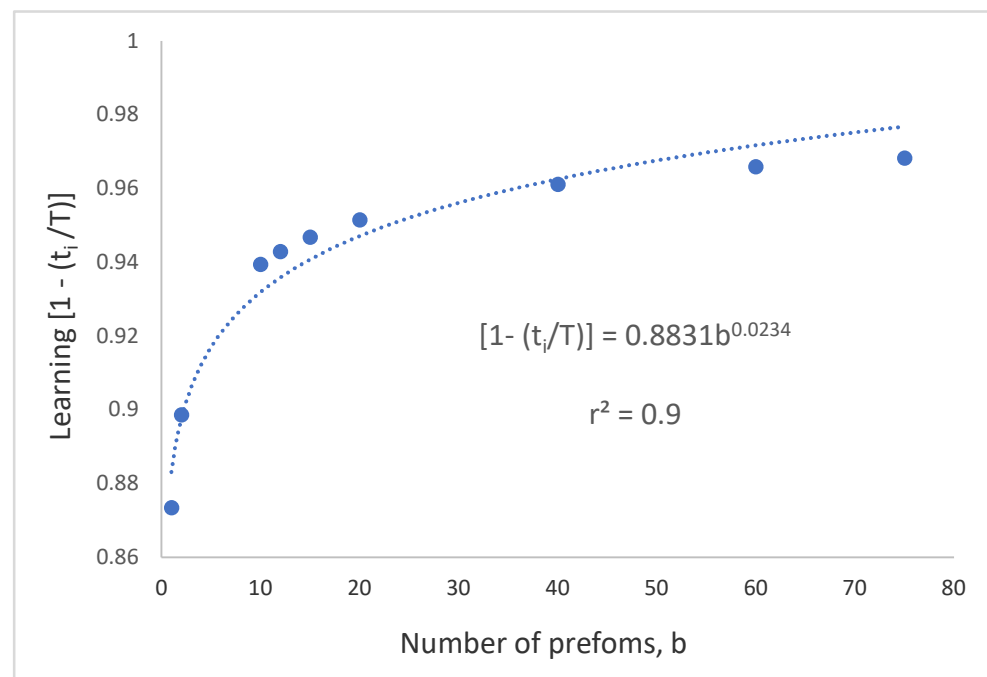


Figure 15. Learning as a function of manufacturing time and number of preforms.

Figure 15 shows a sharp initial increase in learning as a function of manufacturing time and the number of preforms produced, followed by a levelling off until there is no discernible increase in learning after a cumulative production of 80 preforms. Correlation coefficient  $r^2$  is 0.96, denoting a strong correlation between manufacturing time  $t_i$  and  $b$ , the cumulative production of preforms. Exponent  $c$  has a value of 0.0234.

An alternative to continuous production of 15 preforms of the same complexity and size as the commercial preform is to acquire a more efficient Jacquard loom so that manufacturing time, and therefore cost, is reduced. Russell [51], and Pegels [52] observed that while productivity will initially fall with technology updates, it will gradually rise to overtake the level achieved with the old technology. However, Lee [36] and Hill [53] pointed out that reduced manufacturing cost through learning will not happen unless there is a willingness to learn, an ability to learn and, in many cases, an investment in learning. Many factors were identified that determine the learning curve for a given individual, team, factory or industry, including

- Management styles and actions
- Corporate culture
- Organisation structure
- Technology
- Capital investment
- Engineering
- Product design
- Direct and indirect labour efficiency
- Economy of scale
- Plant layout
- Process improvement

To maximise learning, productivity and competitiveness, Skinner [54] emphasised a limited, manageable set of products and markets for lowering costs, especially overhead. Therefore, to maximise learning and hence productivity in preform manufacture, the focus should be on a manageable set of 3D woven preform designs.

A summary of equations for cost, complexity and learning, from the literature and derived by the author, is presented in Table 13.

**Table 13.** Equation summary.

Equation	Attribution	No.
Cost = Material + Tooling Cost + Labour + Overheads	MA	1
$C_1 = C_m / (1 - f)$	MA	2
$C_2 = C_t / n_r (1 + n_r / n_t)$	MA	3
$C_3 = 1 / n_r (C_c / Lt_{wo})$	MA	4
$C_4 = C_{oh} / n_r$	MA	5
$C_{mc} = mC_m / (1 - f) + C_t / n (1 + n_r / n_t) + 1 / n_r (C_c / Lt_{wo} + C_{oh})$	MA	6
$C_{tooling} = t_i / T (C_t / t_{wo})$	JC	7
$C_{salaries} = t_i / T \sum C_{total\ annual\ salaries}$	JC	8
$C_{overhead} = \sum C_{general\ annual\ overhead}$	JC	9
$C_{overhead} = t_i / T \sum C_{general\ annual\ overhead}$	JC	10
$C_{p_i} = mC_m / (1 - f) + t_i / T (C_t / Lt_{wo} + \sum C_{total\ salaries} + \sum C_{general\ overhead})$	JC	11
$t_i / t_b = m(R_i / R_B)^n$	JC	12
$R_i = \sum (A_i + sub - features) (\sum SE_i)$	JC	13
$R_b = (A_b) (\sum SE_i)$	JC	14

$t_i = m(R_i/R_B)^n t_b$	JC	15
$C_{pi} = mC_m/(1 - f) + m(R_i/R_B)^n t_B/T \left( C_t/Lt_{wo} + \sum C_{total\ salaries} + \sum C_{general\ overhead} \right)$	JC	16
$C_i = 77181n^{1.3203}$	JC	17
$t_i/t_b = 6.2714(R_i/R_b)^{0.3258}$	JC	18
$t_i/t_b = 1.1872(R_i/R_b)^{0.9328}$	JC	19
$C_i = mC_m/(1 - f) + 6.27(R_i/R_b)^{0.3358} t_b/T \left( C_t/Lt_{wo} + \sum C_{total\ salaries} + \sum C_{general\ overheads} \right)$	JC	20
$C_i = \frac{mC_m}{(1 - f)} + 1.19 \left( \frac{R_i}{R_b} \right)^{0.9328} \frac{t_b}{T} \left( \frac{C_t}{Lt_{wo}} + \sum C_{total\ salaries} + \sum C_{general\ overheads} \right)$	JC	21
$y = C_1 x^b$	JC	22
$t_i = 233b^{-0.32}$	JC	23
Learning = $[1 - (t_i/T)] = n^c$	JC	24

JC—James Clarke.MA—Michael Ashby.

### 5. Conclusions and Recommendations for Further Work

3D woven preforms are promising materials for composite parts in numerous applications, for example wind turbine spar caps. They have unique mechanical properties and have the potential to reduce composite manufacturing costs due to near net-shape resin transfer moulding. At present, they are not widely used due to a perception of high cost and demanding safety protocols in market sectors such as aerospace. A predictive resource-based technical cost model (TCM) for bespoke manufacturing of 3D fabrics was developed based on the principles that cost is determined by resources such as tooling, labour and other overheads and that manufacturing time, and therefore cost, will scale with preform complexity. An expression for a cost scaling feature factor was introduced relating preform manufacturing time to preform architectural complexity, defined as a function of the number of fibre tows and preform shape.

The model is based on Equation (16) (Table 13) for costing the manufacture of 3D preforms and utilises two principles. Firstly, the manufacturing time for a single bespoke preform will depend on the unique complexity of that preform. Secondly, the resource cost for a given preform, for example tooling cost, will be a function of the time required to make that preform as a proportion of total annual production time (Equations (7), (8) and (10), Table 13). Loom tooling is not dedicated for a given preform. Plotting manufacturing time against preform complexity for seventeen preforms enabled derivation of constants  $m$  and  $n$  in Equation (12). Inserting these values into Equation (16) enables estimation of the manufacturing cost of a new 3D preform with a given architecture  $R_i$ :

$$C_{pi} = \frac{mC_m}{(1 - f)} + m \left( \frac{R_i}{R_b} \right)^n \frac{t_B}{T} \left( \frac{C_t}{Lt_{wo}} + \sum C_{total\ salaries} + \sum C_{general\ overheads} \right)$$

Approximate resource costs for tooling, labour and overheads together with manufacturing times for seventeen unique preforms with varying architectures such as single layer, layerto layer and orthogonal were provided by a 3D preform manufacturer. The preforms were made on either a Weavebird handloom or a Jacquard loom. A hypothesis was proposed that preform manufacturing time will increase non-linearly with preform complexity.

Table 10 summarised model-estimated costs based on differing values for constants derived from separate plots for Jacquard and Weavebird preforms, and a plot with both Jacquard and Weavebird preforms. Eight preforms were woven on the Jacquard and nine on the Weavebird. Manufacturing time was plotted against preform complexity to derive separate plots for the Jacquard and Weavebird looms. For the separate looms, manufacturing time for a preform was shown to have a strong correlation with preform complexity. Analysis of the plots (Table 11) showed that those with nine Weavebird and eight Jacquard woven preforms gave the strongest positive correlation with preform complexity, as measured by correlation coefficient  $r^2$ , 0.78 and 0.89, respectively. Therefore, the

hypothesis of preform manufacturing time increasing non-linearly with preform complexity is considered valid based on the cost information and preform data provided. More data from a wider range of preforms of varying complexity are required to fully validate the non-linear relationship between manufacturing time and complexity.

A composite parts manufacturer received a quote for a single large, complex preform currently made by a US manufacturer for £7500. The cost of the new preform was compared with cost estimates for the preform based on data from preforms made on either the Jacquard or Weavebird looms. Analysis of the plots showed that the Jacquard weaves large, complex preforms more efficiently than the Weavebird. Therefore, the estimated cost for the preform, £21,087 based on data derived from the plot for eight Jacquardwoven preforms, was judged the most realistic although almost three times that of the US-supplier's cost of £7500. Based on a weight of 3132kg, the cost per kg for the US fabric is £2.4/kg. The raw fibre (E-glass) cost is £1/kg, so the material cost proportion for the fabric is 42%. For one-off preform manufacture, the material cost proportion varied from 3.7% to 4.9%, depending on whether the preform is to be made on a Weavebird or Jacquard loom. A recent cost modelling study of mass-produced wind turbine spar caps made with glass fibre composite [5] showed material proportions ranging from 35% to 52%, similar to a cost proportion of 42%, implying that the US-supplied fabric has been similarly mass produced, resulting in a cost per preform of £7500 compared to a one-off manufacturing cost of £21,087. A learning curve was derived based on a learning rate from the estimated labour and machine time proportions of total preform manufacturing time. From the learning curve, continuous production of 15 preforms resulted in a cost per preform of £8001, assuming no reduction in other costs such as tooling and infrastructure.

In concluding, the results imply that it is possible to make unique 3D woven preforms competitively on a suitable loom machine, provided that sufficient learning is embedded in the manufacturing organisation coupled with greater automation. Although studies have indicated that cost per part will initially increase following machine installation, cost per part will fall below the level present before machine installation as new learning is embedded for successful machine operation. This should encourage increased uptake of suitably designed 3D woven composites in a wider range of applications.

Further work could investigate mass customisation, where short manufacturing runs for a part of given size and complexity are coupled with fast turnaround times and tool changes for another part. This can be very expensive owing to a lack of embedded learning in a fast-changing production environment. Short runs of bespoke 3D woven preforms could be modelled more accurately if extensions of traditional learning curve models incorporating multi-variate analysis can be developed. Multi-variate learning curves are based on two or more independent variables and are required when quantitative and qualitative factors run in tandem, e.g., when fast tool changes are required for a run of new preforms. To date, development of multi-variate analysis tools for constantly changing scenarios has been sparse, a key issue being lack of real time manufacturing process data. However, recent advances in digital twin technology enabling real time imaging of a manufacturing operation based on worker performance and process data should encourage the development of multi-variate learning curves for improving worker learning so that the cost of short production runs of 3D woven preforms is reduced.

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