Revised paper submitted for publication in IJCIM, Dec 2005

Casting cost estimation in an integrated product and process design environment

R. G. Chougule
Research Scholar, Mechanical Engineering Department, IIT Bombay, India
chougule@me.iitb.ac.in

B. Ravi *
Associate Professor, Mechanical Engineering Department, IIT Bombay, India
bravi@me.iitb.ac.in

Abstract

A casting cost estimation model, driven by the solid model of the part and its attributes (material, geometric, quality and production requirements) is presented. It is meant for product designers with little knowledge of the process, enabling design modifications for cost reduction in early stages, when the cost of such modifications is low. Analytical equations have been developed to estimate the cost related to material and conversion (energy and labour). A parametric model has been developed for tooling cost, driven by part complexity, which is computed from the part solid model. Parameters related to process plan and methoding/rigging (feeding and gating), required for accurate estimation of casting costs, are semi-automatically generated by process planning and casting methoding programs developed in our lab. The programs are in turn linked to a web based intelligent collaborative engineering system called WebICE. This enables exchange of casting project data (including cost data) among product designers, tool makers and foundry engineers over the Internet, enabling design modifications to achieve the targeted cost. An industrial example is presented to illustrate the entire system.

Keywords: Casting, computer aided design, cost estimation, collaborative engineering, integrated product process design, parametric costing, solid model, web based engineering.

1. Introduction

It has been well established that over 70% of the total development cost of a product is frozen during the design phase, though this phase accounts for less than 7% of the total cost (Hundal 1993). Devoting more resources for early identification and prevention of potential manufacturing problems through concurrent product and process design significantly reduces the overall cost and lead-time. To aid decision-making when a choice is to be made among various alternatives for geometric, material or process parameters, an early cost estimation tool is useful and perhaps even essential. It enables product engineers to perform 'what-if' experiments and study the effect of different designs on manufacturing cost. It can also be used during design iterations to verify if the targeted cost can be achieved (design to cost). With intensifying global competition, manufacturing cost estimation at design stage is generating considerable interest among researchers and practicing engineers.

This investigation focuses on early cost estimation of cast components. Casting is an important manufacturing process and cast parts are found in 90% of manufactured goods

---

*Contact address: Prof. B. Ravi, Mechanical Engineering Department, Indian Institute of Technology, Powai, Mumbai 400076, India. Phone: (+91-22) 2576 7510 Fax: (+91-22) 2572 6875 E-mail: bravi@me.iitb.ac.in

and equipment (DoE, 1999). Most original equipment manufacturers (OEMs) outsource the castings from foundries. Each foundry usually specialises in a particular process (such as green sand casting, investment casting or gravity die casting), focussing on a narrow range of metals (either ferrous or non-ferrous) and applications (in terms of size/weight and geometric complexity). It may have a unique combination of equipment, automation level, worker skill and past experience. The tooling (patterns, core boxes, moulds) and methoding (feeding and gating systems), which greatly affect casting quality and yield, are designed in different ways based on knowledge gained from previous projects. These factors lead to significant variations in manufacturing cost among different foundries. Ironically, most foundries do not maintain detailed cost data, making it difficult to establish the profitability of specific casting projects. This is becoming critical in the light of increasing pressure from original equipment manufacturers to reduce casting prices on a continuous basis.

Many castings, though more economical than similar parts made by other processes, have a significant potential for further cost reduction by minor design modifications that lead to better product-process compatibility. However, with limited knowledge about casting processes and inadequate information about the facilities and capabilities of a particular foundry, design engineers cannot be expected to accurately estimate casting costs, especially for new products. Thus in practice, even those product designers who are aware of the benefits of early cost estimation and design-to-cost philosophy, are unable to achieve the same owing to a lack of suitable tools.

This paper presents our research work on developing a systematic methodology for early casting cost estimation, suitable for design engineers. It will enable analysing the combined effect of preliminary design of product, tooling and process on cost, facilitating minor design changes to reduce cost while maintaining the desired functionality and quality. The present work focuses only on the manufacturing cost; the cost of transportation, customs, duties, taxes and other elements affecting the price are not considered. A brief review of literature related to various approaches for cost estimation, focussing on work in casting domain, is presented in the following section. Our overall methodology is presented next, including an integrated product process design environment incorporating the proposed model for early cost estimation. Finally, the proposed approach is illustrated with an industrial example.

2. Previous work

A number of cost estimation approaches are available today for estimating product cost at design stage. These include intuitive, analogical (Duverline and Castelain 1999, Wang *et al.* 2003), analytical (Feng and Zhang 1999), feature based (Feng *et al*. 1996, Ou-Yang and Lin 1997) and parametric (DoD 1999, Farineau *et al.* 2001). The *intuitive method* is based on the experience of the estimator, especially with similar parts and interpretation. The *analogical method* involves comparison of a new product with similar existing products. Case based reasoning has been applied to improve the results of the analogical method (Duverline and Castelain 1999). The *analytical method* involves decomposition into elementary parts and tasks for each part, and empirical equations are used for estimating the cost of various tasks. The *feature based method* uses geometric features (such as slot, hole and rib) of the product and tooling as the basis for cost estimation. The *parametric cost estimation* methods involve formulating relations between product characteristics and its cost using available data. Since it gives quick estimates without detailed data related to downstream activities, it is gaining application in manufacturing domain. Examples include estimation of the cost of injection moulds (Fagade and Kazmer, 2000), and disc brakes (Cavalieri *et al.* 2004).

A few researchers have focused on cost estimation of a particular operation or domain such as sheet metal working (Weustinck *et al*. 2000), hole making (Luong and Spedding 1995), and injection moulding (Yuh-Min and Jang-Jong 1999). Bidanda *et al.* (1998) developed a castability analysis and cost estimation system for permanent mould cast components. However, very little work has been reported on cost estimation of sand casting that accounts for over 75% of casting production.

The major cost elements of a casting such as material, tooling, labour, energy and overheads have been identified by early researchers (Chronister 1975, Jain 1987 and Kulkarni 1988). In practice, many foundries and their customers still estimate cost based on component weight, corrected for the expected level of production difficulties, scrap and yield. The weight based method involves accounting all expenses (material, energy, labour, etc.) and total weight of salable castings produced, during a predetermined period. Based on this data, the average rate of castings per kg is calculated, and is used for calculating the cost of new castings based on their weight. The method works well in mass production foundries making castings of similar characteristics, but is not suitable for job shop or batch type foundries that have a wide range of products. To alleviate these problems, more elaborate cost models have been proposed by identifying and calculating the detailed cost elements (Creese 1992, Creese and Rao 1995). Ajmal and Dale (1990) developed a simple computer aided process planning and cost estimating system for foundry application driven by a database and interactive user input.

The cost of tooling (pattern, core box, mould, etc.) is amortized over the number of castings produced, and can be a significant proportion of the casting cost, especially when order size is low. It is driven by product geometry, tooling material and order quantity, among other factors. Most of the cost models developed so far do not provide any facilities for estimating the tooling costs based on product and process parameters, and expect the user to provide the cost based on past experience. In general, the cost models available for casting domain require detailed knowledge of tooling design and manufacturing process; they are more suitable for use at manufacturing stage by foundry engineers.

The DFMA (Design for Manufacture and Assembly) software developed by Boothroyd Dewhurst Inc. (2003) has a detailed casting cost estimation module aimed at product designers. It however, requires considerable amount of interactive input about the process, such as the time required for each activity and the corresponding labour rate. Also, it does not consider the effect of two key parameters that significantly affect casting cost: internal quality requirement (which depends on the end application) and yield (which varies with casting geometry, metal and process).

To summarize, early cost estimation enables assessing various design alternatives to arrive at the most economical one. Since the total cost depends on the tooling and process parameters also, the cost model must consider these too. Yet, it must be easy-to-use by product designers with limited knowledge of downstream activities. While a number of cost models based on analogical, analytical, feature-based and parametric methods have been evolved, and used for early cost estimation of machined, moulded and sheet metal parts, there is very little published literature on early cost estimation of castings.

The work presented in this paper attempts to bridge this gap by developing a mathematical model for casting cost estimation and implementing the same in an integrated product-process design environment. The model is driven by a database of material and process dependent cost factors, minimizing user inputs. The goal is to enable design engineers to estimate casting costs accurately, even with limited knowledge of casting process. A secondary goal is to implement the cost model in a web based environment, so that product, foundry and tooling engineers can update the relevant factors, carry out iterations of 'what-if' analysis and collaboratively evolve a compatible set of product, tooling and process parameters. We focus on early cost estimation of sand cast components (ferrous as well as non-ferrous), which constitute over 75% of casting production worldwide, but have received the least attention from researchers so far.

3. Cost estimation methodology

The overall casting cost estimation methodology is shown in figure 1. The user input for cost estimation includes only part solid model, 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 part model is used for automatic computation of geometric attributes such as casting volume and weight, minimum and maximum section thickness, cored hole size and shape complexity.

All the above inputs in turn drive process design, which is completed by semi-automatic programs for casting process planning and methoding (feeding and gating design). Process planning 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). A case based reasoning approach, which involves searching for the process plan of the closest matching product manufactured earlier, has been employed for this purpose. Methoding 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). These are designed and modelled using a 3D methoding program.

The output of the process design programs, along with the geometric, material, quality and production attributes of the part, is used for casting cost estimation. The cost model is described in detail next, followed by casting process design in a subsequent section.

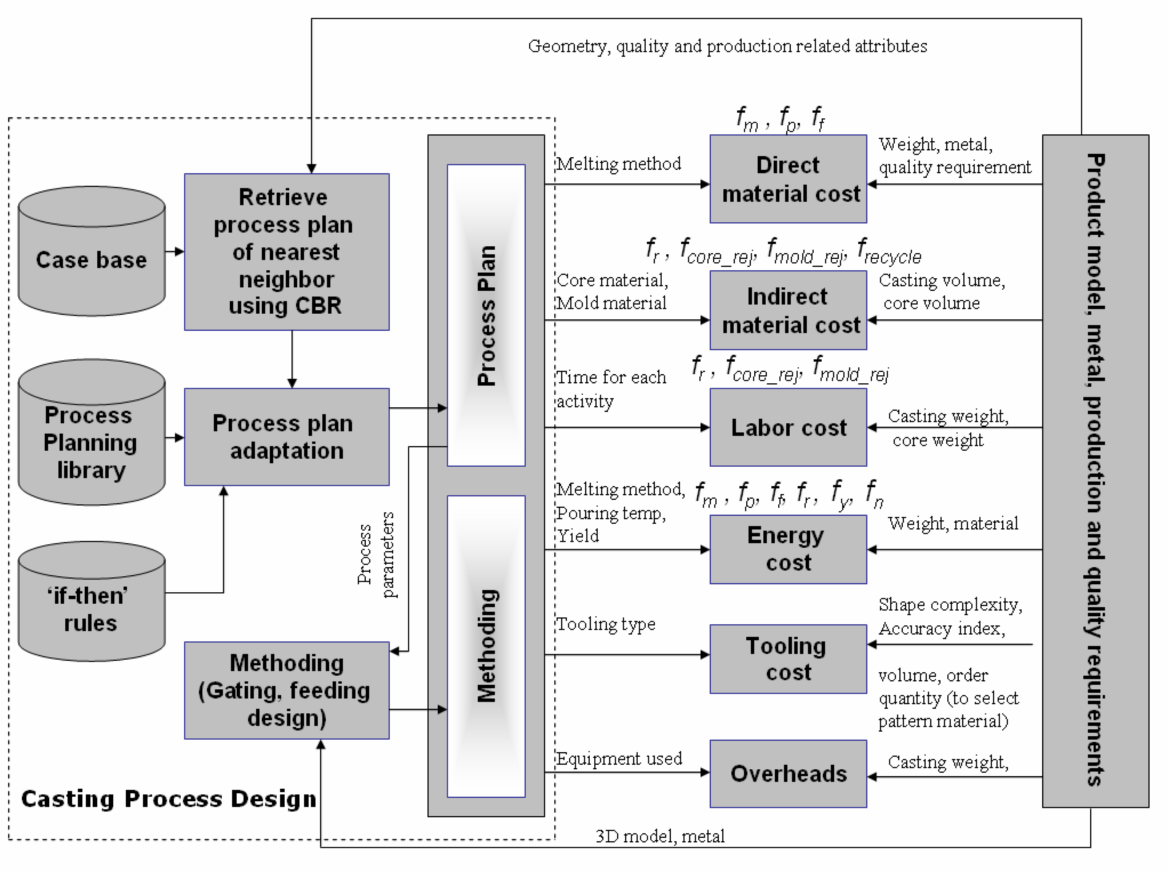


Figure 1. Cost estimation system - overall architecture

The main elements of casting cost are material, labour, energy, tooling and overheads. These are primarily driven by product and process parameters. The cast metal and part weight forms the basis of material cost. Process planning data in terms of process/equipment used and hours required for each activity forms the basis of labour cost. Energy cost is estimated based on the casting weight, yield, pouring temperature and melting equipment. Tooling cost is the most difficult to estimate, and a parametric approach has been evolved for this purpose. Overheads are assigned based on casting weight. Cost modifiers have been proposed to incorporate the effect of losses/rejections at different stages of production. They also help in customising the program for a specific foundry, and correcting the results for different types of castings. The total casting cost is given as the sum of costs corresponding to material, labour, energy, tooling and overheads.

$$C_{casting} = C_{material} + C_{labour} + C_{energy} + C_{tooling} + C_{overheads} \tag{1}$$

Other costs related to interest rate, fixed cost, delivery, taxes, duties and premium can be added. These elements are not considered in the present work, which focuses only on manufacturing cost driven by product design. The equations for estimation of costs related to material, labour, energy, tooling and overheads are presented in the following subsections. The equations are generalised for any currency, that is, the cost values will be obtained in the same currency as that used for the material, labour and energy rates.

3.1 Material cost

The material cost involves both direct and indirect materials. Direct materials (cast metal or alloy) appear in the final product whereas indirect materials are essential for production but are not included in the final product. Moulding sand, dispensable cores, insulating sleeves, chills etc. are indirect materials. The direct material cost can be determined from the casting weight. However, the actual amount of metal consumed is more than the weight of manufactured castings, owing to irrecoverable losses during melting, pouring and fettling. The basic metal cost equation has been modified to incorporate these factors. Since rejected castings (defective castings that cannot be repaired) are re-melted, the factor for rejection is not considered in direct material cost equation. The material cost is given as the sum of the costs of direct and indirect materials as,

$$C_{material} = C_{direct} + C_{indirect} \tag{2}$$

$$C_{direct} = c_{unit\_metal} \times w_{cast} \times f_m \times f_p \times f_f \tag{3}$$

Where,

c_{unit_metal} = Unit metal cost
w_{cast} = Casting weight = $\rho_c \times V_{cast}$
ρ_c = Casting metal density
V_{cast} = Casting volume
f_m = Factor for metal loss in melting = 1.01-1.12 (see Table 1)
f_p = Factor for metal loss in pouring = 1.01-1.07
f_f = Factor for metal loss in fettling =1.01-1.07

The melting loss factor for various melting methods and rejection factors for various quality levels given in table 1 and table 2 respectively, have been determined based on deliberations with experts from industries and from related literature (Beeley 1972).

Table 1. Melting loss factor and furnace efficiency factor

Furnace	f_m	f_η
Cupola furnace	1.05-1.12	3.0-3.5
Induction furnace	1.01-1.04	1.4-2.0
Electric arc Furnace	1.02-1.07	2.0-2.5
Oil/gas fired furnace	1.05-1.10	3.25-3.5

Table 2: Casting rejection factor

Metal/alloy	Quality level	Maximum void size	f_r
Grey iron	1	0.01-0.10	1.05-1.10
	2	0.10-1.00	1.02-1.05
	3	1.00-2.00	1.00-1.02
Steel	1	0.01-0.05	1.07-1.12
	2	0.05-1.00	1.05-1.10
	3	1.00-2.00	1.00-1.05

Indirect materials depend on the process. The moulding sand and core sand constitute the main element of indirect material cost. The cost of moulding sand depends on the type of sand (silica, olivine, zircon, sodium silicate, etc.), composition (amount of binder), mould 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 mould 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. The total indirect material cost is given as,

$$C_{indirect} = C_{mould\_sand} + C_{core\_sand} + C_{miscellaneous} \tag{4}$$

$$C_{mould\_sand} = c_{unit\_mould\_sand} \times f_{recycle} \times f_r \times f_{mould\_rej} \times \left(\frac{\rho_c \times V_m}{r_{metal\_sand}} - \rho_{core\_sand} \times V_{core} \right) \times \frac{1}{n_c} \tag{5}$$

$$C_{core\_sand} = c_{unit\_core\_sand} \times f_r \times f_{core\_rej} \times \rho_{core\_sand} \times V_{core} \tag{6}$$

Where,

C_{mould_sand} = Mold sand cost
C_{core_sand} = Core sand cost
$C_{miscellaneous}$ = Miscellaneous material cost
$c_{unit\_mould\_sand}$ = Unit mould sand cost
$c_{unit\_core\_sand}$ = Unit core sand cost
$f_{recycle}$ = Factor for recycled sand =0.1-1.0
f_r = Factor for casting rejection = 1.00-1.12 (see Table 2)
f_{mould_rej} = Factor for mould rejection
f_{core_rej} = Factor for core rejection
r_{metal_sand} = metal to sand ratio (given later)
V_m = Metal volume per mould $= (n_c \times V_{cast}) + V_g + V_f$
V_f = Volume of all feeders per mould
V_g = Volume of entire gating system
ρ_{core_sand} = Core sand density
V_{core} = Core volume
n_c = Number of cavities per mould

3.2 Labour cost

The labour cost is a function of equipment, labour 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, mould weight and number of castings, respectively. The labour cost is given as,

$$C_{labour} = f_r \times \left(\sum_{act=1}^{n} f_{rej\_act} \times c_{unit\_labour} \times l_{act} \times t_{act} \right) \tag{7}$$

Where,

c_{unit_labour} = Unit labour cost
l_{act} = Number of workers involved in activity *i*
t_{act} = Time for activity *i* per component
n = Number of activities

f_{rej_act} = Rejection factor for activity i
= f_{core_rej} for core making activity =1.00 – 1.20
= f_{mould_rej} for mould making activity = 1.00 – 1.10
= 1 for other activities

3.3 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 mould making, core-making, cleaning and fettling. The energy cost is given as the sum of costs for melting and other energy as,

$$C_{energy} = C_{melting} + C_{other\_energy} \tag{8}$$

$$C_{melting} = c_{unit\_enery} \times f_{\eta} \times w_{cast} \times f_y \times f_r \times f_m \times f_p \times f_f \times [(c_{ps} \times (t_{melt} - t_{room}) + L + c_{pl} \times (t_{tap} - t_{melt})] \tag{9}$$

Where,

c_{unit_energy} = Unit energy cost
f_{η} = Factor for furnace efficiency (see Table 1)
f_y = Factor for overall yield (gating and fettling)
c_{ps} = Specific heat of metal at solid phase
c_{pl} = Specific heat of metal at liquid phase
t_{melt} = Pouring temperature of metal
t_{room} = Room temperature
t_{tap} = Tapping temperature (molten metal removal from furnace)

The cost of other energy is assigned based on the weight of a casting. The rate of assigning is calculated by dividing other energy costs over a period of time by the total weight of castings manufactured during that span.

3.4 Tooling cost

The cost of tooling is difficult to estimate, since it is not yet developed at the product design stage and detailed tooling process plan is not available. This is best tackled by a parametric methodology driven by parameters related to product geometry, material, quality and order quantity. The methodology can give fairly accurate results depending on the instances of cost data of past cases used for deriving the parametric equations. Based on deliberations with casting and tooling experts, major factors influencing tooling cost were identified as tooling material, size, accuracy and shape complexity. The tooling material (wood, aluminium, cast iron, steel, etc.) is usually selected based on order quantity. For a given tooling material (in this case, cast iron), the tooling cost equation has been developed through regression analysis using data collected from tool-makers (Table 3). The equation gives the relative cost of tooling of different shapes, but in the same material. This is multiplied by a cost index to give the actual cost, taking into account variations between manufacturers and countries (currency), and divided by the order quantity to obtain the amortised cost of tooling (per casting). The value of cost index used in the present investigation is 1000 (for currency in INR).

$$C_{rel\_tool\_cost} = \exp(0.629 \times V_{cast} + 0.048 \times C_{ac} + 0.023 \times C_s + 0.739) \tag{10}$$

$$C_{tooling} = c_{index} \times c_{rel\_tool\_cost} / Q \tag{11}$$

Where,

$C_{rel\_tool\_cost}$ = Relative tooling cost for cast iron tooling
$C_{tooling}$ = Amortised cost of tooling (cast iron tooling)
C_{index} = Tooling cost index that varies with manufacturer, currency and time
V_{cast} = Casting volume in m^3
C_{ac} = Accuracy index on 1-100 scale (explained later)
C_s = Casting shape complexity
Q = Order quantity

Table 3. Tooling cost regression data for cast iron tooling

Component Name	Volume x 10^{-3} (m^3) (V_{cast})	Accuracy Index (C_{ac})	Shape Complexity (C_s)	Actual Tooling cost in INR (C_{act_tool})	Actual relative tooling cost ($C_{rel\_tool\_cost}$) $= \frac{C_{act\_tool}}{1000}$	Estimated relative tooling cost
Cube	1.00	5	6.0	3000	3.0	3.05
Sphere	1.20	10	10.0	4000	4.0	4.25
Cube with hole	1.50	20	12.0	6000	6.0	7.18
Bracket	0.93	25	25.0	14 000	14.0	12.31
Stand	0.87	25	25.0	15 000	15.0	12.30
Pulley	4.80	30	20.0	17 000	17.0	13.95
Lug	0.32	40	27.5	22 500	22.5	26.65
Knuckle	0.10	40	48.0	42 000	42.0	42.88
Ball valve	0.98	50	32.5	39 000	39.0	48.24
Differential casing	0.56	40	55.0	65 000	65.0	50.45
Auto cylinder	0.61	50	42.0	60 000	60.0	60.12
UL Valve	0.17	45	60.0	60 000	60.0	71.88
Globe valve	10.10	80	35.0	250 000	250.0	214.91
Steam valve	38.05	80	78.0	500 000	500.0	592.77
Hydraulic lift	40.10	80	80.0	600 000	600.0	622.05
Engine block	46.94	90	92.0	1500 000	1500.0	1328.42

The cost index can be determined by dividing the actual tooling costs by the relative tooling cost for the same casting. An average value of the cost index can be computed for a given tool manufacturer and used in the above equation. For example, if the tooling costs for bracket, auto cylinder and globe valve for another tool manufacturer are 400, 1500 and 6000 USD respectively, then the respective cost indices will be 32.5, 25 and 28, giving an overall cost index of 28.5.

Similar equations are being developed for wooden and epoxy patterns. The particular equation to use (pattern material) can be selected depending on the casting order quantity.

The shape complexity is estimated from the 3D model. For this purpose, an equation to calculate the shape complexity in terms of surface area and number of cored features has been developed using regression analysis (Chougule and Ravi 2004). To eliminate the effect of the absolute value of surface area (for example a cube of any size will have same shape complexity) it is expressed in terms of area ratio as follows.

$$C_s = 0.3 \times C_a + 0.8 \times C_c - 14 \tag{14}$$

Where,

C_s = Shape complexity

C_a = Area ratio = *100* x (*1 – (surface area of cube of equal volume / surface area of part))*

C_c = Core complexity factor = $100 \times \left[1 - \left(1/\sqrt{1+n}\right)\right]$, where n = number of cores

For determining the shape complexity for a new component from its 3D model, values of C_a and C_c are determined and then shape complexity is calculated using the above equation.

The accuracy index has been assigned on 1 to 100 scale depending on the application. For example, engine block and valve castings require a high value of accuracy index whereas bracket and stand castings require a lower value. The designer can specify the accuracy index for the component based on application and referring to the accuracy index values given for sample components (table 3).

3.5 Overhead costs

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

$$C_{overheads} = C_{administarion} + C_{depriciation} \tag{15}$$

$$C_{administarion} = w_{cast} \text{ x } C_{administarion\_rate} \tag{16}$$

$$C_{depriciation} = w_{cast} \text{ x } C_{depriciation\_rate} \tag{17}$$

Where,

$C_{administarion}$ = Administration cost per component

$C_{administarion\_rate}$ = Administration cost rate per kg

$C_{depriciation}$= Depreciation cost per component

$C_{depriciation\_rate}$ = Depreciation cost rate per kg

The administration and depreciation rates are calculated by dividing the corresponding costs over the period of time by the total weight of castings manufactured during that span. The case based reasoning methodology (explained later) facilitates retrieval of these rates at the design stage. Further, the web implementation of the system enables updating the rates for cost estimation.

4. Integrated product process design

An accurate estimation of casting cost requires a detailed knowledge of the process. To enable casting cost estimation at product design phase, a methodology for integrated product process design has been developed. As mentioned earlier, process design involves process planning and methoding. For process planning, a case based reasoning approach using the nearest neighbour algorithm developed in an earlier investigation (Chougule and Ravi 2004) has been employed. For methoding, a 3D casting design software has been linked to the cost estimation program. Both casting process planning and methoding design are briefly explained next.

4.1 Casting process planning

The case based reasoning (CBR) approach involves retrieving a similar previous case (casting project) from the case base depending on part attributes, and adapting the process plan of the retrieved case to the new case. This approach eliminates the need for classification and coding (group technology), and enables better case retrieval. The attributes that have been identified for retrieving a previous casting project (case) include:

- *Casting metal/alloy*
- *Geometric attributes:* maximum casting length, casting weight, minimum and maximum wall thickness, core hole diameter, shape complexity
- *Quality attributes:* surface roughness, tolerance and maximum void size
- *Production attributes:* Order quantity, production rate, sample lead-time, and production lead-time.

For case retrieval, the user specifies the values of the attributes and the corresponding weights representing relative importance of attributes (Chougule and Ravi 2003). To improve the efficiency of case retrieval, the case base is first screened for compatible cases, and the nearest neighbour is then identified from the screened cases.

The first step in screening involves determination of the most suitable process for a new product by comparing its attribute values with the capabilities of different metal-specific processes stored in a database. The attributes used for these purpose include casting material, weight, minimum section thickness, surface finish, tolerance and delivery quantity (a subset of the attributes used for case retrieval). The casting processes covered in the library include green sand casting, high pressure sand casting, shell mouldings, no bake process, gravity die casting, low pressure die casting, high pressure die casting, wax investment casting and foam investment casting. The cast metals include grey iron, ductile iron, steel, aluminium, copper and zinc. Then the case base (database of previous projects) is searched to shortlist the cases that are manufactured by the same process. This helps in reducing the overall time for retrieving the most appropriate case, and prevents the accidental retrieval of a case that may have high similarity value (explained later) but an incompatible process. The nearest neighbour identification involves calculating the similarity of the new case to the short-listed cases using the equation,

$$Sim(N,P)=\sum_{i=1}^{n} w_i \times sim(n_i, p_i) \tag{18}$$

$$sim(n_i, p_i)=1-dist(n_i, p_i) \tag{19}$$

$$dist(n_i, p_i) = \sqrt{(n_i - p_i)^2} \qquad (20)$$

where,
$Sim(N,P)$= Similarity of new case to previous case in the case base
$sim(n_i, p_i)$= Similarity of individual attribute values of new case to previous case
$dist(n_i, p_i)$= Distance between individual attribute values of new case to previous case
n_i = Value of attribute i of new case
p_i = Value of attribute i of previous case in case base
w_i = Weight of attribute i
n = Number of attributes

Based on these similarity values, the nearest old case (with respect to the new case) is identified and its process plan is retrieved. In some instances, it may be necessary to modify the retrieved process plan before adapting it to the new casting project. For this purpose, a process planning library containing alternative methods for performing each casting activity (sand preparation, moulding, core making, melting, etc.) has been proposed. Each method is stored in terms of relevant steps and process parameters (with values). For example, the library corresponding to core making has options hot box, cold box, no bake and sodium silicate. To guide the users, and for semi-automatic modification of the retrieved process plan, a knowledge base in the form of 'if-then' rules is currently under development. Further, the system has been implemented in a web based collaborative environment (mentioned later) facilitating involvement of foundry engineers for process plan adaptation or further fine-tuning, if necessary. After case adaptation and modification, the new case forms a part of case-base for future reference. As the case base grows, the probability of finding a suitable matching case will increase, minimising the need for case adaptation.

4.2 Methoding

The methoding (also called rigging) mainly involves designing the gating system (which leads molten metal from the pouring ladle to the mould cavity) and the feeding system (which compensates for volumetric shrinkage during casting solidification). Related decisions include casting orientation and mould parting. The gating system comprises of pouring basin, sprue, sprue well, runner(s), ingate(s) and filter(s). It is designed to fill the mould cavity within a suitable range of time, distribute the metal uniformly and minimize defects owing to either slow filling (misruns and cold shuts) or fast filling (mould erosion and inclusions). The feeders are designed (in terms of location, shape and size) so that they solidify later than the hottest spots inside the casting, and supply liquid metal needed to compensate volumetric shrinkage during solidification.

A 3D casting design and analysis software called AutoCAST developed in our lab (Ravi *et al.* 1999) has been used for methoding, and its functioning is briefly described here. The program first carries out solidification simulation to identify the hottest region inside the casting. The nearest top or side face is selected to connect a feeder. The feeder dimensions are computed to ensure that the geometric modulus (ratio of volume to cooling surface area) of the feeder is greater than that for the region around the hot spot, for a standard feeder shape (usually cylindrical, with height to diameter ratio ranging from 1.0 to 2.0). The ingate is connected to a side feeder (if existing) or to the thickest section of the casting around the parting line. The sprue location and runner layout are decided semi-automatically. The pouring time is calculated using an empirical equation (different for each metal-process combination) containing casting weight, average section thickness and pouring temperature. This in turn drives the calculation of the dimensions of gating channels. The 3D models of the feeder(s) and gating models are then generated by the program itself and connected to the casting model. The number of cavities in the mould is decided based on the size of the casting and standard sizes of moulds. Finally, the factor for yield and metal to sand ratio are calculated as:

$$f_y = 1 + \frac{w_f + w_g}{n_c \times w_{cast}} \tag{21}$$

$$r_{metal\_sand} = \rho_c \times \left(n_c \times V_{cast} + V_f + V_g \right) \Big/ \rho_{sand} \times \left[V_{l \times w \times h} - \left(n_c \times V_{cast} + V_f + V_g \right) \right] \tag{22}$$

Where,

w_f = Weight of all feeders per mould
w_g = Weight of the entire gating system
$V_{l\text{x}w\text{x}h}$ = Moulding box volume

The program enables even inexperienced users to come up with a fairly ‘good-first’ methoding design. An iteration of feeder and gating design for a typical casting, followed by solidification simulation to verify its internal quality, is usually completed within an hour.

5. Implementation and results

The overall methodology has been implemented in a web-based framework called WebICE (Web-based Intelligent Collaborative Engineering) developed in our laboratory. The WebICE facilitates web-based creation, updating and exchange of casting project data. The project data is stored in a Casting Data Markup Language (CDML), defined using XML (Ravi and Akarte 2002). The CDML consists of two parts: CDML tree and data blocks. The CDML tree represents the hierarchical relationship between different types of information essential for collaboration between product, tooling and foundry engineer, whereas the data blocks are used for storing the actual project data. The hierarchical tree structure enables easy identification of the desired information.

The actual working of system has been demonstrated with cost estimation of an industrial body cap casting. The input to the system is a 3D model of the casting (in STL format), metal name, production requirements (order quantity, production rate, sample lead time and production lead time) and quality requirements (maximum void size, surface finish, tolerance). The casting methoding software AutoCAST linked to WebICE automatically computes the overall dimensions of the casting, minimum and maximum section thickness, casting weight and number of cores. The values of these attributes are shown in table 4. Based on the relevant attributes mentioned earlier, the nearest case (previous casting project) is identified using case based reasoning methodology. The comparison of attributes (mapped on 0-100 scale) of the nearest case (a pulley casting) and body cap is shown in figure 2. Since the nearest case is similar to the present case, its process plan (methods, steps, process parameters) is retrieved and applied to the body cap (figure 3). If necessary, the user can modify the retrieved process plan using the library.

Table 4. Input for cost estimation

Attribute	Value
Material	Grey cast iron
Maximum casting size	255 mm
Weight	14.35 kg
Minimum section thickness	12 mm
Maximum section thickness	36 mm
Number of cores	2
Minimum core size	46 mm
Maximum core size	95 mm
Shape complexity	28
Maximum void size	0.5 mm
Surface finish	8 μm
Tolerance	1 mm
Order quantity	5000 units
Production rate	25 per hour
Sample lead time	45 days
Production lead time	15 days

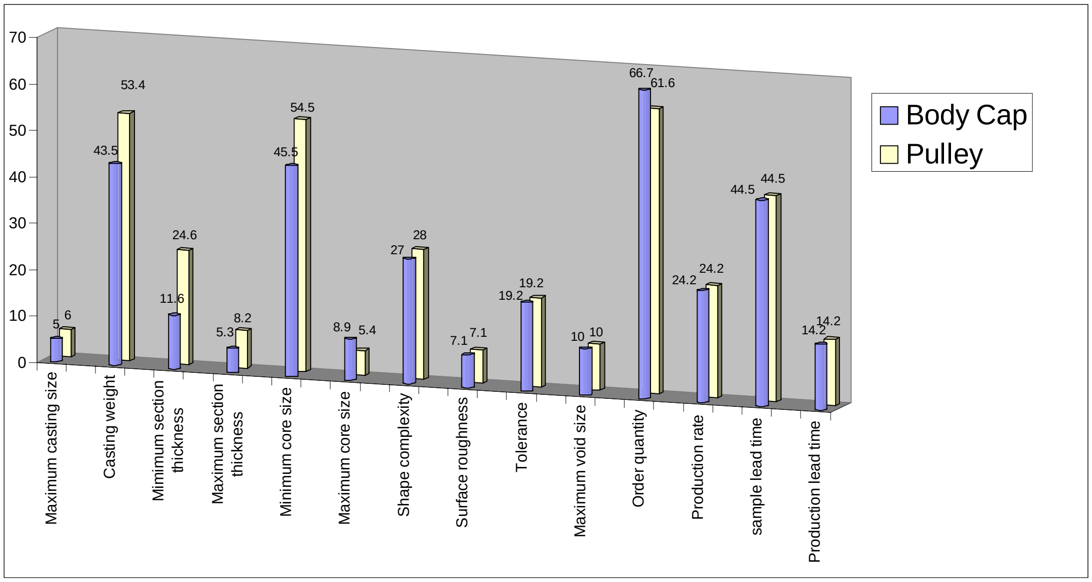
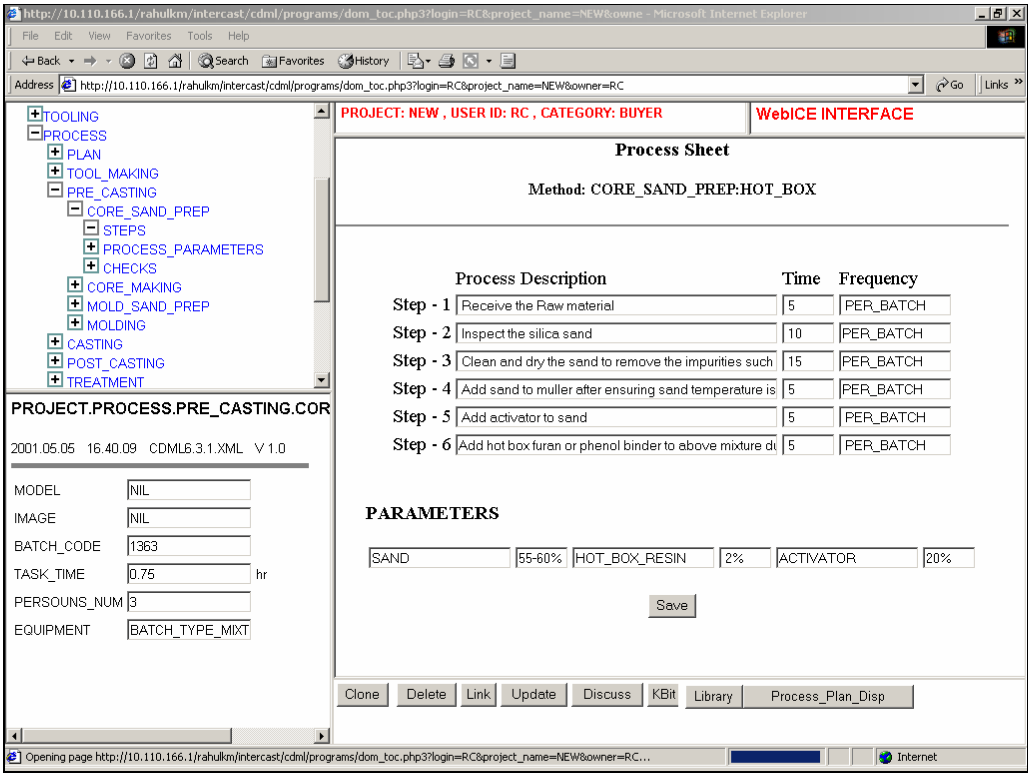


Figure 2. Comparison of retrieved case with new case



PROJECT: NEW , USER ID: RC , CATEGORY: BUYER

WebICE INTERFACE

Process Sheet

Method: CORE_SAND_PREP:HOT_BOX

	Process Description	Time	Frequency
Step - 1	Receive the Raw material	5	PER_BATCH
Step - 2	Inspect the silica sand	10	PER_BATCH
Step - 3	Clean and dry the sand to remove the impurities such	15	PER_BATCH
Step - 4	Add sand to muller after ensuring sand temperature is	5	PER_BATCH
Step - 5	Add activator to sand	5	PER_BATCH
Step - 6	Add hot box furan or phenol binder to above mixture dı	5	PER_BATCH

PARAMETERS

SAND	55-60%	HOT_BOX_RESIN	2%	ACTIVATOR	20%

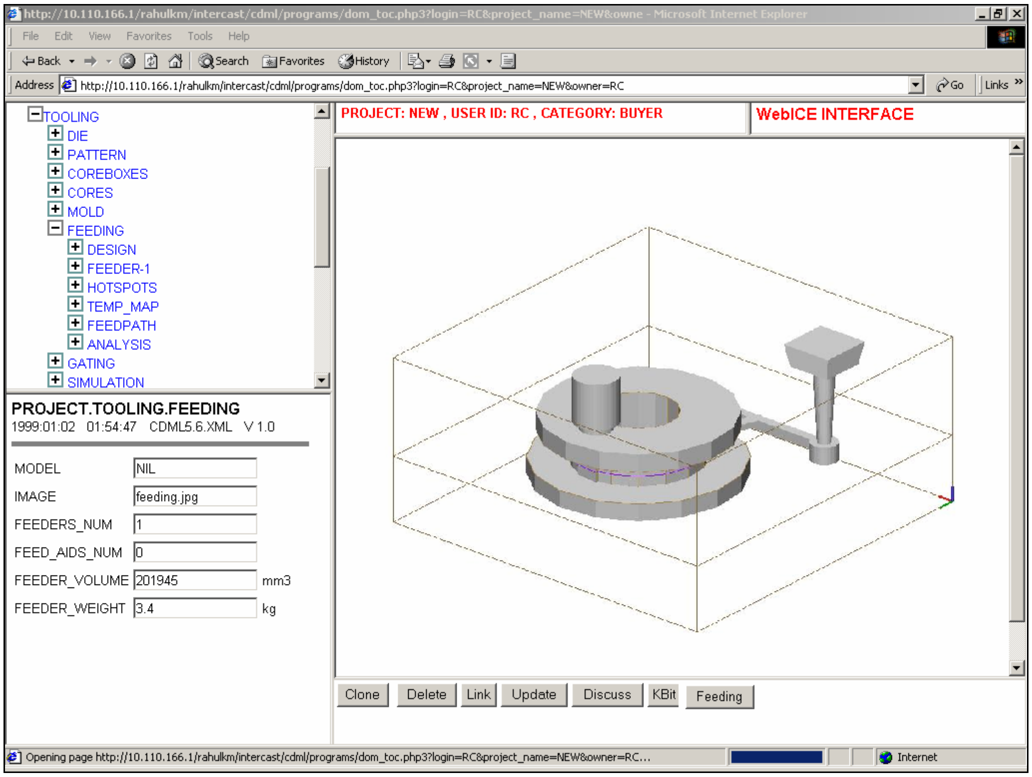
PROJECT.PROCESS.PRE_CASTING.COR

2001.05.05 16.40.09 CDML6.3.1.XML V 1.0

MODEL	NIL	
IMAGE	NIL	
BATCH_CODE	1363	
TASK_TIME	0.75	hr
PERSOUNS_NUM	3	
EQUIPMENT	BATCH_TYPE_MIXT	

Figure 3. Process plan (partial)

The casting model along with metal and major process parameters form the main input to the methoding functions of AutoCAST. The results of feeding and gating design are passed to the WebICE system (figure 4) for cost estimation (figure 5). The cost modifiers are taken from the tables related to the cost model, based on product requirements and process parameters. The cost elements of the body cap casting are summarized in table 5. The results obtained are comparable with the actual casting cost calculated using the weight based approach used in practice. The actual body cap cost supplied by the foundry is INR 500. This is arrived at by first calculating the average per kg rate of similar castings based on cost accounting. The average rate (INR 35 per kg) x casting weight (14.35 kg) gives INR 502.25 as the casting cost, which is rounded off to INR 500. However, the weight based method cannot be used by design engineers, since they may not have access to the detailed cost data of the supplier foundry. Also, this method does not give the cost break up of new castings, which is valuable for identifying areas for cost reduction and for ‘what if’ analysis at the design stage itself. The proposed model overcomes all these limitations of the weight based method. It can be used for castings produced in job shop and mass production foundries with equal accuracy.



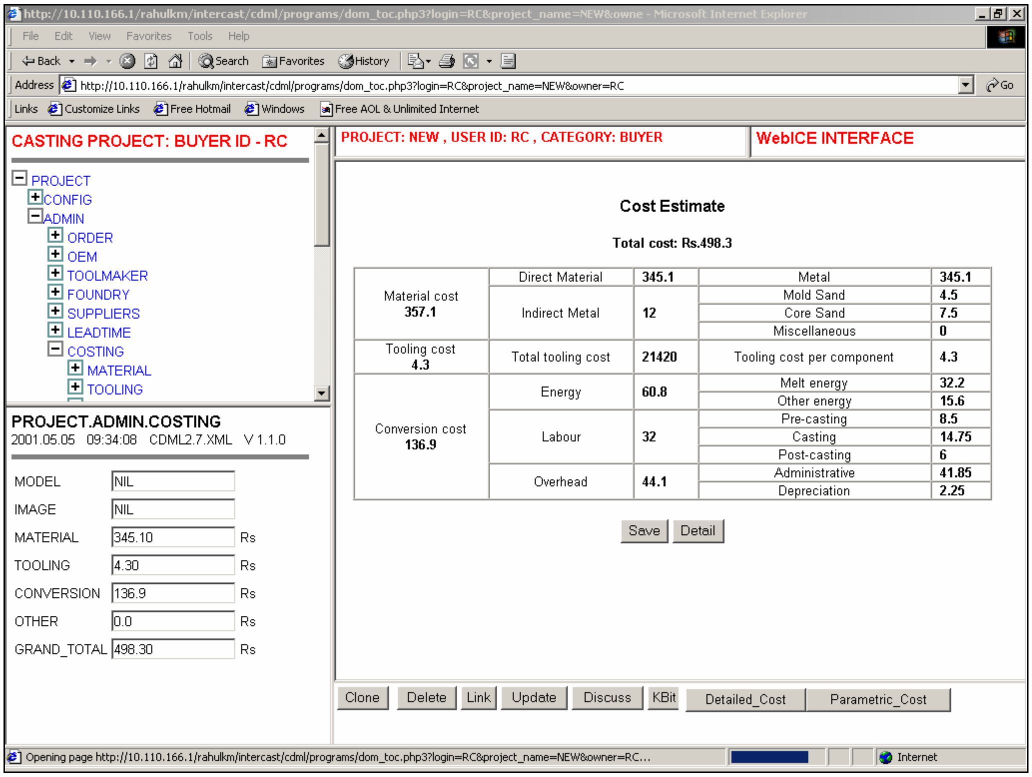
PROJECT.TOOLING.FEEDING

1999:01:02 01:54:47 CDML5.6.XML V 1.0

MODEL	NIL	
IMAGE	feeding.jpg	
FEEDERS_NUM	1	
FEED_AIDS_NUM	0	
FEEDER_VOLUME	201945	mm3
FEEDER_WEIGHT	3.4	kg

Opening page http://10.110.166.1/rahulkm/intercast/cdml/programs/dom_toc.php3?login=RC&project_name=NEW&owner=RC...

Figure 4. Methoding



PROJECT.ADMIN.COSTING

2001.05.05 09:34:08 CDML2.7.XML V 1.1.0

MODEL	NIL	
IMAGE	NIL	
MATERIAL	345.10	Rs
TOOLING	4.30	Rs
CONVERSION	136.9	Rs
OTHER	0.0	Rs
GRAND_TOTAL	498.30	Rs

Cost Estimate

Total cost: Rs.498.3

Material cost **357.1**	Direct Material	**345.1**	Metal	**345.1**
	Indirect Metal	**12**	Mold Sand	**4.5**
			Core Sand	**7.5**
			Miscellaneous	**0**
Tooling cost **4.3**	Total tooling cost	**21420**	Tooling cost per component	**4.3**
Conversion cost **136.9**	Energy	**60.8**	Melt energy	**32.2**
			Other energy	**15.6**
	Labour	**32**	Pre-casting	**8.5**
			Casting	**14.75**
			Post-casting	**6**
	Overhead	**44.1**	Administrative	**41.85**
			Depreciation	**2.25**

Opening page http://10.110.166.1/rahulkm/intercast/cdml/programs/dom_toc.php3?login=RC&project_name=NEW&owner=RC...

Figure 5. Cost estimate

Table 5. Summary of cost (in Indian Rupees; 1 INR ≈ US$ 0.022)

Product: Body cap Material: Grey cast iron Part weight: 14.35 kg Part volume: 1.83x10^{-3} m3 Shape complexity: 28
Accuracy index: 35 Order quantity: 5000 Core weight: 2 kg

Cost Element	**Input from product design**	**Input from process plan / foundry information**	**Cost modifiers**	**Unit/ total cost**	**Cost (INR)**
Direct Material	Part weight	Equipments used (to select cost modifiers)	f_m=1.05, f_p=1.07, f_f=1.07	20.00 INR/kg	345.10
Indirect material	Part volume	Mold box size = 450 x 450 x 250 Cavities per mould = 1, Feed aids = Nil Gating and feeder volume = 1.092x10^{-3} m3 Mold sand type = Green sand Core sand type = Hot box	f_{mould_rej} = 1.01 f_{core_rej} = 1.02 $f_{recycleI}$ =0.10	Mold sand- 1.2 INR/kg Core sand- 3.0 INR/kg	12.00
Labour	Part weight core weight	Time per component in min Melting = 14.75 *(Time per heat 80 min, labours involved 4, capacity 1.3 t/hr)* Core sand preparation = 1.5 *(Time per batch 45 min, labours involved 3, capacity 250 kg)* Mold sand preparation = 0.0 *(Continuous sand mixture hence labour time neglected)* Moulding = 3.0 Core making = 4.0 Shakeout = 1.0 Fettling = 5.0	f_r=1.05, f_{mould_rej} = 1.01 f_{core_rej} = 1.02	60 INR/hr	32.00
Tooling	Part volume, accuracy index, shape complexity, order quantity	Production method		21420	4.30
Energy (Melting + other)	Part weight	Tapping temperature = 1500 ^{o}C Yield = 0.76	f_n=2, f_y=1.3, f_m=1.05, f_p=1.07, f_f=1.07, f_r=1.05	4.00 INR/unit	60.80
Administration overheads	Part weight	Annual administrative cost = 3 000 000 Annual foundry turnover = 1000 t		3 INR/kg	41.85
Depreciation overheads	Part weight	Investment in equipment = 4 000 000 Equipment life = 30 years Annual foundry turnover = 1000 t		0.15 INR/kg	2.25
					Total cost = INR 498.30

The web based implementation of system facilitates viewing of the results by all team members (design, tooling and foundry) irrespective of their location. This can potentially lead to discussions for identifying part, tooling or process parameters for overall cost reduction. The team members can also adjust the cost rates (material, energy, labour, etc.), which vary from one region to another, and cost factors, which depend on local facilities.

6. Conclusion

A hybrid model combining analytical and parametric approaches, has been developed for early cost estimation of castings, and implemented in an integrated product-process design environment. A number of cost modifiers have been proposed to improve the accuracy of cost estimation; this also enables fine-tuning and customisation, if necessary. The model has been validated by an industrial example. The cost estimated by a product designer (with little experience of the casting process, but using the proposed cost estimation system) matched closely with that estimated by an experienced foundry engineer. A systematic approach for cost estimation will give more accurate results and better insights (cost breakups) than the weight based method currently used in practice. Further, web-enabling of the entire system promotes collaboration between product designer, tool-maker and foundry engineer for cost reduction.

References

Ajaml, A., and Dale, B.G., 1990, A computer aided foundry specific planning and estimating system: Its development and some operating results. *International Journal of Engineering Costs and Production Economics*, 13(1), 57–67.

Beeley, P.R., 1972, *Foundry Technology*, (London: Newnes-Butterworths).

Bidanda, B., Kadidal, M., and Billo, R.E., 1998, Development of an intelligent castability and cost estimation system. *International Journal of Production Research*, 36(2), 547–568.

Boothroyd and Dewhurst Inc., 2003, *Design for Manufacture Concurrent Costing Software – User Manual* (Boothroyd and Dewhurst Inc: RI).

Cavalieri, S, Maccarrone, P., and Pinto, R., 2004, Parametric vs. neural network models for the estimation of production costs: A case study in the automotive industry. I*nternational Journal of Production Economics*, 91(2), 165-177.

Chougule, R.G., and Ravi, B., 2003, Casting process planning using case based reasoning. *Transactions of American Foundry Society*, 2003, 111.

Chougule, R. G., and Ravi, B., 2004, Variant process planning of castings using AHP-based nearest neighbor algorithm for case retrieval, (submitted for *International Journal of Production Research*)

Chronister, T.G., 1975, The Cost of making castings. *Casting Engineering*, 7(4), 8–11.

Creese, R.C., Adithan, M., and Pabla, B., 1992, *Estimating and Costing for the Metal Manufacturing Industry* (New York: Marcel Dekker Inc.).

Creese, R.C., and Rao, A., 1995, Scrap vs. Profitability. *Modern Casting*, August 1995, 38–41.

Department of Defence (DoD), 1999, *Parametric Cost Estimating Handbook*. Available at http://www.jsc.nasa.gov /bu2/PCEHHTML/pceh.htm.

Department of Energy (DoE), 1999, *Energy and Environmental Profile of US Metal Casting Industry*, A report published by Office of Industrial Technology, Department of Energy, USA.

Duverlie, P., and Castelain, J. M., 1999, Cost estimation during design step: parametric method versus case based reasoning method, *International Journal of Advanced Manufacturing Technology*, 15(12), 895–906.

Fagade, A., Kazmer D., 2000, Early cost estimation of injection molded components, *Journal of Injection Molding Technology*, Sept 2000.

Farineau, T., Rabenasolo, B., Castelain, J.M., Meyer, Y., and Duverlie, P., 2001, Use of parametric models in an economic evaluation step during the design phase. *International Journal of Advanced Manufacturing Technology*, 17(2), 79–86.

Feng, C., Kusiak, A., and Huang, C., 1996, Cost evaluation in design with form features. *Computer Aided Design*, 28(11), 875–885.

Feng, S., and Zhang, Y., 1999, Conceptual process planning – a definition and functional decomposition. *Proceedings of the 1999 International Mechanical Engineering Congress and Exposition*, 10, pp. 97–106.

Hundal, M.S., 1993, Rules and models for low cost design. *Proceeding of ASME National Design Engineering Conference*, Chicago, March 8-10, (New York: ASME, DE-Vol.52, Design for Manufacturability), pp. 75–84.

Jain, P.L., 1987, Analysis of cost effectiveness for selection of pattern material. *Indian Foundry Journal*, 33(1), 27–30.

Kulkarni, A., 1988, Cost control in foundries through innovation. *Indian Foundry Journal*, 34(1), 21–25.

Luong, L., and Spedding, T., 1995, An integrated system for process planning and cost Estimation in hole making. *International Journal of Advanced Manufacturing Technology*, 10(6), 411–415.

Ou-yang, C., and Lin, T., 1997, Developing an integrated framework for feature-based manufacturing cost estimation. *International Journal of Advanced Manufacturing Technology*, 13(9), 618–629.

Ravi, B., and Akarte, M.M., 2002, Casting Data Markup Language for web-based collaborative engineering. *Transactions of American Foundry Society*, 110, 93–108.

Ravi, B., Creese, R. C., and Ramesh, D., 1999, Design for casting- A new paradigm to prevent potential problems. *Transactions of American Foundry Society*, 107.

Wang, H., Zhou, X. H., and Ruan, X. Y., 2002, Research on injection mould intelligent cost estimation system and key technologies. *International Journal of Advanced Manufacturing Technology*, 21(3), 215-222.

Weustink, I., Brinke, E., Streppel, A., and Kals, H.J.J., 2000, A generic framework for cost estimation and cost control in product design. *Journal of Materials Processing Technology*, 103, 141–48.

Yuh-Min, C., and Jang-Jong, L., 1999, Cost-effective design for injection moulding. *Robotics and Computer-Integrated Manufacturing*, 15(1), 1–21.