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# 3D WOVEN PREFORMS AND PROPERTIES FOR TEXTILE COMPOSITES

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## SUMMARY

3D woven fabric preforms exist in many forms. They could reduce aircraft weight by 30%. Software can specify weave structures and link to manufacture, but modelling of geometry and properties is a key to link empirical skills of the textile industry to an engineering design culture. There are opportunities for wider use, notably solid composites in construction and honeycomb structures for impact protection.

*Keywords: 3D woven fabrics, aerospace composites, modelling, honeycomb composites, construction, costs*

## INTRODUCTION

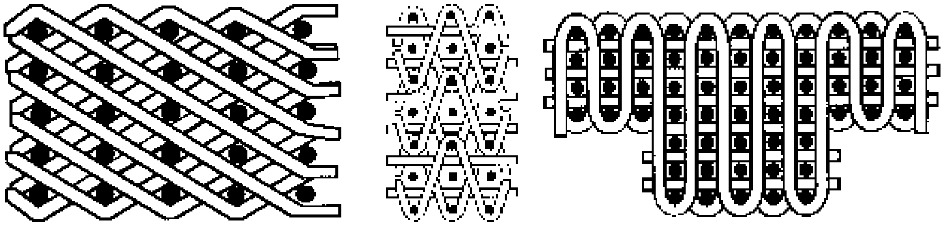
### 3D weaving

All textiles have a 3D internal structure, but macroscopically most can be regarded as thin 2D sheets. By 3D fabrics, we mean (1) thick multilayer fabrics in a simple regular form or (2) made in more complicated 3D shapes, (3) hollow multilayer fabrics containing voids and (4) thin 3D shells in complex shapes. 3D fabrics can be made by braiding, knitting or nonwoven processes, but for composites weaving is the preferred method. A variety of different structures can be formed. In a simple form of 3D weaving, yarns run in X (across), Y (along) and Z (through) directions, reversing only at the edges of the fabric. In 2D woven fabrics, interlacing is needed to give coherence to the material and this gives a wavy crimp to the yarn paths, but crimp can be avoided in 3D woven fabrics as the material is held together by straight yarns passing back and forth through the fabric. In other forms of 3D woven fabrics, more complex interlacing may occur, but except at edges of the cross direction, yarns always run continuously along and across the fabric; Z direction yarns may run all the way from top to bottom or reverse between layers.

Some simpler 3D woven fabrics have an old history. Velvet is woven as a two-layer fabric with crossing threads, which are then cut to give the pile. Some fabrics used in paper-making or filtration are two- or three-layer structures. These are multi-layer fabrics, in which neighbouring 2D weaves are linked by yarns crossing from one layer to the next. Hollow tubes can be made as two layers on the loom with the weft (fill) crossing from one layer to the other or by circular weaving. For composites, more layers or more complex shapes are needed. A strong interest in 3D woven fabrics for composites developed in the 1980s, though some of the proposed methods needed special machinery, including forms that were imaginative inventions but not really practical for general use. More recently, academic groups and companies have shown that more conventional weaving machines can be adapted for 3D weaving.

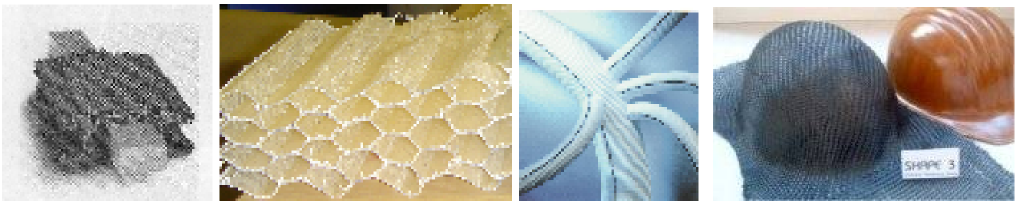
## Fabric types

Examples of different types of 3D woven fabrics are shown in Figures 1 and 2. Many other variants are possible.



(a) (b) (c)

Figure 1. Examples of solid 3D fabrics. (a) Angle interlock over total thickness. (b) Angle interlock in separate layers. (c) Profiled orthogonal.



(a) (b) (c) (d)

Figure 2 Examples of hollow and shell structures. (a) Beam preform. (b) Honeycomb composite. (c) Woven double velour vascular graft by Boston Scientific Company Inc. in 2004 and shown at Extreme Textiles Exhibition in New York. From McQuaid (3). (d) Dome fabric with composite helmet.

## Issues

It has been stated by Pritchard of Boeing [1] that 3D woven fabrics have the potential to reduce aircraft weight by 30%. In another article [2] he identifies the challenge as finding a composite that will take the stresses in curved components, such as those used to join the body of the aircraft to the wing, where poor resistance to axial compression on the inside of a bend leads to failure. There is a better chance of achieving this with a 3D fabric preform than with other composite structures. The density of through-the-thickness yarns, which would tend to prevent buckling of axial yarns, could be greater in curved sections than in straight sections.

There are two main advantages of 3D fabric preforms. One is improvement in through-the-thickness performance, which gives more freedom to design composites with optimum mechanical properties in all directions and particularly greater resistance to delamination. The other is that preforms can be made close to the required shape, which is finalised in the consolidation process. Production of the composite component can thus be an automated operation, with much lower cost than lay-up methods.

In order to develop a viable industrial base for 3D fabric composites, it is necessary that the traditional empirical craft-based methodology of the textile industry, which relies on great practical skills and intuition, should be changed to a quantitative approach, which matches the CAD procedures for aircraft, cars, trains, ballistic protection, construction and other engineering applications. A major current limitation is the lack of ability to produce realistic geometric models of 3D fabric structures and predict properties. There is then a need for testing of sample forms in order to validate predictions. Some testing of actual components will be needed to give confidence that the product will meet the critical standards of demanding applications, but the amount of trial-and-error needed to achieve a satisfactory design would be much reduced.

Cost reduction is always a goal, though if aircraft weight can be reduced, the material cost is less important. For applications where the advantages of weight reduction are not as great, for example in automobiles or construction, lowering cost through the manufacturing sequence is more important. Lower cost would be an important factor in increasing the market for 3D fabric composites. The main driving force for 3D woven fabric has been in carbon fibre composites for aerospace. Protection of military, police or security personnel, either in vehicles or through protective clothing, is another developed application. There have been various specialised uses. Even though in total these require substantial amounts of material, they are dwarfed by other potential uses. Some markets, notably in construction, have been blocked by a conservative unwillingness to use new materials. Effort is needed to find a greater variety of applications.

## MODELLING, PREDICTION AND TESTING

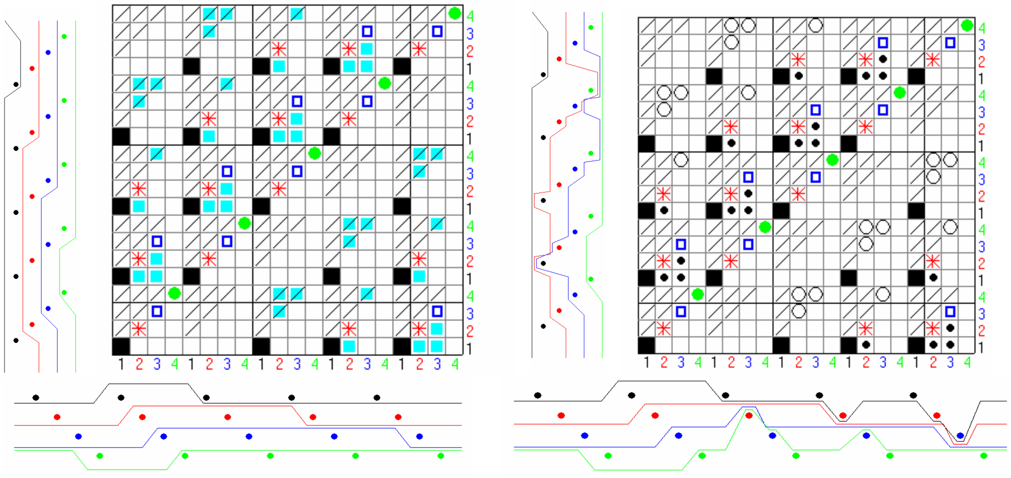
### The problem of textile experience

Textiles have been produced for thousands of years. Around 200 years ago, ingenious inventors transformed machines from manual to power-driven operation. Over the last 100 years, there have been many advances as electrical power and control became possible. Although an engineering design approach was adopted for machinery development and conrol, a tradition of intuitive and empirical skills, followed by evaluation of sample fabrics, remains the way in which materials are developed. Quantitative modelling is regarded as being more difficult than qualitative insight. For the ingenious advances in 3D fabrics for medical uses this is fine, because the surgeons have a similar qualitative mind. The approach is less effective in dealing with engineers used to quantitative design procedures. In order to satisfy a need, prototypes must be manufactured and tested and this becomes increasingly costly.

The same problem arose 20 years ago with ropes for mooring oil rigs in deep water. Collaboration between consultants with expertise in ropes and marine engineers was needed to produce an engineering design guide. One problem here was to specify rope stiffness values to put into mooring analysis programs, because the polyester rope extension was nonlinear, time dependent and imperfectly elastic; another was to identify failure modes and predict safe limits for use. It should be an aim of those concerned with achieving the potential of 3D fabrics to produce similar engineering design guides related to the needs of different applications. Carbon fibre properties are easier to deal with, but the effect of multi-directional fibre paths need to be modelled. For ropes CAD programs were developed to predict the response of structures with several levels of twist.

## Weave structure and geometry

Traditionally the multiplicity of 2D weaves has been designed by blacking selected squares on point paper to show whether the warp yarn was under or over the weft yarn. This can be adapted for 3D weaving, but is more complicated. Weave Engineer® from TexEmg Software Ltd computerises the process. As a simple example, the computer input for a multilayer fabric follows the following stages:
Step 1: Specify number of layers in the multi-layer weave.
Step 2: Specify weave formula for layer 1. Continue for all layers.
Step 3: Specify warp and weft ratios for layers (relative number of ends per unit width).
The result is a set of layers of 2D weaves, Figure 3(a), with suggestions for the stitching (interlacing) between layers to give the multilayer fabric, Figure 3(b). The user has an option to modify the stitching to generate the required 3D weave.



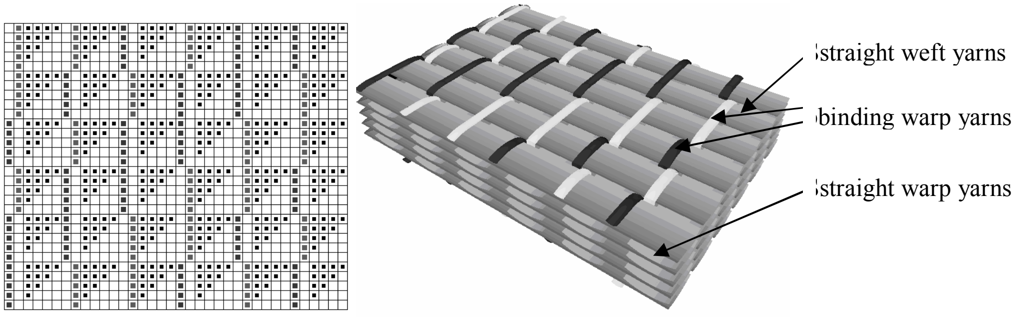
(a) (b)

Figure 3. (a) Separate layers of a multi-layer fabric. (b) With stitching between layers.

Figure 4 gives an example of the design of an orthogonal weave created using Weave Engineer®. Hollow CAD® is used for the design of 3D hollow woven architectures, Figure 5. These programs provide the topological structure and can be output to instructions for computer control of weaving.

The next step is to model the actual geometry but this is more difficult. Except for monofilaments or hard-twisted yarns, the cross-sections of yarns are indeterminate. Their volume and shape depend on the forces between yarns as they cross one another and the yarn cross-sections in turn affect the curvature of the yarn paths. Although there has been academic research on woven fabric mechanics, mostly on 2D plain weaves, for 60 years, it is only in the last ten years that useful modeling programs have been produced.

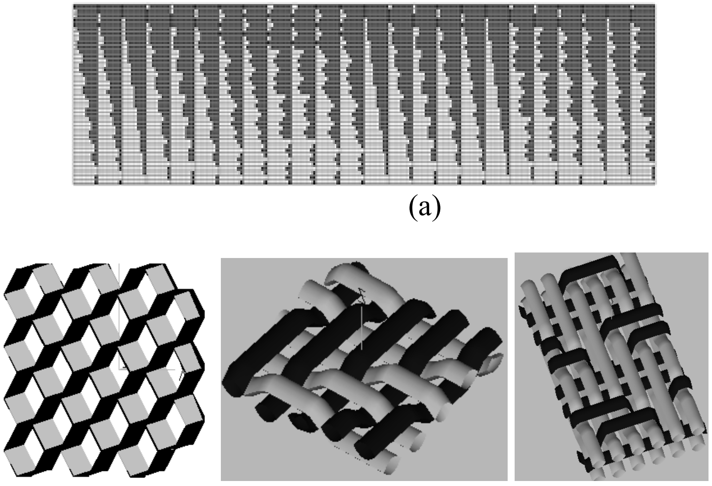
An important point is that an input of parameters of fabric design does not conform to the stress-free state. The known parameters are yarn linear density and yarn length between crossovers. The other parameters are warp and weft spacing, but these will have different values in the fabric as designed, in the fabric as it is woven, and in the fabric as it relaxes after being taken off the loom. The first step in modeling load-elongation curves is thus to determine the stress-free state. A preferred method is to minimize the tensile, bending and flattening energies of the yarns, in order to verify, or at least approximate, the real fabric geometry under zero stress. This is followed by determining changes under biaxial tension, plus shear forces and bending moments when their effects are to be modeled. Minimising energy will give the internal geometry in an externally deformed state. Repeating the minimisation after a small displacement in the required direction will give change in energy from which the force or moment can be calculated. Hence the load-deformation is obtained.



(a) (b)

Figure 4. Orthogonal weave created using Weave Engineer®.

| (a) weave design matrix | (b) 3D fabric |
|---|---|
| left column of each cell | black binder warp running across top of fabric |
| second column of each cell | white binder warp running across top of fabric |
| four columns on right of each cell | straight warp yarns, seen pale grey on front edge, running back across fabric |



(a)

(b) (c) (d)

Figure 4. Design of 3D hollow architecture using Hollow CAD®. (a) Weave design matrix. (b) The cellular structure (c) The weave used for the single layer cell walls. (d) The weave used for double layers where three walls join.

Similar procedures need to be developed for 3D fabrics, though the points for which yarn lengths are specified may be different. In one respect, the problem is simpler. For use in composites, the fabric preforms are not subject to large forces. What is needed is to know the fabric geometry, particularly the spaces between yarns and any misorientaion of yarns, under the small forces imposed when the fabric is consolidated with matrix. Deformation in the composite is limited to small strains. Established methods of mechanical analysis should be applicable, provided the fabric geometry is known.

The above procedure leads from the manufacturer to the user. A complementary need is for the user to understand what is needed. Many performance properties may be involved: strength, stiffness, rheology, fatigue resistance, directional effects etc. What improves one property may harm another, so that it is necessary to specify optimum values for some properties subject to minimum requirements for others. The rules that apply to a new material will not be the same as for old materials. In ropes for deepwater moorings, the oil industry at first thought that the newer high-performance fibres would be needed, but it turned out that polyester had the best combination of properties. The ropes need a low enough stiffness to limit peak loads as the rig rises and falls under wave motion and a high enough stiffness to limit lateral displacements due to tides and winds. For aerospace composites, carbon fibres are the obvious fibre to use, but these have a range of combinations of strength and stiffness to choose from. It may be that what is right for one set of yarns in a 3D woven fabric may not be right for other sets. The optimum solution will come from a synthesis of mechanics of materials and mechanics of operation. This is a challenge which textile and composites researchers will have to meet in cooperation with aerospace researchers, in order to provide quantitative modelling through the total system, not striving for academic perfection but aiming close enough to the target to be industrially effective.

## APPLICATIONS, COSTS AND MARKETS

### Established composite markets

For aerospace, automobile and other markets which have been penetrated by composites to replace metals, the use of 3D fabrics is a natural development driven either by improving properties, achieving performance that cannot be matched by current techniques, or by reducing total system costs.

### Hollow fabrics

3D hollow fabrics offer new opportunities. For a 3D hollow fabric with *n* layers, *n* sets of warp ends and *n* set of picks will be used for the fabric construction. The adjacent layers can be connected either along the warp direction, weft direction, or any direction. Depending on the rules followed in connecting the layers, various types of 3D hollow fabrics can be created. The cross-section of the 3D fabrics is either self-opening or can be opened by applying external force. The tunnels in the 3D fabric can run in any direction, and may not necessarily be straight. The specification of structural parameters and the coding format has been described by Chen [3]. For the example shown in Figure 4, there are single fabrics layers between voids and double layers where cells join.

After consolidation, 3D composite reinforcements fall into the category of 3D cellular (honeycomb) materials, which can be super-light, energy absorbent, voluminous and strong. Theoretical analyses on the 3D honeycomb composites has been carried out [4, 5] and it was suggested that the honeycomb composites have advantages over other types of cellular materials in energy absorption and force attenuation. Chen [3] describes a finite element analysis (FEA) to predict (a) transmitted force as functions of penetration and time and (b) energy absorption in impact on a cellular woven composite. Factors studies included cell opening angle, cell size, cell wall length ratios, composite thickness and composite density. The predictions of energy absorption in Table 1 shows how FEA can be used to optimize the honeycomb structure and the greater energy absorption compared to a solid structure.

Table 1 Energy absorption of various cellular structure composites

| | 8L3P | 8L4P | Solid |
|---|---|---|---|
| Kinetic Energy(J) | 8.3954 | 8.30704 | 8.09379 |
| Strain Energy(J) | 8.10308 | 4.36588 | 1.34834 |
| Energy Absorption | 96.5% | 52.6% | 16.7% |

Based on the FE analysis, an experimental study of 14 systematically designed and manufactured 3D honeycomb textile composites was carried out. The intended application was in leg-guards to give protection to police from low-velocity impact by missiles, sticks or metal bars. As an experimental srudy, fabrics were woven from polyester yarns in a flat form. Before impregnation, they were opened by inserting two sets of metal wires coated with PTFE. The consolidation solution was made as a mixture of resin LY5152 and hardener HY5052 with a mixing ratio of 100:38. After the resin has been applied on the fabric, the samples were placed in the fume cupboard for quicker hardening. A low-speed, drop-weight impact tester was used to measure the change in acceleration of the impact head and the transmitted force beneath the specimen. Figure 5(a) shows the superiority of the honeycomb composite to a foam protector and Figures 5(b) and (c) show simulated impact.

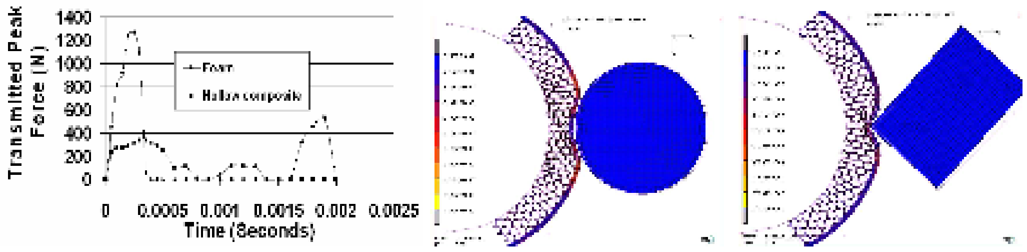


Figure 5. (a) Force transmission. (b) (c) Impact simulation.

The study showed that the performance and properties of the honeycomb composites can be engineered by specifying structural parameters of the 3D hollow fabrics. It also showed that the 3D hollow fabric composites are light in weight and are good in impact energy absorption and in impact force attenuation [4, 5, 6].

## New markets

Composites divide into two main categories. At one extreme, the early use of cotton composites, paper for decorative laminates and GRFP (glass fibre reinforced plastics) are comparatively low technology operations. At the other, advanced composites, with a strong engineering design input, have been dominated by carbon fibres in uses such as aerospace, specialist cars, and high-performance sporting goods. In between, there is an opportunity for engineering uses that are somewhat less demanding but where low cost is needed for a large volume market. Mass market vehicles and construction are the most obvious examples.

The use of 3D fabrics in near-net shapes is a significant way to reduce manual labour costs, because the whole piece can be put in a mould instead of having to lay up multiple layers. This development needs to be taken a stage further by automating the operations, either in a continuous production line or by sequential transfer between stages.

The other way to reduce costs is to use cheaper fibres. Glass fibre, in its various forms, is the obvious fibre to try, but there is another fibre that has been neglected for rigid composites, but is dominant in flexible composites through the reinforcement of rubber. Polyester is now the world's general purpose fibre and the scale of its production makes it one of the cheapest fibres, though E-glass is similar in price. Table 1 shows some illustrative properties of polyester, glass and carbon fibres, though there are ranges of values for each fibre type.

Table 2. Fibre properties. Approximate values from Hearle (2001, 2008).

| | | polyester | E-glass | S-glass | carbon |
|---|---|---|---|---|---|
| cost | US$/kg | 3 | 3 | 15 | 15 |
| density | g/cm$^3$ | 1.4 | 2.5 | 2.5 | 2 |
| strength | N/tex = GPa/(g/cm$^3$) | 0.8 | 1.2 | 1.6 | 2 |
| | GPa | 1.15 | 3 | 4 | 4 |
| modulus | N/tex = GPa/(g/cm$^3$) | 13 | 29 | 34 | 150 |
| | GPa | 18 | 72 | 86 | 300 |

Polyester has much lower values of strength and stiffness on an area basis but approaches glass on a weight basis. The lower density leading to greater thickness of components will tend to increase bending stiffness. In considering any application, it is important to know how much deformation is allowable. If moderate deformations are acceptable, or even useful in reducing impact forces, polyester would be a contender. There is another potential advantage. High-tenacity polyester yarns mixed at yarn or fabric stage with a lower melting variant could be thermally bonded. Recycling into other uses would be easy. It might even be possible to dispense with a binder fibre and just use heat and pressure, as in Ward's compaction process.

A technical/economic evaluation from Hearle et al [7] gave the estimates for material costs for a simple beam shown in Table 2. Glass or polyester composites are competitive with steel in strength but not in bending stiffness. However the lower weight would change the system design parameters and greater deformation might be allowable. A continuous manufacturing process for forming a 3D woven fabric composite is illustrated in Figure 5. For an automated sequential process, the cut would occur between weaving and consolidating. The estimated manufacturing costs are shown in Table 4 and add little to the material costs. The devil in the detail is that production approaching a million meters per year would be needed to achieve the economics. How can one move to that market size unless there are manifest advantages or state subsidy?

Table 3. Simple beam: cost and property comparisons.

| | steel | glass | polyester | aramid |
|---|---|---|---|---|
| MATCH BREAK LOAD | | | | |
| area $m^2$ | 0.0086 | 0.0021 | 0.0070 | 0.0024 |
| weight kg/m | 68.40 | 4.35 | 9.82 | 3.20 |
| material £/m | 13.7 | 4.79 | 9.62 | 52.97 |
| MATCH STIFFNESS | | | | |
| area $m^2$ | 0.0086 | 0.0132 | 0.0239 | 0.0111 |
| weight kg/m | 68.40 | 27.84 | 33.52 | 14.74 |
| material £/m | 13.70 | 30.61 | 33.52 | 244.31 |

Figure 5. A production scenario, from Hearle et al (1995).

## CONCLUSION

3D woven fabrics have a considerable potential to produce composites with improved properties. When the total manufacturing pipeline is taken into account, costs are lower than methods involving lay-up of prepreg or other current methods. Costs would be reduced by automated methods for producing material in quantity for large-volume markets.

An immediate need is to develop 3D fabric composites for future aircraft. In addition to satisfying technical requirements, particularly for curved joints, an expansion of manufacturing capability and carbon fibre production would be needed. CAD software is available for specifying fabric topology, i.e. diagrammatic weave structure, and linking this to computer control of weaving machines. What is lacking is the ability to model realistic fabric geometry and predict properties. CAD software is needed to match the skills of the textile industry to the engineering design culture of the applications. The longer term opportunity is to develop 3D fabric composites for new large volume applications such as vehicles and construction at a competitive cost

Table 4. Manufacturing cost estimate.

| | |
|---|---|
| **Estimated rate of production: 2 meters per minute** | |
| ANNUAL PRODUCTION AT 80% EFFICIENCY: 840,000 meters | |
| **Capital costs scenario** | |
| creel: | £20,000 |
| consolidation: | £100,000 |
| weaving machine: | £40,000 |
| associated gear: | £ 40,000 |
| Jacquard: | £30,000 |
| automation: | £100,000 |
| feed/transport: | £10,000 |
| other items: | £ 20,000 |
| **Production costing** | |
| TOTAL CAPITAL COST: £360,000 | |
| depreciation of capital cost over five years | £ 72,000 pa |
| finance at 5% | £18,000 pa |
| OPERATING LABOUR | |
| 2 people for 5 shifts: 10 x £15,000 | £150,000 pa |
| ENERGY | £ 15,000 pa |
| SUB-TOTAL | £255,000 pa |
| OVERHEAD AND PROFIT | £255,000 pa |
| TOTAL ANNUAL COST £510,000 pa | COST PER METER £ 0.60 |

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