Charge Mixing Optimisation Using Linear Programming

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Introduction

With the world advancing so fast and coming up with innovations at never before speed in various aspects of human life, why can't foundries think innovative about their foundry operations and make them world-class by adopting technology which can pay for itself and make the operations cost-efficient. This can lead to reduction in cost, time, etc. and thereby giving competitive advantages either by reducing the sales prices or increasing the profit margins.

While adopting these new self-financing technologies, this has to seen whether they are moving away from the concept of producing castings as an 'art' or producing castings as a 'science'. The foundry industry has been adopting many new concepts such as laser based 3D imaging giving direct inputs to make solid modelling software, 3D printing of patterns, simulating of liquid flow in casting and thereby fixing the positions of runners, risers, partition lines, etc. Now foundries also have to think of new avenues in the same league to have cutting-edge technology to reduce the foundry operation cost.

The example of popular taxi services "Ola" and "Uber" has taught that if the issues are looked at innovatively, solutions can be achieved which are meeting the requirements of all the stake-holders (except for the old taxi-driving community but slowly they are also moving to Ola / Uber) and are cost-effective as well. Another example in the same league could be Tesla cars developed by Mr. Elon Musk and his team. Considering the issues with fossil fuels and the cars running on them, Mr. Musk developed these new generation cars. These cars are so advanced that they can update their software over internet and various new features (such as enabling auto-pilot option) to the car can be added after the car is connected to the internet (so no need to go to the service centre) and at the same time, the Tesla cars can also 'know' the faults in them and can communicate with the car manufacturer over internet and get the solution for those issues as well.

Cost Break-up of Foundry Operations

In order to understand the scope of cost optimisation in foundry operation, first the costs of typical foundries in India are to be broken up, which is given in Fig.1.

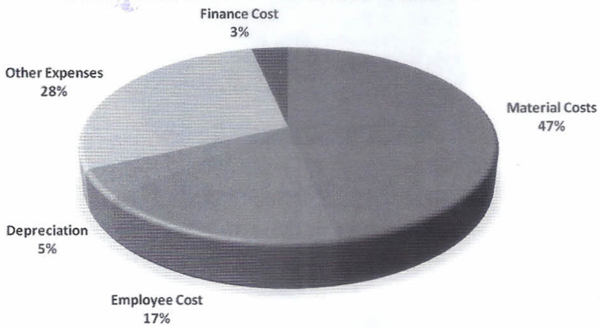

Fig. 1 : Cost Break-up of Foundry Operations (excluding profit / loss)

Notes : 1. Source[1]

2. 'Other expenses' include 'energy costs' as well.

Which Costs can be Optimised

As per popular management principles, concentration may first be given on the high cost areas as a moderate saving of say 5% in 47% (raw material cost), which would lead to overall cost savings of 2.35%. Compared to this, 5% cost savings in 3% (finance cost) would be giving a meagre overall cost savings of 0.15%. So considering this management principle, focus should be given on raw materials for cost savings as it would give significant results.

Few of the probable areas of cost reduction are listed below:

- **Purchasing the materials in bulk by clubbing the requirements smartly** and thereby getting economy of scale (or Economic Order Quantity / EOQ). Most of the companies are already carrying out this activity. Advantage of say upto 1% to 5% of the material cost can be gained depending upon the negotiation skills in today's tight market. There could also be some small savings by clubbing the quantities of transport instead of transporting smaller quantities (less than truck-load). Generally, most of the ERP packages have an option of calculating the EOQ based on the ordering cost, inventory carrying costs, etc. and most of the organisations are using some or the other ERP packages.
- **Hedging of Raw Material Cost** i.e. future buying of raw materials when the costs are low and then use it when the costs go up. There would be some savings depending upon the volatility of the market and risk prediction and risk taking capacity of the organisation. However, in steady market not much savings can be accrued. This type of savings is achieved by commercial persons having very deep knowledge of trading and it depends more on individuals, even though many new software are coming in market to predict the future prices based on regression analysis, the costs of the software is still

quite high and also need very high-end computers for number crunching. Considering these issues, this option is ruled out for most of the small and medium foundries.

- Using of returns to the maximum extent in the charge-mix. If used properly, the re-use of returns and rejects can reduce the costs to a great extent, as the cost of the returns / rejects is already recovered in the costing of good castings. So, practically these returns / rejects are free costs and can reduce the manufacturing cost to that extent. However, if the returns or rejects have chemistry different from what is required in the final chemistry, sometimes the returns turn out to be a costly affair to reach to the desired chemistry. A very basic example of this could be say, to use nickel-based returns for making castings that do not need nickel in the chemical composition. So other elements are to be added to take out all nickel from the molten metal. Considering this aspect before using the returns, it needs to be doubly sure of the final output chemistry and the chemistry of the returns / rejects.
- **Judiciously mixing the raw materials to get the exact output chemistry in first go or charge-mix optimisation.** This strategy has 2 advantages: first is savings in cost due to judicious mixing of raw materials and second is savings in energy cost as the correct chemistry is achived in the first go and the furnace need not be heated till correct chemistry is achieved. This energy savings to the tune of 1% to 5% of the energy cost could be an additional bonus.

How to Optimise the Charge Cost

Being technical minded and rational thinkers, people should concentrate on the third and fourth of the above options for cost reduction. In these options, the output chemistry, input chemistry, recovery of each alloying element in the raw materials, melting losses, etc. are known to all. By putting all these details and then by chemical balance the best raw material combination can be found out to achieve the desired chemistry by trial and error. The following techniques may be used:

1. **Calculator, pen and paper (old school of thought):** This may take some time and the accuracy of the calculations depends upon person to person. This method may lead to lots of dependency on a particular person and hence, the charge mixing technique becomes an "art" of that person. Also since lots of calculations are involved, it takes a lot of time. So, in order to reduce the time, generally this person uses a template and makes small changes here and there to reduce the calculation time. Sometimes, other distractions on the shop-floor can lead to wrong charge-mix calculations. So, this method is not dependable for mass production as it has too many IFs and BUTs and since it is based on the trial and error method of the calculating individual, it cannot be ensured that this is the optimal charge-mix giving the least cost. Moreover, when the person calculating this charge-mix is not present, the operations may hamper or other persons use their 'skills' to calculate the charge based on previous experience. In such cases, the charge-mixing may still move away from optimal charge-mix cost.
2. **Spread-sheets Calculation Method :** This is one of the most popular methods of charge-mix calculation. In this method, all the details stated above are fed in various worksheets of a spreadsheet and then the actual calculations are performed by the spreadsheet programme. Since the calculations are made by the computer programme, the speed of calculation and accuracy is high. In this method, couple of persons are aware of the inputs and working of the "customised" spread-sheets and this can again lead to the charge-mixing as an "art" controlled by those individuals. Sometimes, errors in entering the chemistry of raw materials / output chemistry may lead to errors in charge-mix calculations. However, since most of the persons are aware of working of spreadsheets, many companies / organisations have developed their "customised" spreadsheet programmes for internal use as it takes very less effort to train the new persons to use the 'customised' spreadsheet programme.
3. **Customised Software Method :** A company / organisation develops a customised charge-mixing software based on their requirements from internal / external software vendor after taking inputs from their in-house charge-mix calculating experts. These in-house experts give inputs about chemical balance, calculation methods, etc. to the software professionals. So, this kind of software is advanced version of the above option 2, wherein the graphical user interface (GUI) or front-end is designed in better way for the users, however, the back-end works on the similar fashion as stated in the above option 2. These types of systems are not developed and used by many companies due to additional development cost involved and no significant cost savings occur compared to the above option 2.
4. **Linear Programming based Software Method :** These types of software are specifically designed for charge mixing taking best practices from various foundries all over the globe. These types of software can also be integrated with other system such as Spectrometers to reduce the errors in entry of chemistry / dual data entry. ERPs such as SAP can also be integrated to these software to get the inventory and purchase-related data. The best practices in these kind of software when combined with linear programming solver can lead to most optimal solutions which cannot be optimised further and thus giving good amount of consistent cost savings over the above 3 options.

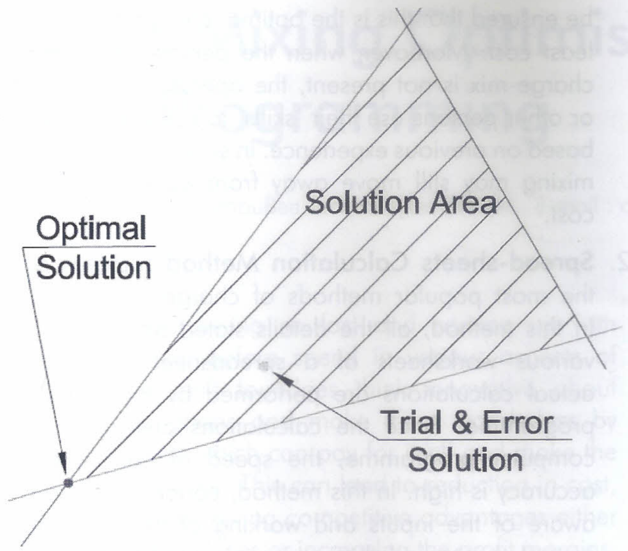

Fig. 2 : Difference between Linear Programming based optimal solution and trial & error based solution for 2 dimensional problems (in foundry there are always more than 2 dimensions).

Refer to Fig. 2, the first 3 of the above options would lead to the trial and error solution. While arriving at the solution, whether the solution is the optimal solution is not known as only few known variables can be controlled and then to come to a conclusion that this is the best possible solution (ignorance is bliss). As against this, using linear programming, which is a very systematic approach, a solution can be arrived at which is the most optimal solution and considering the properties of linear programming method, it may not be possible to further optimise this solution.

Most of the readers would be aware of the first 2 options. A few people would be aware of the third option as well. For the benefit of all the users, the 4th option is discussed in detail.

Linear Programming

When one has to find out the value of only one variable, then one equation is sufficient. Few examples of this type of equations are:

(1) $x + 5 = 0$, which gives the value of $x = -5$

(2) $3x = 18$, giving a value of $x = 6$

When one has to find out values of say two variables, then it at least two equations are needed for finding out the correct values of those variables. With one equation, correct values of two variables cannot be derived as mathematically there could be infinite solutions to this 2 variable one equation problem. Example of this is popular line slope equation $y = mx + c$ in which the value of variable y is to be found out based on the value of x. So by inputting various values of x coordinates, value of y coordinate is obtained and thereby path of a continuous line and not a single point. So from this one equation, it can be seen that for every value of x there is corresponding value of y and there is no exact solution as in the above point.

So to get the value of two variables, these equations can be solved by simultaneous equation method. Few of the examples of this type of equations are:

(1) $3x + 2y = 12$ & $10x + 5y = 35$. After solving these two equations, the values of $x = 2$ and $y = 3$ can be worked out.

(2) $3x . 4y = 38$ & $10x / 50y = 1$, giving values of $x = 10$ and $y = 2$.

Now there are 3 unknown variables, so to get their exact values, ideally 3 different equations are needed. Hence, it can be generalised that to get the values of 'n' unknown variables, 'n' equations are needed.

With the above mathematical background in mind, now come to the issue of output chemistry of castings. Wherein generally percentages of at least 5 alloying elements is controlled in a casting (say Fe, Si, Mn, carbon & sulphur), which is fixed by external agencies such as clients and can be treated as imposed constraints.

Other constraints could be:

- Availability / stock of each raw material.
- Internal conditions (know–how, quality, previous experiences in mechanical tests).
- Any other customer requirements.

The list of the constraints would be specific to each foundry and this list may vary depending upon the working style at each foundry and the client combination.

To achieve the above output chemistry, various raw materials would be used which could include say:

- Pig iron
- Casting returns,
- HMS of various types say
  - Turning and boring scrap
  - Sheet metal scrap (low carbon steel)
  - Rods / TMT bar scrap, etc.
- Ferro-x (manganese, silicon, chromium, etc.) alloys, etc.
- Pure elements such as copper, graphite, etc.

Now each of the above raw materials has its own chemistry. Considering only 5 alloying elements of each of the above raw materials (except for pure elements), if 5 of the above raw materials are used, then there will be about 5 x 5 = 25 variables.

Also for each of the five alloying elements in the above raw materials, there would be different recovery factor (as 100%

recovery would not be achieved for each of the alloying elements as per the chemistry of the raw material, furnace temperature, flux chemistry, etc.). So, there would again be 25 variables for the recovery factor of the above 5 raw materials.

Since the prices of the raw materials are not constant and vary depending upon the demand supply curve, it needs to consider that while optimising the costs of the raw materials used. This input would go towards the objective of "to reduce the overall cost of the charge".

If the above inputs are just added, then there will be 5 imposed constraints (of chemistry) for finished goods. Then, there are 25 variables for raw materials and their chemistry + 25 variables for recovery percentage of each of the alloying elements and the objective of overall cost reduction. When all these are clubbed, it becomes too complicated. With all said and done about human brain and its capacity, it becomes almost impossible for any average person to practically calculate the accurate charge-mix just before the start of the next batch of furnace with all these different inputs using either "Paper & pencil method" / "Spread-sheet method". So the best solution to solve these kind of problems is **Linear Programming**.

The linear programming (LP) method is first developed in 1827 by French mathematician Mr. Joseph Fourier. This method is generally used when there are many variables compared to the number of equations required to solve them. In linear programming, the most optimal solution can always be achieved for a given set of constraints and variables. For the given set of constraints, it may be possible that there could be two solutions of same value, however mathematically / technically there would not exist any better solution than that arrived using Linear Programming method. For more details of Linear programming method, the interested readers can read on Wikipedia[2] or similar websites.

So with linear programming, foundrymen can arrive at the best / optimal charge-mix for given set of conditions. If any of the conditions changes, i.e. say price of one raw material is reduced / increased. Then again the earlier solution arrived using Linear Programming might not be optimal and new optimal solution has to be calculated.

Currently what people in the foundry industry do is, they arrive at the charge-mix based on the expertise of foundry supervisor/foundry manager. This person based on his / her own judgement, calculates the charge-mix. Most of them are not aware of the current raw material prices, so their solution may be good based on the chemical balance of few alloying elements and guidelines from top management about using a particular raw material more because it is cheaper than other raw materials (however how much cheap is not known to them). So this charge-mix calculated by the foundry persons may not be optimal price-wise or in overall manner.

Take a couple of examples to elaborate this point. For one company 'x', they are creating almost 95% to 99% pure Fe by removing all the alloying elements in it. Rest of the amount is carbon depending upon the casting requirements. Then they add suitable alloying elements as per their requirements in the ladle.

If the cost of raw materials is calculated as per conventional practices (i.e. chemical balancing) then the per tonne cost of the charge-mix is 26,233. Following is their raw material input this company uses per tonne of finished goods produced. If the constraints are put in terms of output chemistry and chemistry, prices & recovery of each alloying element in the raw materials in the leanear programming method, following solution can be obtained:

Raw Materials used	Conventional Method in Kg per tonne	Linear Programming Method in Kg per tonne
Pig Iron	370	277
HMS	493	576
DRI	123	89
Turning Scrap	31	78
Misc	62	55
TMT Bars	31	33
Total Cost	**26,233**	**25,807**

So with linear programming method there is a savings of 1.63% for getting a plain metal. This 1.63% of 47% of raw material cost would give overall savings of 0.76% in the cost. None would have thought of getting a cost savings in producing pure Fe. But in case of linear programming it is possible to get the cost savings in this seemingly impossible case as well. If proper cast iron with all the alloying elements are considered, a cost savings of approx. of upto 4% can be achieved (instead of 1.63% shown above). This can help foundrymen a lot in making foundry operations profitable to that extent.

Now take another example of company 'y' producing complex chemistry of GX-40 CrNi 25-12 type steel[3]. This company wanted to use a fixed quantity of 450 kg of GX-40 returns per tonne of steel. Hence, it can be seen that the quantity of this raw material in conventional method (spreadsheet method) and linear programming method is same. As per the desired chemistry, the spread sheet method calculated the charge as shown below.

Materials Used	Conventional Method Quantity (kg)	Linear Programming Quantity (kg)
Steel Scrap	250	0
FeCr	210	163
FeMn	13	0
FeSi	14	13.6
Graphite	1	0
Nickel	62	38.4
Return GX-40 (Stock = 450 kg)	450	450
Return CF8M (Stock = 450 kg)	0	234
Return GS-52 (Stock = 250 kg)	0	16
Ingot 3.8C-0.7Mn-3.15Si	0	85
Charge Cost per Tonne	**1,04,655.84**	**90,072.95**

First of all in this example, the linear programming software 'searched' for other low cost returns / raw materials before consuming high value steel scrap, FeMn alloy, FeCr alloy, etc. This change in approach lead to the raw material savings to the tune of 17.24% of 47% giving us the final results of 8.1% overall cost savings!

Even though, above examples of charge-mix are taken for ferrous foundries. Since the mathematical principles are same, effectively linear programming can be used for optimising the costs of non-ferrous foundries as well. Based on the understanding following could be typical values of cost savings achieved through the use of Linear Programming based software.

- Cast Iron: 4% (About 15,000 US$ /(1000 tonnes))
- Aluminium: 8% (About 120,000 US$ / (1000 tonnes))
- High Alloyed Steel: 15% (About 250,000 US$ / (1000 tonnes))

Surely, most of the foundries do not have such a huge margin of 8%. So, all this cost savings can lead to additional profit or reduction in costs to get the competitive advantage. It is upto the individual foundry to keep 100% additional cost savings with them, or pass on some per cent of this cost savings to the client by reducing the costs and thereby beating the competition and gaining additional business.

Conclusions

Linear programming even though about 190 years old technique, for variety of reasons nobody had thought of using it in calculating charge-mix earlier. If 'innovative' constraints are put in the linear programming to let the system calculate the charge-mix, very good and encouraging results can be achieved in reducing cost and thereby improving the sales volumes. Another advantage of this method is since the mundane work of charge calculations is performed by the computers, the foundry supervisors / managers get more time in doing some creative and productive work for improving quality, 5S, TPM, TQM, etc. activities and thereby improving the overall performance of the foundry.

References

1. From the Annual reports (audited balance sheet) published on the websites of 5 publicly traded foundries / companies on various stock exchanges in India. These details are for Financial Year ended on 31st Mar 2016. Under each head shown in the chart, we have added costs for these 5 companies and taken simple average of those figures and then converted into the percentages.
2. Wikipedia - https://en.wikipedia.org/wiki/Linear_programming
3. Article "Software for the Optimization of Raw Materials in Casting: A Key to Quality and Competitiveness" by Mr. Alberto Montenegro Correa published in WFC 2014.

Source : Foundry Review