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Teaching cost awareness in design for manufacture

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Abstract
For Industrial Design undergraduate students an awareness of manufacturing capabilities and costs is important in designing for and selecting production processes. It is often difficult to include accurate cost information and set problems in a realistic context. To overcome this the Boothroyd and Dewhurst Design for Manufacture Toolkit has been used to support teaching in a Level 2 Design for Manufacture module. This is a suite of cost estimating software that incorporates an extensive database of materials, machines and processing information.

The paper outlines two tasks, using the sheet metalworking and the injection moulding modules of the software, that enable students to gain an understanding of the various factors involved in manufacturing costs. After analysing a part, a full breakdown of costs for material, tooling and processing of the part can be obtained. Students can then change particular parameters and note the effects on the cost.

The introduction of the software has helped students to gain a better appreciation of how their design decisions on the form influence the making of a part and the manufacturing costs. Use of the software is to be extended to Level 3 and postgraduate teaching.

Introduction
The Industrial Design Engineering (BSc) course at Brunel University has the aim of teaching students the technological and aesthetic requirements in design. This allows students to develop skills so that they can design high quality functional products. One of the Level 2 modules on the course is Design for Manufacture worth 10 credits. The module examines the principal metal and polymer processing methods with the emphasis on what a process can achieve rather than how a process works. The syllabus aims to help students select suitable processes to manufacture their products and design appropriately for the process, exploiting its capabilities.

One of the difficult areas with this approach is providing a distinction between what is technically achievable and what is economically justifiable. There are many texts on manufacturing processes, e.g. Bralla and Groover which provide general economic information on processes, but it tends to be comparative. A few offer basic methodologies for costing designs, e.g. Swift and Booker, Boothroyd et al. However these tend to be complex and difficult for students to apply to their designs. The problem with general comparisons between competing processes is that it has less relevance to the students and it is hard to get across all the different factors that influence the cost of processing.

To try and overcome this problem, we have introduced into the module the use of the Boothroyd and Dewhurst Design for Manufacture Toolkit. This is a package of cost estimating software for five manufacturing processes, injection moulding, machining, sheet metal working, die casting and powder metallurgy. It enables geometric models of parts to be built and used for determining the cost of production. The software contains comprehensive databases of materials, machines and processing information allowing comparison of different approaches to the manufacture of a part.

This paper will describe two assignments given to students which used the sheet metalworking and the injection moulding programs. The assignments gave students the opportunity to investigate the effects of altering various parameters in the production of parts.
Figure 1 The part used in the sheet metalwork exercise, with envelope dimensions 660 mm x 150 mm x 45 mm

<table>
<thead>
<tr>
<th>Cost Category</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base of press working cost</td>
<td>1.23</td>
</tr>
<tr>
<td>Set-up of machine(s)</td>
<td>0.01</td>
</tr>
<tr>
<td>Other machine stoppages</td>
<td>0.22</td>
</tr>
<tr>
<td>Reject parts</td>
<td>0.03</td>
</tr>
<tr>
<td>Material cost</td>
<td>1.42</td>
</tr>
<tr>
<td>Total piece part cost</td>
<td>2.91</td>
</tr>
<tr>
<td>Cost of press working die</td>
<td>0.02</td>
</tr>
<tr>
<td>Total cost of part ($)</td>
<td>2.93</td>
</tr>
</tbody>
</table>

Table 1 Full cost data for the part when 1000000 parts have been made in 20 batches

Sheet metalworking exercise

The aim of the first assignment was for students to establish the effects of altering the production quantities and batch sizes in the production of a part. Figure 1 shows the part that was used in the exercise. The part was specified as being made from carbon steel (medium carbon, hot rolled in 16 gauge) and manufactured using special purpose equipment using individual die, sheet power sheared into strips and blanked. The software requires entry of the following data:
- Length and width of the smallest rectangular envelope to fit around the part when it is flat;
- Length of the perimeter of the part;
- Total surface area of the part;
- Number of standard (round, oval and rectangular) holes and non-standard holes;
- Total area removed by the holes;
- The perimeter length of non-standard holes;
- Number and total length of bends;
- Number and perimeter lengths of other features such as lances, beads, notches, flanges and depressions.

This information enables the software to determine the complexity of the tooling required to produce the part. Once the part descriptions have been entered the production parameters are required which include, production quantities and batch sizes. The cost of production per part can now be determined. The results of an analysis on the part in Figure 1 is shown in Table 1.

In the assignment students were required to investigate the following with respect to the part:
- a) to determine the effect on part cost of changing the number of batches while keeping the total production quantity constant (Table 2 & Figure 2);
- b) to determine the effect on part cost of altering the total production quantities while maintaining a constant batch size (Table 3);
- c) to determine the effect on part cost of altering the total production quantities while maintaining a constant number of batches (Table 4 & Figure 3).
<table>
<thead>
<tr>
<th>No of Batches</th>
<th>1</th>
<th>100</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>5000</th>
<th>10000</th>
<th>20000</th>
<th>50000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch Size</td>
<td>1000000</td>
<td>10000</td>
<td>2000</td>
<td>1000</td>
<td>500</td>
<td>200</td>
<td>100</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>Set-up</td>
<td>0.005</td>
<td>0.07</td>
<td>0.33</td>
<td>0.67</td>
<td>1.33</td>
<td>3.33</td>
<td>6.66</td>
<td>13.31</td>
<td>33.28</td>
</tr>
</tbody>
</table>

Table 2  The results of altering the number of batches whilst maintaining a constant total production of 1,000,000 parts

<table>
<thead>
<tr>
<th>No of Batches</th>
<th>1</th>
<th>100</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>5000</th>
<th>10000</th>
<th>20000</th>
<th>50000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch Size</td>
<td>1000000</td>
<td>10000</td>
<td>2000</td>
<td>1000</td>
<td>500</td>
<td>200</td>
<td>100</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>Set-up</td>
<td>0.005</td>
<td>0.01</td>
<td>0.02</td>
<td>0.04</td>
<td>0.09</td>
<td>0.17</td>
<td>0.34</td>
<td>0.67</td>
<td>1.93</td>
</tr>
<tr>
<td>Total Cost</td>
<td>2.92</td>
<td>2.99</td>
<td>3.08</td>
<td>3.25</td>
<td>3.6</td>
<td>4.3</td>
<td>5.7</td>
<td>10.65</td>
<td>31.32</td>
</tr>
</tbody>
</table>

Table 3  The effect of changing the product life volume with 3 levels of constant number of batches
By comparing the results of the tables it is possible to determine the following features.

a) If the product life volume is constant then increasing the number of batches will increase the set-up costs per part. This is because as the size of the batch reduces, so the set-up cost is disbursed over a smaller number.

b) As the product life volume decreases, then the costs of the press working die per part increases. This is because the cost of the dies is spread over a smaller quantity.

c) Maintaining a constant batch size as the life volume changes means that set-up costs per part remain constant, due to set-up costs being determined by the size of the batch.

Injection moulding exercise

The task for injection moulding allowed students to see how changes in design features on a part would alter the manufacturing costs. Figure 4 shows the part that was used in the exercise. Prior to the assignment a lecture was given detailing the principles applied in the software to calculate the costs. This explained how the cost of moulding was based on the making of the mould, the amount of material used, and the processing time. The tool making costs are determined by the geometric complexity of the part and if any cores or internal lifters are required to achieve holes, depression and undercuts. The processing time is greatly influenced by the wall thickness which dictates the cooling time. This means...
Figure 4  The part for the injection moulding exercise, which has envelope dimensions of 200 mm x 150 mm x 150 mm. The dotted lines show a depression on the inside of the wall.

<table>
<thead>
<tr>
<th></th>
<th>Original Design</th>
<th>Redesign</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time (min)</td>
<td>Cost (£)</td>
</tr>
<tr>
<td>Process/part</td>
<td>0.94</td>
<td>1.35</td>
</tr>
<tr>
<td>Material/part</td>
<td>-</td>
<td>1.03</td>
</tr>
<tr>
<td>Tooling /part</td>
<td>-</td>
<td>0.02</td>
</tr>
<tr>
<td>Total/part</td>
<td>0.94</td>
<td>2.40</td>
</tr>
<tr>
<td>Product Life</td>
<td>2000000</td>
<td></td>
</tr>
<tr>
<td>Volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Cavities/mould</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Mould Costs</td>
<td>£48739</td>
<td></td>
</tr>
</tbody>
</table>

Table 5  Comparison of results between the original and a redesign of the injection moulded part

that the thinner and more uniform the wall thickness can be made then the shorter the cooling time that would be required.

The part for the assignment therefore exhibited some poor design feature such as thick non-uniform walls, an internal undercut, staggered parting line and sharp corners. Students were free to provide any design changes that they wished provided that the part maintained its exterior envelope dimensions and the five holes in the part remained in the same locations.

To analyse the part with the software it is necessary to build up a solid model in the geometric calculator to give the required geometric information. This is achieved using the software's modelling features in an additive or subtractive basis. Full dimensional information is not required as the software only need to know the size of the features and not their relationships. The walls of the part can therefore be constructed in the model by adding together the different sections, or taking the overall envelope and the removing the holes.

In addition to the geometric information the software requires information on the number of cores required and from which direction, the tolerances and surface finish required and the production life of the product.

The results of changing the wall thickness from an average of 5 mm and a maximum of 9 mm to a uniform thickness of 2 mm, eliminating the depression and reducing the tolerance requirement are shown in Table 5. There is a reduction in cost of £0.95 and in
processing time of 0.66 min. The processing time reductions are achieved primarily by the reduction of the wall thickness allowing the part to cool in a quarter of the time previously required. The mould cost was also marginally reduced but due to the large number of parts there is not any notable effect on tooling costs per part.

Assessment

The assessment of the two assignments was based on three main areas. Firstly the accuracy of data entry was examined as this reflected understanding in the use of the software and care in reading the brief. Secondly was the amount of experimentation conducted by the student, i.e. the range of values for the sheet metalworking exercise and the extent of design changes in the injection moulding exercise. Lastly the students were required to write a brief discussion about their changes and what the results and implications were. This was used to determine how the students interpreted their results.

Discussion

The tasks set in these two exercises were of quite different natures and this was reflected in the response of the students. The sheet metalwork exercise was highly directed and involved a straight analysis of the part and manipulation of the production data that was used. The majority of students sampled an appropriate range of numbers and provided graphs to show the trends and were able to distinguish which elements of the part costs were altered and why. A few students though did not experiment sufficiently with the data to determine notable changes in the costs and were unable to provide a conclusion.

The injection moulding exercise gave a greater freedom of choice in the changes they could make. Despite use of other solid modelling software on the course a number of students found conceptual difficulties in how they could construct their models and more guidance was required to help them. Part of the problem is that the record of building up the model is shown in a text format, there is no visual model. The sheet metal part was more straightforward as the geometric calculator in the software works more like a two dimensional system.

With the injection moulded part, information about the part’s function was deliberately withheld to give the students the freedom to make what ever changes they felt appropriate to get the most out of the process. However some students seemed to be inhibited by this because they felt they could not make design decisions for the part without knowing its usage. Once it had been explained that they had the freedom to make their own changes and to comment on the effects they had on production costs they were able to proceed on this basis. It might be more appropriate to provide the context for the part or use a simple product such as a craft knife for the assignment.

In general the students made use of design suggestions made in lectures aiming for uniform wall thickness and rounding of corners etc. Some went further in suggesting reducing tolerance requirements and eliminating or incorporating some features, such as the wall depression, to ease the tool making procedures.

The advantages that were found in using the software in the module were:
• being a practical exercise it helped to provide variety within the modules delivery;
• the software was easy for students to start using;
• results from the analysis could be obtained quickly, the first task would take about one hour to complete;
• the layout of results are clearly presented and students could determine how their design changes affected the various elements that made up the total cost per part;
• the data base of machines and materials was extensive but could be changed or added to with your own data.

Some of the problems encountered were:
• students require a good understanding of the manufacturing process involved prior to using the software, its use therefore has to be fitted in around the lecture schedule;
• to avoid problems of copying between students, each student was given a different set of dimensions for the task, this increases the preparation and marking time required;
• some students found the geometric modelling difficult, particularly with the injection moulding software, as they were required to build up a text-based representation rather than a visual model.

These two example assignments provide a very structured approach to using the software for the students. The software has also been used in a Level 3 module where a student analysing a selected product can choose a part to analyse with the software before and after redesign. It is also hoped to make use of the package in a new MSc course. The software offers the flexibility to structure class use and assignments at an appropriate level.

Conclusions

The software was easy for students to start to use and gain results. Its inclusion in the module helped to enhance the content and support information provided in lectures. It gave the students the opportunity to discover the impact of their design changes on a part and gain a better appreciation of what can be achieved with a process. Students require a good understanding of the particular process to gain the most from using the software and this can be provided with a lecture prior to using the program. The flexibility of the software offers many other opportunities to incorporate it in other areas of the degree course in the Department.

References