1. Introduction

Today, metal casting industry has to operate and compete on a global level, and meet ever-rising expectations of customers in terms of quality assurance, shorter lead-time, smaller lot size and lower pricing. To enable continuous cost reduction, it is necessary to develop and use a reliable yet easy-to-use casting cost estimation methodology. Such methods can be implemented in a computer program to:

(a) generate more accurate quotations to avoid the pitfalls of over and under-quoting,
(b) carry out ‘what-if’ analysis to study the effect of internal factors such as rejection, yield, wastages, material recycling and equipment/method used on casting cost,
(c) monitor the effect of external factors such as raw material prices, energy and labour rates on casting cost, and
(d) identify cost elements that have the largest potential for cost reduction, based on the above results.

A comprehensive casting cost estimation methodology has been developed at I.I.T. Bombay based on several years of research, to identify the most important parameters in casting cost, and implemented in a computer program. The program can be used in two modes. In ‘manual mode’, the user has to enter the values of casting weight, shape complexity, yield, etc. In ‘semi-automatic mode’ the program analyses the geometric shape of the casting, designs and models the methoding (feeders and gating system), checks internal quality by simulation, and uses these values for cost estimation. The methodology and its implementation in an integrated environment for casting design, simulation and cost estimation is described next.

2. Casting cost estimation model

The main elements of casting cost are material, labor, energy, tooling and overheads (Chronister 1975, Jain 1987, Kulkarni 1988, Creese 1992). These are primarily driven by product and process parameters (figure 1). The detailed equations for estimation of these cost elements developed in our work are presented in the following subsections.
1.1 Material cost

Material cost includes direct and indirect materials. Cast metal or alloy that appears in the product constitutes direct material cost. This can be determined from the casting weight. However, the actual amount of metal consumed is more, owing to irrecoverable losses during melting, pouring and fettling. The direct material cost is given by:

$$C_{\text{direct}} = c_{\text{unit\_metal}} \times w_{\text{cast}} \times f_m \times f_p \times f_f$$

Where,
- $c_{\text{unit\_metal}}$ = Unit metal cost
- $w_{\text{cast}}$ = Casting weight = $\rho_c \times V_{\text{cast}}$
- $\rho_c$ = Casting metal density
- $V_{\text{cast}}$ = Casting volume
- $f_m$, $f_p$, $f_f$ = Factors for metal loss in melting, pouring and fettling respectively

Indirect materials depend on the process. The molding sand and core sand constitute the main element of indirect material cost. The cost of molding sand depends on the type of sand (silica, olivine, zircon, sodium silicate, etc.), composition (amount of binder), mold box size and layout. Core sand cost mainly depends on the type of sand (represented by the core-
making process) and volume of cores. Cost modifiers for mold rejection, core rejection, casting rejection and sand reclamation have also been considered. Miscellaneous indirect materials (such as insulating sleeves, chills and chaplets) are added depending on use.

\[
C_{\text{mold\_sand}} = c_{\text{unit\_mold\_sand}} \times f_{\text{recycle}} \times f_{r} \times f_{\text{mold\_rej}} \times \left( \frac{\rho_{m} \times V_{m}}{r_{\text{metal\_sand}}} - \rho_{\text{core\_sand}} \times V_{\text{core}} \right) \times \frac{1}{n_{r}}
\]

\[
C_{\text{core\_sand}} = c_{\text{unit\_core\_sand}} \times f_{r} \times f_{\text{core\_rej}} \times \rho_{\text{core\_sand}} \times V_{\text{core}}
\]

Where,
- \( C_{\text{mold\_sand}}, C_{\text{core\_sand}} \) = Mold and core sand cost
- \( c_{\text{unit\_mold\_sand}}, c_{\text{unit\_core\_sand}} \) = Unit mold and core sand cost
- \( f_{\text{recycle}}, f_{r}, f_{\text{mold\_rej}}, f_{\text{core\_rej}} \) = Factor for recycled sand, casting rejection, mold and core rejection
- \( r_{\text{metal\_sand}} \) = Metal to sand ratio
- \( V_{m} \) = Metal volume per mold = \((n_{r} \times V_{\text{cast}}) + V_{g} + V_{f}\)
- \( V_{f}, V_{g}, V_{\text{core}}, V_{\text{box}} \) = Volume of all feeders, gating system, core and mold box
- \( \rho_{\text{core\_sand}} \) = Core sand density

1.2 Labor cost

The labor cost is a function of equipment, labor and time required for various activities in casting production. This information is contained in the process plan. Some of the activities such as melting, sand preparation and shakeout, are performed for a batch. The time per component for these activities has been calculated based on casting weight, core weight, mold weight and number of castings, respectively. The labor cost is given as,

\[
C_{\text{labor}} = f_{r} \times \left( \sum_{i=1}^{n} f_{\text{rej\_act}} \times c_{\text{unit\_labor}} \times l_{\text{act}} \times t_{\text{act}} \right)
\]

Where,
- \( c_{\text{unit\_labor}} \) = Unit labor cost
- \( l_{\text{act}} \) = Number of workers involved in activity \( i \)
- \( t_{\text{act}} \) = Time for activity \( i \) per component
- \( f_{\text{rej\_act}} \) = Rejection factor for activity \( i \)
- \( n \) = Number of activities

1.3 Energy cost

Metal casting is an energy intensive process, and melting of metal constitutes the most important factor in energy cost. The energy required for melting is estimated using a thermodynamic equation, and corrected by incorporating cost modifiers related to furnace efficiency, losses and yield. Other energy-intensive activities include mold making, core-making, cleaning and fettling cost for which can be assigned based on the weight of a casting. The energy cost is given as the sum of costs for melting and other energy as,
\[
C_{energy} = C_{melting} + C_{other\_energy}
\]
\[
C_{melting} = c_{unit\_energy} \times f_{\eta} \times w_{\text{cast}} \times f_y \times f_r \times f_m \times f_p \times f_f \times [(c_{ps} \times (t_{melt} - t_{room})) + L + c_{pl} \times (t_{tap} - t_{melt})]
\]
Where,
\[
c_{unit\_energy} = \text{Unit energy cost}
\]
\[
f_{\eta} = \text{Factor for furnace efficiency}
\]
\[
f_y = \text{Factor for overall yield (gating and fettling)}
\]
\[
c_{ps}, c_{pl} = \text{Specific heat of metal at solid phase and liquid phase respectively}
\]
\[
t_{melt}, t_{room}, t_{tap} = \text{Pouring, room and tapping temperature respectively}
\]

### 1.4 Tooling cost

Empirical equations can be developed for tooling cost estimation by analysing the pattern, core box or mould costs for a variety of castings. The equations for the cost of medium size cast iron tooling (patterns and core boxes for sand casting) manufactured by conventional machining and CNC machining are given below (Chouugle and Ravi, 2005).

\[
C_{rel\_tool\_cost} = (1.59 \times V_{\text{cast}} + 0.07 \times C_{ac} + 0.45 \times C_s) \ldots \text{with conventional machines}
\]
\[
= (11.36 \times V_{\text{cast}} + 1.34 \times C_{ac} + 0.15 \times C_s) \ldots \text{with CNC machining centre}
\]
\[
C_{tooling} = 1000 \times C_{rel\_tool\_cost} / Q
\]
Where,
\[
C_{rel\_tool\_cost} = \text{Relative tooling cost}
\]
\[
C_{tooling} = \text{Amortized cost of tooling}
\]
\[
V_{\text{cast}} = \text{Casting volume in m}^3
\]
\[
C_{ac} = \text{Accuracy index on 1-100 scale}
\]
\[
C_s = \text{Casting shape complexity}
\]
\[
Q = \text{Order quantity}
\]

Similar equations can be developed for wooden and epoxy patterns. The particular equation to use depends on the pattern material, which is selected depending on the casting order quantity.

Overhead costs include administrative overheads and depreciation cost. These costs are assigned based on the weight of the casting.

### 3. Integration with Casting Design

The cost model has been implemented in software program called AutoCAST. The following steps are involved:

(a) Giving inputs to the program: This includes the part solid model, specifying the casting material, quality attributes (maximum void size, surface finish, dimensional tolerance) and production requirements (production rate, order quantity, sample lead time and production lead time). The geometry related attributes (casting weight, shape complexity, number of cores, etc.) are automatically determined from the part model.

(b) Methoding design: This involves design of feeding system (number, location, shape and size of feeders and feedaids) and gating system (location, shape and size of sprue, pouring
basin, well, runners, ingates and filters). The methoding is verified by mould filling and solidification simulation to predict internal defects (such as sand inclusions and shrinkage porosity). The methoding can be modified and verified again until satisfactory internal quality is achieved.

(c) Process planning: This deals with decisions related to methods, equipments, steps, time required, tooling type and process parameters such as type of mould or core sand, sand composition, melting charge, pouring time, pouring height, cooling time and quality checks (Chougule and Ravi, 2005). For this purpose, the closest similar previous casting is identified from the project database and its process plan is copied and modified, if necessary to obtain the plan for the new casting project.

(d) Cost estimation: Based on the results of the above three steps (part design, methoding design and process plan), the casting cost is estimated using the methodology described earlier, and presented to the user.

Fig 2: Integration with casting design and analysis

4. Industrial Example

The cost elements of a gray iron body cap casting (figure 2) estimated using the above methodology are summarized in table 1. The input values determined by process planning and methoding program are given below:
(a) Input from product design and requirements

Part weight: 14.35 kg  
Part volume: 2.03x10⁻³ m³  
Shape complexity: 28  
Accuracy index: 35  
Order quantity: 5000  
Core weight: 2 kg

(b) Input from methoding

Mold box size = 450 x 450 x 250 mm  
Cavities per mould = 1  
Gating and feeder volume = 1.092x10⁻³ m³  
Yield = 0.63  
Feed aids = Nil

(c) Input from process planning and other administrative information

Mold sand type = Green sand  
Core sand type = Hot box  
Melting time = 14.75 min \textit{(time per heat 80 min, labors involved 4, capacity 1.3 T/hr)}  
Core sand preparation time = 1.5 min \textit{(time per batch 45 min, labors 3, capacity 250 kg)}  
Mold sand preparation time = 0.0 min \textit{(continuous mixture, hence labor time neglected)}  
Molding time = 3.0 min  
Core making time = 4.0 min  
Shakeout time = 1.0 min  
Fettling time = 5.0 min  
Tapping temperature = 1500 °C  
Annual administrative cost = Rs. 30,00,000  
Equipment life = 30 years  
Investment in equipment = Rs. 40,00,000  
Annual foundry turnover = 1000 T

Table 1: Summary of casting cost

<table>
<thead>
<tr>
<th>Cost Element</th>
<th>Cost modifiers</th>
<th>Unit/ total cost (Rs)</th>
<th>Cost per Casting (Rs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Material</td>
<td>(f_m=1.05), (f_p=1.07), (f_r=1.07)</td>
<td>20.00 Rs/kg</td>
<td>345.10</td>
</tr>
<tr>
<td>Indirect material</td>
<td></td>
<td>Mold sand- 1.2 Rs/kg</td>
<td>12.00</td>
</tr>
<tr>
<td></td>
<td>(f_{mold_{rej}}=1.01)</td>
<td>Core sand- 3.0 Rs/kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(f_{core_{rej}}=1.02)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(f_{recycle}=0.10)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Labor</td>
<td>(f_r=1.05), (f_{mold_{rej}}=1.01), (f_{core_{rej}}=1.02)</td>
<td>60 Rs/hr</td>
<td>32.00</td>
</tr>
<tr>
<td>Tooling</td>
<td></td>
<td>21000 (by conventional machining)</td>
<td>4.20</td>
</tr>
<tr>
<td>Energy (Melting + other)</td>
<td>(f_n=2, f_y=1.6, f_m=1.05, f_p=1.07, f_r=1.05)</td>
<td>4.00 Rs/unit</td>
<td>60.80</td>
</tr>
<tr>
<td>Admin. overheads</td>
<td>3 Rs/kg</td>
<td>41.85</td>
<td></td>
</tr>
<tr>
<td>Depreciation overheads</td>
<td>0.15 Rs/kg</td>
<td>2.25</td>
<td></td>
</tr>
<tr>
<td><strong>Total cost</strong></td>
<td></td>
<td></td>
<td><strong>498.20</strong></td>
</tr>
</tbody>
</table>
The total estimated cost is Rs. 498.20, which is comparable with the actual casting cost calculated using the weight based approach used in practice (Rs. 500). The actual cost was given by the average rate (35 Rs per kg) x casting weight (14.35 kg) = Rs. 502.25, which is rounded off to Rs. 500. The average rate for similar castings was arrived at by the foundry based on detailed cost accounting. The proposed method gives the cost break up of castings, which is valuable for identifying areas for cost reduction and for ‘what if’ analysis to enable cost reduction. Further, the entire methodology, starting from 3D model input to methoding, process planning and cost estimation takes less than 30 minutes on a standard computer, and can be used even by engineers with very little experience in computers.

5. Conclusion

The traditional weight based costing currently practised in the casting industry has two limitations: (a) it may not reflect the true cost of a casting, leading to situations when a foundry does not know if it is making a profit or a loss on a particular casting, and (b) it does not give the cost break up, which is needed for identifying areas for cost reduction and for verifying the extent of reduction by modifying the methoding, process or equipment. These limitations particularly affect small and medium sized foundries. The methodology developed in our work overcomes both these limitations, and provides a systematic approach for casting cost estimation driven by the design of product, tooling, methoding and process plan. It can be applied to industrial castings in both manual mode, and semi-automatic mode (using the program developed for this purpose). We hope this methodology will be useful in improving the cost competitiveness of our foundries. The authors welcome any feedback on its practical application in industry and suggestions for further improvements.

References