Cost Estimates to Guide Pre-selection of Processes

*A. M. K. Esawi and M. F. Ashby**
Mechanical Engineering Department, The American University in Cairo, 113 Kasr El Aini St., P.O. Box 2511, Cairo 11511, Egypt
**Engineering Design Centre, Cambridge University Engineering Department, Trumpington Street, Cambridge CB2 1PZ, UK*
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ABSTRACT

A *process* is a method of shaping, joining or surface-treating a material. Process selection has three steps. The first is to identify, from the "menu" of all available processes, the subset which can give a chosen material to the desired shape with the desired detail, precision and finish. The second is to choose, from among these, the ones that will do so at the lowest cost. The final step is to investigate the most promising processes in depth, exploring considerations such as availability, in-house experience, safety and environmental issues. The first two steps can be thought of as *process pre-selection*. Components have to be assembled and finished to create products. Here too, the ability to rank by cost, however crudely, helps guide pre-selection.

Cost models are reviewed from the perspective of material and process selection. An approximate model is useful provided it has generality – that is, it must allow comparison of very different processes. Many approaches fail in this. One that works, based on *resource consumption*, is developed here and its use for selection is illustrated. It has been implemented as part of a tool that allows rapid pre-selection from a database of 112 processes.

1. Process pre-selection.

A process, in the sense used in this paper, is a method for shaping, joining or surface-treating a material. There are many processes, each with its own characterising attributes: the materials with which it is compatible, the shapes it can make, the features it can create, and so forth. Process selection is the act of identifying, from among these, the process best suited to meet the requirements of a design. As detailed elsewhere (Esawi and Ashby, 1998b; Ashby, 1999), process selection has three steps: *screening*, *ranking* and a search for *supporting information*. In the first step, all processes that cannot meet the design requirements are screened out, leaving only those that can achieve them. In the second, the surviving candidates are ranked by cost, identifying the small number that are most promising for deeper exploration. In the final step, supporting information is sought for each of the top-ranked candidates – details of the shapes it can make, the materials with which it is compatible, and case studies of its application in other products and so forth.

The first two steps can be thought of as pre-selection. They identify the subset of processes that are worth exploring in depth. The last step, in which detailed information for the most promising candidates is assembled and reviewed, is the one in which the final selection is made. We are here interested in pre-selection, requiring methods for screening the large population of processes to identify those that have promise, and for ranking them to guide the final, in-depth exploration,. The ranking, almost always, involves consideration of cost.

2. Estimating cost

Cost models for a manufactured component or system can have several purposes. The required output of a cost-estimating method depends on the purpose for which it is to be used. When the purpose is that of competitive bidding, the model must deliver an absolute cost, and do so with precision; an error of a few % here makes the difference between profit and loss. When the purpose is that of guiding the selection of a process, our interest here, the model need only give a relative cost and this can be useful even when it is approximate: in the early stages of design or of selection an estimate which is accurate to within a factor of two is helpful.

Function-costing (Boothroyd, 1988, Allen and Swift, 1990, Wierda, 1988, French, 1992) or *parametric methods* (Hoult and Meador, 1997) interpolate the cost of a component or system that is a variant of an existing family for which historic cost data already exist. They are feasible only if two conditions are met: first, the component must be a member of a closely related family; and second, the family must have many members with established costs, providing the historical data. They have the merit that they can be applied to large, complex systems. Thus the cost of large coal-fired power plants scales with the output, costing around $1500/kW. That of subsonic passenger aircraft scales with the number of seats: $200,000 per seat is typical. That of large oil tankers scales with their displacement: something like £1000/tonne. Here a function metric – power output, passenger capacity, displacement – is used as a surrogate for cost.

Similar empirical, or *cost scaling methods* can be used at the component level (Hoult and Meador, 1997, Boothroyd et al, 1994; Ostwald, 1998, Weustink et al 1998, Ulrich and Eppinger, 2000, Swift 2002). They are based on correlations, again using historical data, for the cost of making a part with a given set of *features*. Thus the cost of a sheet metal part with features made by shearing, drawing and folding can be estimated by analysing correlations between the cost of previously made parts with these features against their size, shape and complexity, and then locating the new part in this field of costs. The method allows high precision and, within a limited domain such as that of sheet stampings, is perhaps the most successful approach to cost estimation early in the design process. But the requirement of correlations based on historical data for a family of closely related products made of the same materials – a narrow domain – is a very restrictive one. The approach is of little help in guiding pre- selection, for here the domain is enormous and the historical data exist only for a tiny part of it.

Activity-based costing methods (Cooper, 1988; Emblemsvåg and Bras, 1994) seek to calculate and sum the cost of each unit operation involved in the manufacture of a component or system (retrieval of materials, set up time, time to perform step, de-mounting time, time to pass to next step…) – information of such detail that it can be established only when the design is in its final phase. The method is helpful in cost-cutting and for competitive bidding when established processes are in place, but it requires a formidable repository of input data – data that are not available in the early stages of a design when many alternative processes are still under consideration.

Resource-based modelling (Esawi and Ashby, 1998; Ashby, 1999) assess the resources of materials, energy, capital, time and information associated with the manufacture of the component. The method is approximate – often values for these inputs are known only within broad limits – but it is comprehensive, equally applicable to all processes no matter how different, since all consume these basic resources. This makes the method well-suited for assessing relative cost, and guiding pre-selection. *Technical cost modelling* (Field and de Neufville, 1988; Clark et al 1997) starts from a similar basis, refining it by adding more detail and incorporating sub-models for the ways in which equipment and tooling cost, production rate and such like scale with the size, complexity and production volume of the component. It becomes useful when a process has been implemented and guidance is sought in optimising its operation.

In what follows the focus is on resource-based cost estimation with the purpose of guiding process pre-selection.

3. Cost modelling for selecting shaping processes.

3.1 The aims of the model

In manufacture, materials are shaped, joined and finished to create products. There are many different ways of creating shape, some using solid-state methods, some liquid state and a few the vapour state. From a practical standpoint it is helpful to classify them under the following seven headings:

- *Vapour deposition methods* such as CVD and PVD.
- *Casting*, the traditional way of shaping metals from the liquid state.
- *Moulding*, used to shape polymers and glasses.
- *Powder methods*, used to shape both metals and ceramics.
- *Deformation processing*, such as forging and rolling, exploiting the plasticity of metals.
- *Machining,* shaping by cutting, can be used to shape almost any material.
- *Composite forming,* special methods developed to shape continuous fibre composites.

Our aim here is a model that allows the ranking of competing processes by cost. Thus it is a *relative* cost that is sought, not an absolute one; factors that affect all processes in a similar way, either by adding a fixed cost or by applying a fixed multiplier, do not change the ranking, and this allows a certain degree of freedom. But the model must also meet certain over-riding constraints, of which the principal ones are these:

- that it can be applied to *all* processes for creating shape from competing (and thus different) materials, allowing comparison between them – it must, for instance, allow a comparison of the cost of a polymer component made by injection moulding with that of a competing design in aluminium made by die-casting; and
- that it can be used early in the design process (since its purpose is to guide design decisions), before many details of the shape are known.

The constraints can be met only by making gross simplifying assumptions, and the results must therefore be seen as broad indicators to guide decision-making, not as precise predictions. With this in mind, we approach the problem in the following way.

3.2 The model

The manufacture of a component consumes resources (Figure 1), each of which has an associated cost. The final cost is the sum of those of the resources it consumes. They are detailed in Table 1. Thus the cost of producing a component of mass m entails the cost C_m ($/kg) of the materials and feed-stocks from which it is made. It involves the cost of dedicated tooling, C_t ($), and that of the capital equipment, C_c ($), in which the tooling will be used. It requires time, chargeable at an overhead rate $\dot{C}_{oh}$ (thus with units of $/hr), in which we include the cost of labour, administration and general plant costs. It requires energy, which is sometimes charged against a process-step (particularly if it is one that is very energy intensive) but more usually is treated as part of the overhead and lumped into $\dot{C}_{oh}$ (as we shall do here). Finally there is the cost of information, meaning that of research and development, royalty or licence fees; this, too, we view as a cost per unit time and lump it into the overhead.

Imagine now the manufacture of a component (the "unit of output") weighing m kg, made of a material costing C_m $/kg. The first contribution to the unit cost is that of the material mC_m magnified by the factor 1/(1-f) where f is the scrap fraction – the fraction of the starting material that ends up as sprues, risers, turnings, rejects or waste:

$$C_1 = \frac{m\,C_m}{(1-f)} \qquad (1)$$

Table 1. Symbols, definitions and units

Resource		Symbol	Unit
Materials:	inc. consumables	C_m	$/kg
Capital:	cost of tooling cost of equipment	C_t C_c	$ $
Time:	overhead rate, including labour, administration, rent …	$\dot{C}_{oh}$	$/hr
Energy:	Power cost of energy	$\dot{P}$ C_e	kW $/kW.hr
Information:	R & D or royalty payments	C_i	$/year

The cost C_t of a set of tooling – dies, moulds, fixtures and jigs – is what is called a *dedicated cost*: one that must be wholly assigned to the production run of this single component. It is written off against the numerical size n of the production run. Tooling wears out. If the run is a long one, replacement will be necessary. Thus tooling cost per unit takes the form

$$C_2 = \frac{C_t}{n}\left\{\mathrm{Int}\left(\frac{n}{n_t} + 0.51\right)\right\} \tag{2}$$

where n_t is the number of units that a set of tooling can make before it has to be replaced, and 'Int' is the integer function. The term in curly brackets simply increments the tooling cost by that of one tool-set every time n exceeds n_t.

The capital cost of equipment, C_c, by contrast, is rarely dedicated. A given piece of equipment – a powder press, for example – can be used to make many different components by installing different die-sets or tooling. It is usual to convert the capital cost of *non-dedicated* equipment, and the cost of borrowing the capital itself, into an overhead by dividing it by a capital write-off time, t_{wo}, (5 years, say) over which it is to be recovered. The quantity C_c/t_{wo} is then a cost per hour – provided the equipment is used continuously. That is rarely the case, so the term is modified by dividing it by a load factor, L – the fraction of time for which the equipment is productive. The cost per unit is then this hourly cost divided by the rate $\dot{n}$ at which units are produced :

$$C_3 = \frac{1}{\dot{n}}\left(\frac{C_c}{L\,t_{wo}}\right) \tag{3}$$

Finally there is the overhead rate $\dot{C}_{oh}$. It becomes a cost per unit when divided by the production rate $\dot{n}$ units per hour:

$$C_4 = \frac{\dot{C}_{oh}}{\dot{n}} \tag{4}$$

The total shaping cost per part, C_s, is the sum of these four terms, taking the form:

$$C_s = \frac{m\,C_m}{(1-f)} + \frac{C_t}{n}\left\{\mathrm{Int}\left(\frac{n}{n_t}+0.51\right)\right\} + \frac{1}{\dot{n}}\left(\frac{C_c}{L\,t_{wo}} + \dot{C}_{oh}\right) \tag{5}$$

The equation says: the cost has three essential contributions – a material cost per unit of production which is independent of batch size and rate, a dedicated cost per unit of production which varies as the reciprocal of the production volume (1/n), and a gross overhead per unit of production which varies as the reciprocal of the production rate $(1/\dot{n})$.

The model can be refined by incorporating functional dependencies of captial cost C_c, tooling cost C_t and production rate $\dot{n}$ on size and complexity. An implementation of this, illustrated by a case study, appears in the Appendix.

3.3 The use of the model for selecting shaping processes

If values can be established for the parameters in equation (5), it can be used to compare the costs of competing processes. Figure 2 shows the unit cost, C, of equation (5) plotted against batch size, n, for three competing processes. At small batch sizes the unit cost is dominated by the "fixed" costs of tooling (the second term on the right of equation (5)). As the batch size n increases, the contribution of this to the unit cost falls (provided, of course, that the tooling has a life that is greater than n) until it flattens out at a value that is dominated by the "variable" costs of material, labour and other overheads. Competing processes usually differ in tooling cost C_t and production rate $\dot{n}$, causing their $C - n$ curves to intersect, as shown in the schematic. Here process C is the most economic at low values of n, process B at intermediate and process A at high n. The "economic batch size", often quoted for a process, is the range of n over which that process is, generally speaking, less expensive than competing processes.

Comparisons of this sort guide the choice of process to make a given part, and highlight cost drivers, suggesting ways to reduce cost. Its implementation requires a database with approximate values for the inputs to equation (5) for a wide spectrum of processes, to be used as a starting point. Once the choice has been narrowed, it becomes practical to seek more accurate values for one or a few preferred processes, but at the pre-selection stage this is impractical – the range of options is too wide. Here we describe one such implementation, CES 4 (2002) and its outputs.

CES 4 contains records for 112 shaping processes representative of the families listed at the beginning of this section*. Each record lists the attributes of the process and contains approximate data for capital and tooling costs, production rate, tool life etc., stored as ranges as shown in Figure 3. The ranges of capital and tooling cost span that typical of injection moulding equipment and they are wide, reflecting the ranges of size and of mould complexity of which this process is capable. Equation (5) contains other parameters not listed in Figure 3 because they are not attributes of the process itself but depend on the design, or the material, or the economics (and thus the location) of the plant in which the processing will be done. The user of the cost model must provide this information, conveniently entered through a dialogue box like that of Figure 4.

This completes the input of parameter-values. One type of output is shown in Figures 5 for two competing processes – injection moulding and thermoforming. The user-defined parameters are listed on each figure. The shaded band brackets a range of costs. The lower edge of the band uses the lower limits of the ranges for the input parameters – it characterises simple parts requiring only a small machine and an inexpensive mould. The upper edge uses the upper limits of the ranges; it describes large complex parts requiring both a larger machine and a more complex mould. Comparing Figures 5a and 5b we note that thermoforming, at low batch sizes, is much less expensive than injection moulding, but that at a batch size of around 1000 injection moulding becomes the cheaper process.

* The database and the selection methodology are explained in detail in Esawi and Ashby, 1998b.

Output of a different sort is shown in Figures 6. Here unit cost is plotted against material cost for a single process at a chosen batch size (here, 1,000). Processing costs dominate provided the material costs less than about \$3/kg – here economies are best found by seeking cheaper mould materials or increasing production rate. But at a batch size of 1,000,000 (not shown) the picture changes – material dominates unit cost unless the material costs less than \$1/kg; if it costs more, economies might be sought by using a cheaper material.

Plots of this sort allow two processes to be compared and highlight cost drivers, but they do not easily allow a ranking of a large population of competing processes. This can be achieved by plotting unit cost for each member of the population for a chosen batch size. It is shown as a bar chart such as that of Figure 7. A dialogue box like that of Figure 4 allows user-defined parameters, including batch size, to be set. The software evaluates equation (5) for each member of the population and orders them by the mean value of the cost suggesting those that are the most economic. As explained earlier, the ranking is based on very approximate data; but note that the most expensive processes in Figure 6 are over 100 times more expensive than the cheapest; an error of a factor of 2 in the inputs changes the ultimate ranking only slightly.

4. Joining processes

Assembly – the joining of the individual parts of a product – is known to be an important cost-driver. Joining methods fall under 4 broad headings:

- *Fasteners*, including rivets, threaded fasteners and snap-fits
- *Thermal welding*, including soldering, brazing, gas, electric and power-beam welding.
- *Mechanical welding*, relying on friction at low or ultrasonic frequencies, and
- *Adhesive*s, both rigid and flexible

The dominant constraints in selecting a joining process are usually set by the material or materials to be joined, by the geometry of the joint itself (butt, sleeve, lap etc) and by the loads it must carry (tension, compression, shear …). When these and secondary constraints (requirements that the joint be water-tight, or demountable, or electrical conducting, for example) are met, the relative cost becomes the discriminator. Some insight can be gained by analysing it in terms of resource consumption, as we did with shaping processes. Following the argument of section 2, we arrive in an obvious way at an approximate joining cost C per unit of production (one unit = one fully assembled product) of:

$$C_j = \sum_{\text{all joints}} \left\{ C_{\text{consumables}} + \frac{C_t}{n_{\text{total}}} + \left(\frac{C_c}{L\, t_{wo}} + \dot{C}_{oh} \right) \left(t_{\text{process}} + \frac{t_{\text{setup}}}{n_{\text{batch}}} \right) \right\} \qquad (6)$$

Here $C_{consumables}$ is the cost of weld-rod, flux, adhesives or fasteners per unit of production. The number n_{total} is the number of joints to be made in the entire production run, which is done in many batches of n_{batch}, each requiring a set-up time t_{setup}. As with shaping, C_t is the cost of dedicated jigs and tooling, C_c is the capital cost of the welding equipment, or adhesive application system, or riveter, scaled as before by a write-off time t_{wo} and load factor L; and $\dot{C}_{oh}$ is the overhead rate. The quantity $t_{process}$ is the time to create a single weld or adhesive joint, or to insert a single fastener.

Detailed studies of assembly costs – particularly those involving fasteners (Boothroyd et al, 1994 and Boothroyd, 1997) – establish that it is the last of the three terms in equation (6) that dominates the cost, and the parameter that most influences its magnitude is the process time $t_{process}$. The key to low-cost assembly is to make it fast. Design for assembly (DFA) addresses this issue. The method (Boothroyd et al, 1994; Boothroyd, 1997) has three steps. The first is an examination of the design of the product, questioning whether each individual part is necessary. The second is to estimate the assembly time $t_{process}$, by summing the times required for each step of assembly, using historical data that relate the time for a single step to the features of the joint – the nature of the fastener, the ease of access, the requirement for precise alignment and such like. At the same time an "ideal" assembly time $(t_{process})_{ideal}$ is calculated by assigning three seconds (an empirical minimum) to each step of assembly. In the third step, this ideal assembly time is divided by the estimated time $t_{process}$ to give a DFA index, expressed as a percentage:

$$\text{DFA index} = \frac{(t_{process})_{ideal}}{t_{process}} \times 100 \qquad (7)$$

This is a measure of assembly efficiency. It can be seen as a tool for motivating redesign: a low value of the index (10%, for instance) suggests that there is room for major reductions in $t_{process}$ with associated savings in cost.

DFA methods available at present focus almost exclusively on joining with fasteners, allowing detailed comparison between alternative choices. They do not so readily allow comparison of these with – for instance – welding methods or adhesive bonding. This drives us back to equation (6) which is sufficiently general that it can, given values for its parameters, allow this comparison. The main conclusions that can be drawn from it are that, for short production runs, tooling costs will dominate, making processes with low tooling costs the best choice – manual welding, for example. For large production runs, the key issue is the reduction in the assembly time, $t_{process}$, favouring processes that are fast – automated spot welding, for instance.

Numerical data for the parameters of equation (6) are very hard to obtain. It is, however, possible to rank the main cost drivers – tooling cost, capital cost and time or rate – as low, medium or high, allowing reasoning like that above to be used to guide selection. Process selection systems (of which CES 4 is an example) attempt to do this.

5. Surface treatment processes

Almost all components and products are given some sort of surface treatment. They range from simple spray painting to elaborate coatings and heat treatments. All add cost. The list below gives a feel for the range.

- *Surface heat treatments*: carburising and the like, induction, flame and laser hardening, and ion implantation
- *Coatings*, involving plating, vapour deposition, thermal spraying, anodising and polymer powder coating
- *Painting and printing*, using oil and water-based pigment and pre-printed films.
- *Grinding and polishing* (mechanical, chemical and electrochemical) add precision and finish.

A surface treatment imparts properties to a surface that it previously lacked (dimensional precision, smoothness, corrosion resistance, hardness, surface texture etc.). The dominant constraints in selecting a treatment are the surface properties that are sought and the material to which they are to be applied. Once these and secondary constraints (the ability to treat curved surfaces or hollow shapes, for instance) are met, relative cost again becomes the discriminator. Here again the resource-based approach gives some insight into the way such treatments increase cost. The obvious adaptation of equation (6) to describe the cost C_{ST} of the treatment is:

$$C_{ST} = C_{consumables} + \frac{C_t}{n_{total}} + \left(\frac{C_c}{L\,t_{wo}} + \dot{C}_{oh}\right)\left(\frac{t_{treatment}}{n_{per\ run}} + \frac{t_{setup}}{n_{batch}}\right) \qquad (8)$$

The terms have the same broad meanings as in equation (6). $C_{consumables}$ is the cost of consumables and coating materials per unit of production – the materials, here, are often expensive, and the wastage sometimes high (paint lost during spraying, spent plating baths, powder loss in powder coating …). Dedicated tooling cost, considerable for shaping processes, are often small for surface treatment (precision grinding is an exception). Capital costs can be high (examples are large heat-treatment furnaces, induction and laser and plasma heating units, and vacuum deposition equipment), but are often used to treat many components at the same time. When this is the case, the treatment time $t_{treatment}$ is interpreted as the real process time divided by the number of parts that are treated in one run, $n_{per\ run,}$ to be distinguished from the total number treated in a set of runs, n_{batch}.

Consider two examples, bringing out the different cost drivers for different treatments. *Painting* is possible with very simple equipment (C_t and C_c both low), but application takes time, and the paint has to dry to some degree before the painted object can be handled, making it slow. Organic-solvent based paints are easier to spray and dry much more quickly than water-based paints, favouring their use despite the considerable environmental problems they create. By contrast, adding *precision and surface finish* involve "machining" operations that do not change the shape significantly, but still remove material. If this is to be done accurately the equipment and tooling must be built to a precision at least as great as that to be created, and they must also be sufficiently rigid that machining forces do not create significant deflections. These are demanding constraints with major influence on the cost of jigs and tooling, C_t, and on the capital cost of the equipment C_c. And the higher the precision and finish, the longer is the set-up time t_{setup} and the slower is the material removal rate, increasing $t_{treatment}$ as well. Cost rises steeply with the desired precision.

As with joining, numerical data for the parameters of equation (8) are very hard to obtain. Instead, pre-selection tools rank the main cost drivers – tooling cost, capital cost and time or rate –as low, medium or high, giving some guidance.

6. The total manufacturing cost

Any product is made up of components, each of which is shaped. These are joined and – either before or after the joining – given a surface treatment. The final cost of the product is the sum of the contributions of shaping, joining and surface treatment:

$$C_{product} = \sum_{components} C_s + \sum_{joints} C_j + \sum_{treatments} C_{ST}$$

As a broad generalisation, when the batch size is small, the total cost is dominated by the cost of dedicated tooling, jigs and fixtures. When the batch size is large, it is dominated instead by the cost materials and time. Thus low-volume production focusses on minimising tooling cost, even if this means that the process is slow; high-volume production, by contrast, requires fast processing and minimum material wastage, even if this requires expensive tooling.

7 Examples of output

Implementing pre-selection requires a database of processes and their attributes, a search engine that can screen out the members that fail to meet the design requirements, and pointers to sources for further information. The CES4 (2002) selection software is one implementation that does this. Its use is illustrated in the two examples that follow.

7.1 A nozzle for a chemical engineering plant

A set of 10 nozzles (Figure 8) is required for high-temperature (1000^{o}C) chemical converters. Each nozzle is to be made of a high chromium nickel-based superalloy, chosen because it offers the required temperature and corrosion-resistant capability. The weight is estimated to be about 0.3 kg and the minimum section thickness to be 3 mm. Each nozzle has an axisymmetric shape with a central circular channel. The specification requires a surface roughness of better than 10 μm and precision better than $\pm$ 0.2 mm. The inputs are summarised in Figure 9.

Applying these as screening criteria leaves, from an initial database of 112 shaping processes, six broad classes: machining from solid, investment casting, CLA/CLV (a variant of investment casting), closed die forging and powder forging (followed by machining to create the central hole). In the second step the surviving candidates are ranked by cost. To do this, the user must provide information that is unique to the design or is company-specific: batch size (the number of nozzles to be made), overhead rate, load factor, capital write-off time etc. The ranking step is shown graphically in Figure 10 with values for these parameters marked on it. Here each bar shows the range of cost of making a nozzle by a given process. Processes that passed the screening step are shown in bold and are labelled. For a batch size of 10, manual investment casting and manual machining from the solid are the cheapest processes – they merit further investigation.

If the batch size in increased to 10,000, the ranking changes. Powder methods now offer the cheapest route, followed by closed die forging and automated investment casting.

7.2 Forming a Jug Kettle

A shaping process is required to make the body of a jug kettle (Figure 11). The candidate material is polypropylene. The kettle holds about 1.5 litres of water, has a diameter of approximately 120 mm and a height of 200 mm. To avoid out-of-round distortion on tilting and pouring, the minimum wall thickness should be 3 mm giving a body-weight of about 0.4 kg. The shape is that of a deep cup. Mis-dimensioning of the kettle will prevent the lid fitting properly, so a tolerance of ±0.5 mm or better is required. The smoothness of the surface is important both for ease of cleaning and for visual appeal, requiring a surface roughness of better than 0.8 µm. These screening criteria are listed in Figure 12.

Applying these, several processes emerge as possible candidates: injection moulding, rotational moulding, and various variants of blow moulding. The next step is to rank them by approximate cost. The kettle, if successful, is expected to sell at least 100,000 units, defining the desired batch size. This and the other user-defined parameters are listed on Figure 13, which shows the cost ranking. It suggests injection moulding and blow moulding for deeper investigation. The final choice between them requires a more detailed exploration, practical when a limited number of candidate-processes have been identified.

8 Summary and Conclusions

The designer, in considering alternative choices of manufacturing-process routes for a given component, wishes to rank possible options by their cost. The cost must be arrived at by a technique that is applicable to all the options - that is, it should be applicable to any shape made of any material, by any process. With this breadth of scope the estimate cannot be accurate -- indeed it may be only of the most approximate kind. But the goal here is that of *ranking*; and for ranking purposes an approximate estimate is good enough. Realistically, the function of the pre-selector described here is to provide guidance in the early stage of design when material and process route are first under consideration, to prompt the user so that potential process routes are not overlooked; and to provide a brief description of the process and its attributes quickly and intelligibly. This, we conclude from our study, is feasible.

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Appendix: Adding Technical Modelling

Equations (5), (6) and (8) are the first step in modelling cost. Greater predictive power is possible by introducing elements of *technical cost modelling, or TCM* (Field and de Neufville, 1988; Clark et al 1997). TCM exploits the understanding of the way in which the control-variables of the process influence production-rate and product properties and uses information on the way the capital cost of equipment and tooling scale with output volume. These and other dependencies are captured in theoretical and empirical formulae or look-up tables that are built into the cost model, giving greater resolution. The challenge is to do this while retaining the breadth of choice described in the main text of this paper. This limits the modelling to that dealing with the two most obvious cost-drivers: the size of the component, and its complexity. Within the normal size and complexity range accessible to a process, capital cost C_c and tooling cost C_t rise with size and complexity, and production rate $\dot{n}$ falls. These dependencies are adequately described by the set of equations

capital cost $$C_c = \overline{C}_{co}\left(\frac{m}{\overline{\overline{m}}}\right)^{x_c}\left(\frac{K}{\overline{\overline{K}}}\right)^{y_c} \quad \text{(A1a)}$$

tooling cost $$C_t = \overline{C}_{to}\left(\frac{m}{\overline{\overline{m}}}\right)^{x_t}\left(\frac{K}{\overline{\overline{K}}}\right)^{y_t} \quad \text{(A1b)}$$

production rate $$\dot{n} = \overline{\dot{n}}_o\left(\frac{m}{\overline{\overline{m}}}\right)^{x_p}\left(\frac{K}{\overline{\overline{K}}}\right)^{y_p} \quad \text{(A1c)}$$

Here $\overline{C}_{co}$, $\overline{C}_{to}$ and $\overline{\dot{n}}_o$ are the capital cost, tooling cost and production rate of a component with a size m equal to the average (geometric mean) $\overline{\overline{m}}$ of the size-range associated with that process:

$$\overline{\overline{m}} = \sqrt{m_{LN}\, m_{HN}} \quad \text{(A2)}$$

where m_{LN} and m_{HN} are the normal lower and upper limits of component mass that the process can handle. K is a measure of complexity on a scale of 1 (simple) to 5 (complex). $\overline{K}$ is an average complexity, set equal to 2 in our calculations. The exponents x and y, positive for capital and tooling cost, negative for production rate, describe the dependence of these on size and complexity; the subscripts "c", "t" and "p" mean "capital", "tooling" and "production rate".

Values for the exponents are found by plotting existing data for cost as a function of size and complexity, by making use of established data for economic batch sizes and by interviews with experts. In general

$$0 < x_c < 1$$

and

$$0 < x_t < 1$$

since values greater than 1 imply that there is no economy of scale. The values differ for different processes. The tooling cost for polymer extrusion, for example, scales with size approximately as $(m/\overline{m})^{0.3}$, whereas that for many casting processes scales only as $(m/\overline{m})^{0.2}$. Values of y, we find, lie in the ranges

$$0 < y_c < 1$$

and

$$0 < y_t < 1$$

Values of x_p and y_p are negative, lying in the ranges

$$-3 < x_p < 0$$

and

$$-3 < y_p < 0$$

The rate of production by machining, for example, is particularly sensitive to complexity, falling as $(K/\overline{K})^{-3}$, while that for casting falls less steeply, as $(K/\overline{K})^{-0.4}$.

One further refinement is added. A process is generally described as having a "normal" range of an attribute (size, for example) of which it is capable, and a wider "extreme" range which it can achieve but with difficulty and therefore at an extra cost. Within the normal range of size associated with a process the cost and rates scale as described above. But between the normal and extremes of the range, it rises more quickly, and becomes prohibitive once the extremes are exceeded. We incorporate this by a further multiplicative factor R:

$$R = \left(1 + \frac{\sqrt{m_{LN}\, m_{LE}}}{m}\right)^2 \left(1 + \frac{m}{\sqrt{m_{HN}\, m_{HE}}}\right)^2 \qquad \text{(A3)}$$

Here m_{LN} and m_{HN} are the normal lower and upper limits, and m_{LE} and m_{HE} are extreme lower and upper limits of component mass that the process can handle. The final corrected cost factors are illustrated in Figure A1. Equations (A1) are used in equation (5) in place of the constant values described in Section 2.

Case Study: Forming a Manifold Jacket

Figure A2 shows a manifold jacket, a part of a space vehicle, for which a batch of 10 is required. It is to be made of nickel. It is large, weighing about 7 kg, and has a 3-dimensional hollow shape of considerable complexity (K = 5). The section thickness is 2 - 5 mm and the requirement on precision is strict (precision ≤ 0.2 mm). Figure A3 lists the requirements.

The design requirements isolate five processes which are capable of making the jacket: *electro-forming, manual machining, automated machining*, *manual investment casting and automated investment casting*. Which is the least expensive? The cost model – with technical modelling added (equations A1, A2 and A3) to account for the effect of complexity and mass on cost – was used to plot the way cost varies with batch size for the five competitive processes as shown in Figure A4. The output shows that for a batch size of 10 units, two processes are markedly cheaper than the others: electro-forming and manual investment casting. For larger batch sizes the results change: as expected, automated processes (automated investment casting) become competitive as the expensive tooling is amortised over a large number of units. Electro-forming remains competitive. Machining, because of the complexity of the shape, is uneconomic at all batch sizes.

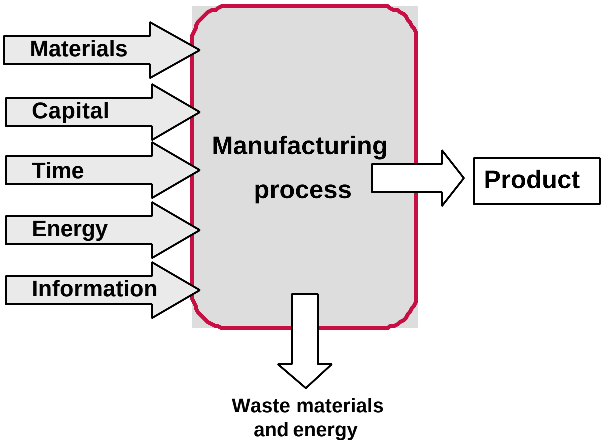


Figure 1. The generic resources that are inputs to a manufacturing process.

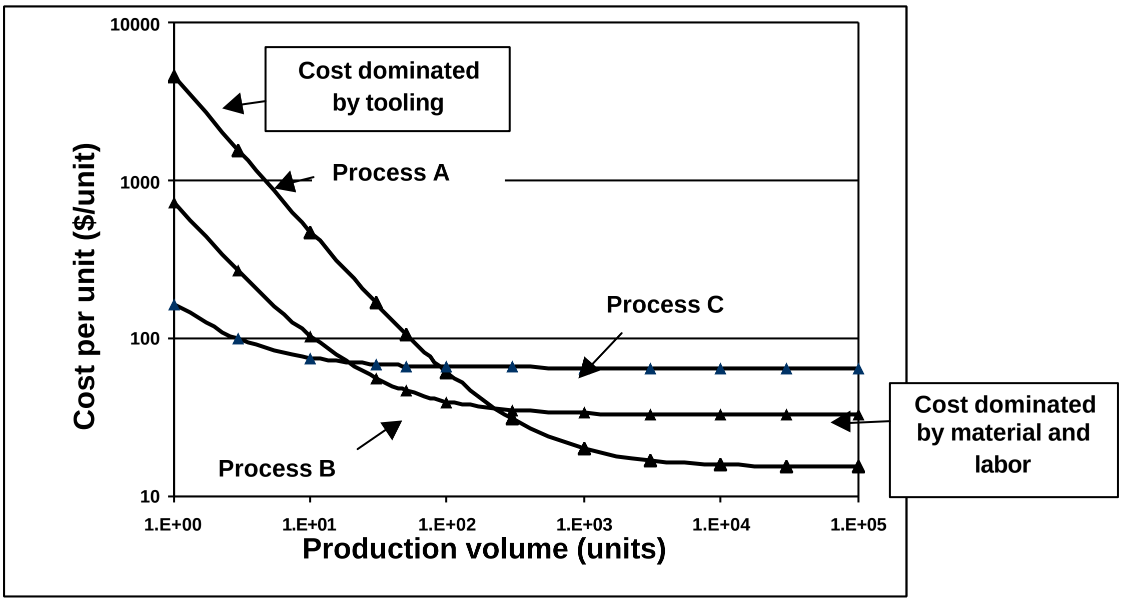


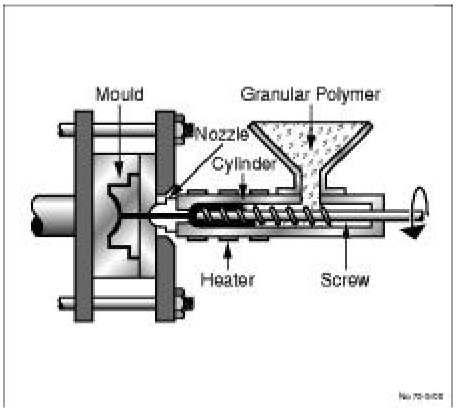
Figure 2 A schematic showing the dependence of unit cost on the number of units made, for three processes, A, B and C. The shape of the curves depends on the parameters of Equation (5).

Injection Moulding

Thermoplastics, thermosets and elastomers can all be injection molded. Co-injection allows molding of components with different materials, colors and features. Injection foam molding allows economical production of large molded components by using inert gas or chemical blowing agents to make components that have a solid skin and a cellular inner structure.

Physical Attributes

Mass range	0.01 - 25	kg
Range of section thickness	0.4 - 6.3	mm
Tolerance	0.1 - 1	mm
Roughness	0.2 - 1.6	µm



Economic Attributes

Economic batch size (units)	1e+004 - 1e+006
Relative tooling cost	very high
Relative equipment cost	high
Labor intensity	low

Cost modelling

Capital cost	*2e+004 -4.5e+005	GBP
Material utilisation fraction	*0.6 - 0.9	
Production rate (units)	*60 - 1000	/hr
Tooling cost	*2000- 2e+004	GBP
Tool life (units)	*1e+004 -1e+006	

Shapes

Circular Prismatic
Non-circular Prismatic
Solid 3-D
Hollow 3-D

Figure 3. An example of a record for a process.

Overhead rate	60	**$/hr**
Mass of component	3.5	**kg**
Batch size	1,000,000	**units**
Capital write-off time	5	**years**
Load factor	0.5	

Figure 4. A dialog box for user-defined parameters for the cost model.

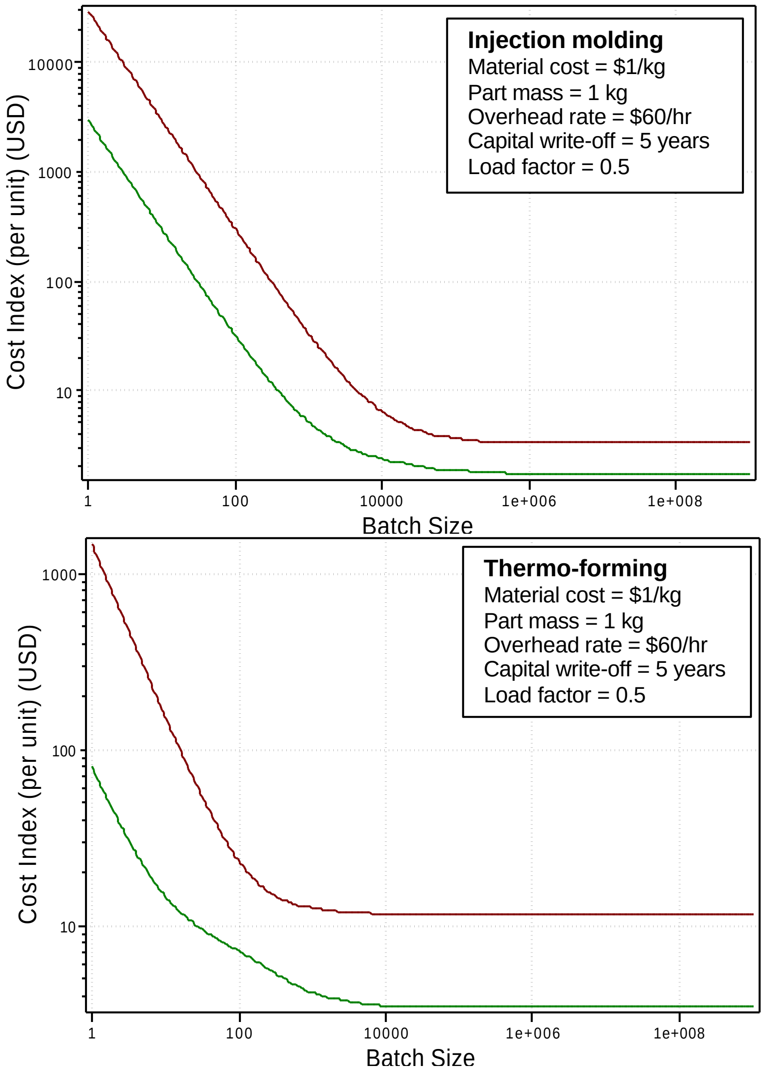


Figure 5 The dependence of unit cost on batch size for two competing processes. The shaped band is explained in the text.

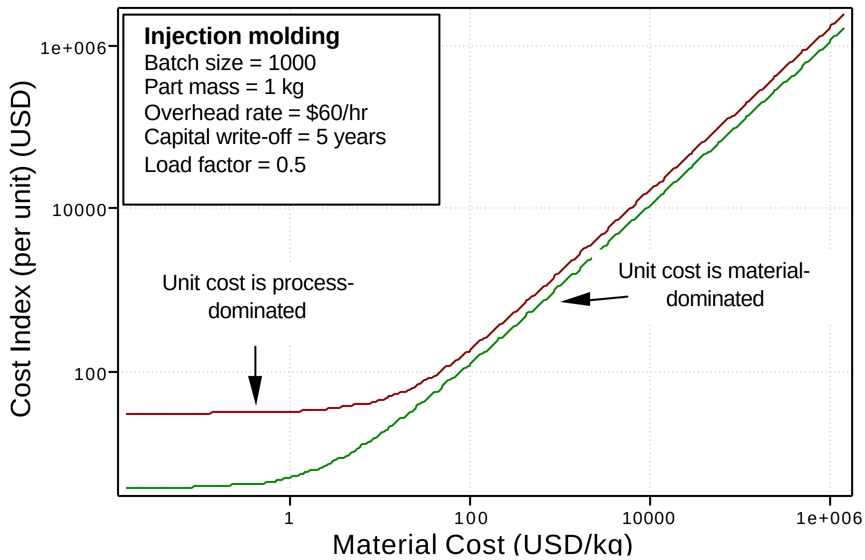


Figure 6. the dependence of unit cost on material cost for as batch size of 1000. The cost is almost independent of material cost for material costs below about $3/kg.

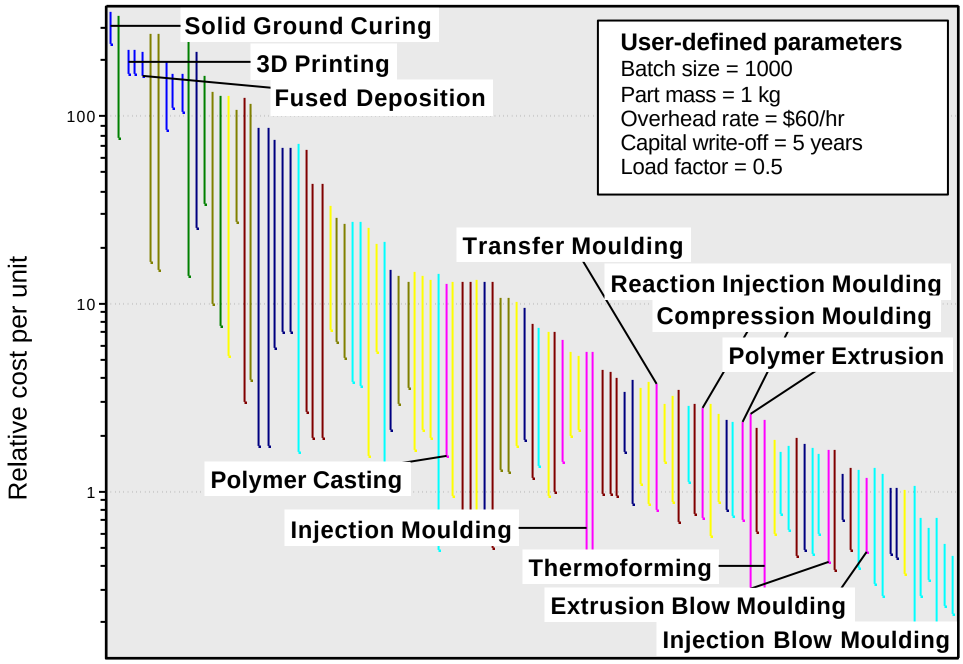


Figure 7. A plot of the relative cost per unit for 125 shaping processes, for a batch size of 1000. Those able to shape polymers are identified.

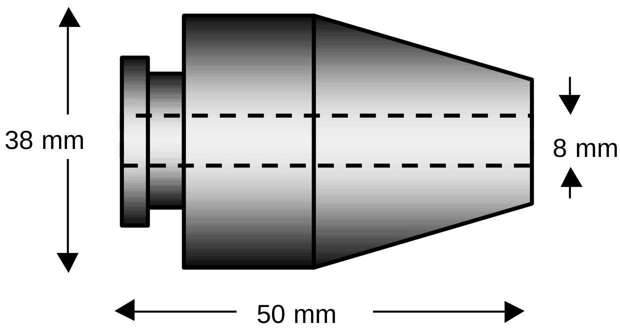


Figure 8. A nozzle, to be made from a nickel base superalloy

Nozzle: data for screening processes

Material class	Nickel based superalloy	
Shape class	3D axisymmetric, hollow	
Mass	0.3	**kg**
Section thickness	3	**mm**
Tolerance	< 0.2	**mm**
Roughness	< 10	mm
Primary	Yes	
Discrete	Yes	

Figure 9. The inputs used to screen processes to shape the nozzle.

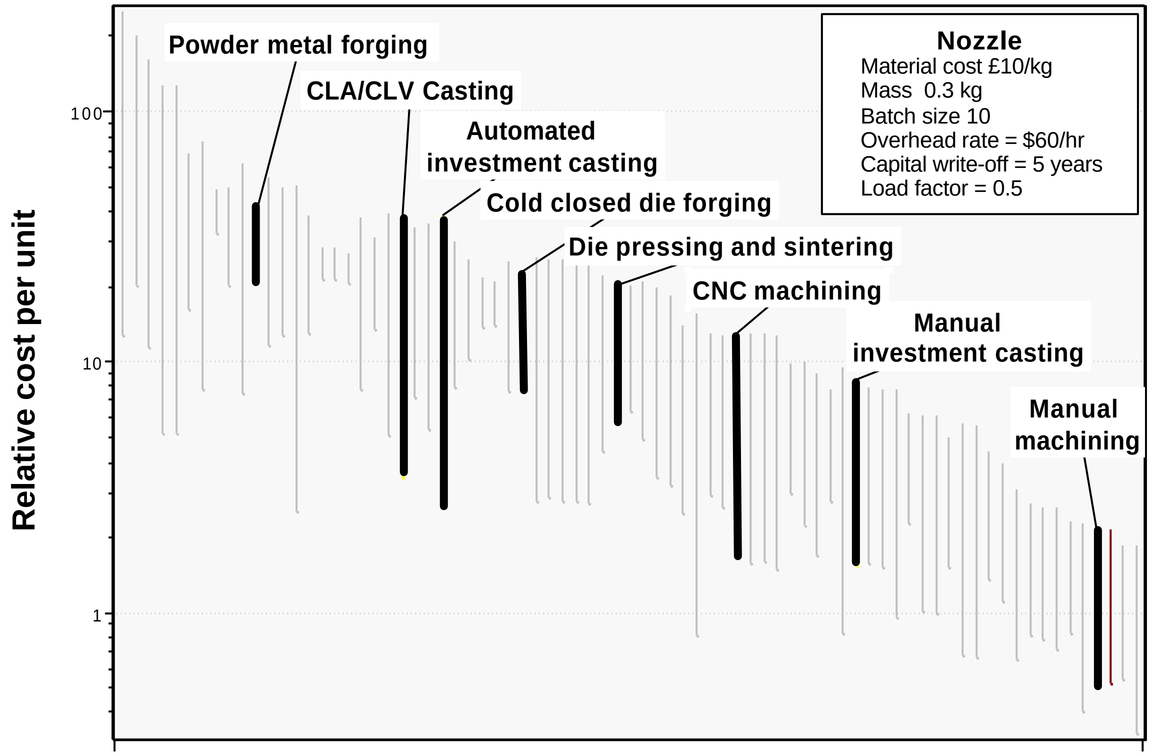


Figure 10. Processes ranked by cost for a batch size of 10. The ones that can shape the nozzle are highlighted and labelled. The ranking changes if the batch size is made larger.

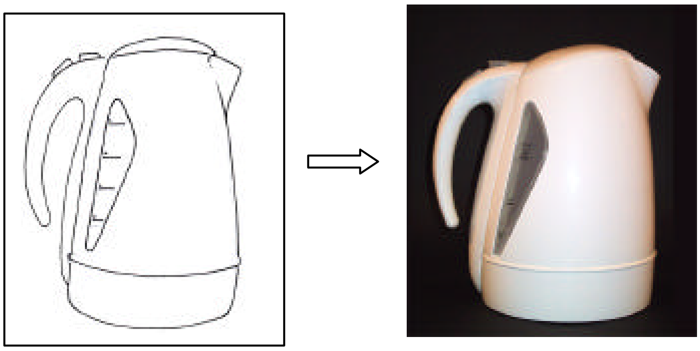


Figure 11. A jug kettle, schematic and real. It is to be made of polypropylene.

Jug kettle: data for screening processes

Material class	Polypropylene	
Shape class	3D hollow, complex	
Mass	0.4	**kg**
Section thickness	3	**mm**
Tolerance	< 0.5	**mm**
Roughness	< 0.8	mm
Primary	Yes	
Discrete	Yes	

Figure 12. The inputs used to screen processes to shape the jug kettle.

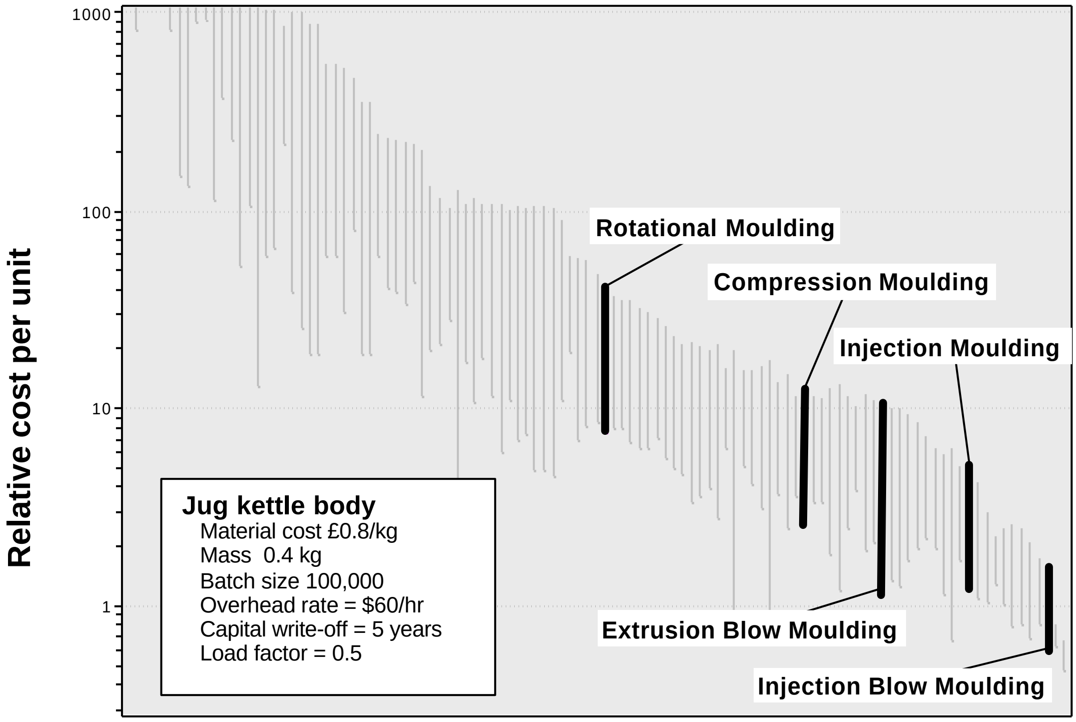


Figure 13. Processes ranked by cost for a batch size of 100,000. The ones that can shape the kettle are highlighted and labelled. The ranking changes if the batch size is made smaller.

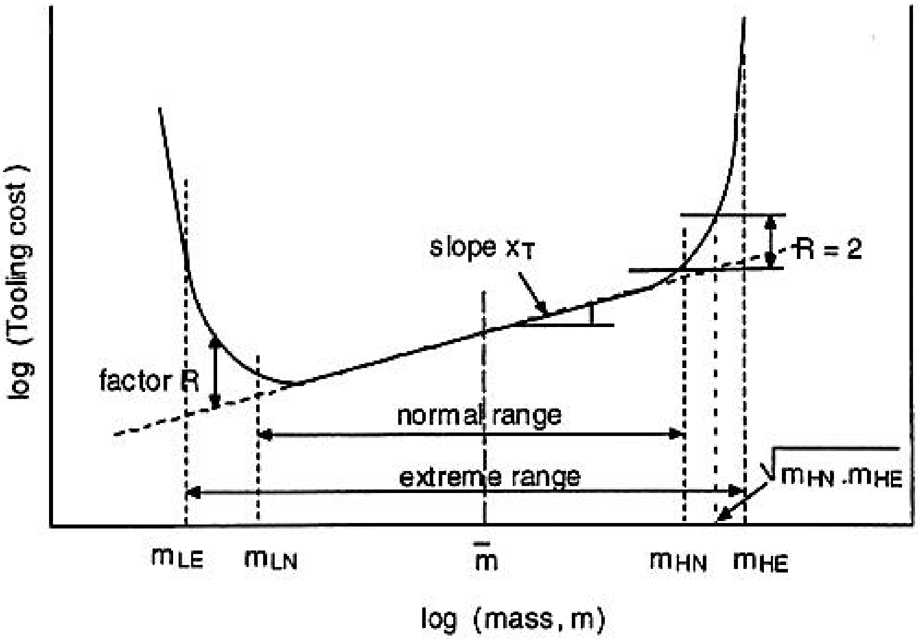


Figure A1 The dependence of tooling cost on mass

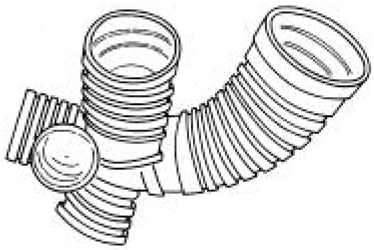


Figure A2 A manifold jacket [source: Bralla (1999)]

Manifold jacket: data for screening processes

Material class	Nickel	
Shape class	3D hollow, complex	
Mass	7	**kg**
Section thickness	3	**mm**
Tolerance	< 0.2	**mm**
Complexity (1 – 5)	5	
Primary	Yes	
Discrete	Yes	

Figure A3 Manifold Jacket Case Study.

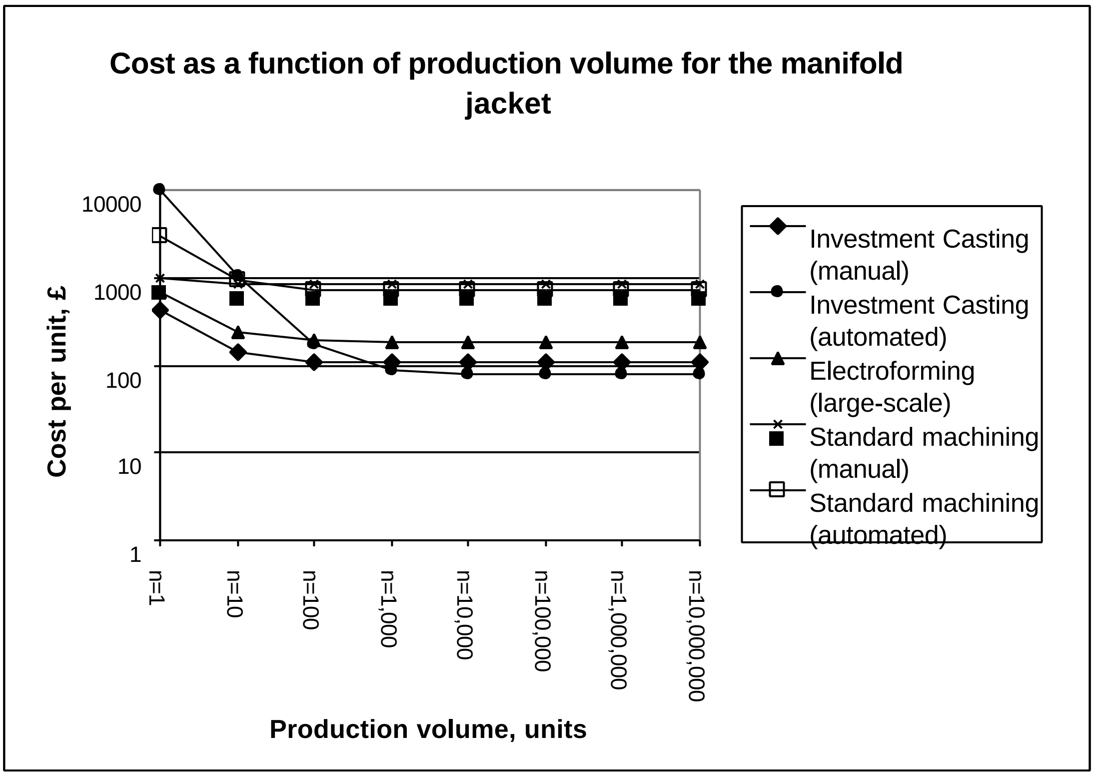


Figure A4 Processes for making the manifold. The two that are least expensive for a batch of 10 are electro-forming and manual machining