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Energy Saving using 7Epsilon

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ABSTRACT

Steve Robinsons[17] of American Foundrymen Society has once argued that foundries with 4% profit margin need to find new sales revenue of US$1 Million to generate US$40,000 operating profits. The case study presented in this paper highlights how an in-process quality improvement exercise resulted in annual saving of US$144,000 by studying in-process data in a melt room on 25 process inputs.

Foundry is an energy intensive industry. Energy costs for foundries are around 15% of the cost of castings. In recent years foundries have become energy aware and many have installed energy meters with on-line energy monitoring systems to report energy consumption (kWh) per tonne, charge or furnace with varying sampling frequency.

This paper highlights how 7 Steps of 7Epsilon were implemented and in-process data for a foundry was visualised using penalty matrices to discover energy saving opportunities. With ISO 9001:2015 on the horizon there is an urgent need to change the foundry culture - across the world - towards capturing, storing, reusing in-process data as well as organisational knowledge in order to demonstrate in-process quality improvement. The 7Epsilon approach offers a structured methodology for organizational knowledge management as well as in-process quality improvement.

Keywords: Energy optimisation, Melting process, Iron Foundry, Six Sigma, 7Epsilon, In-process Quality Improvement, Energy

INTRODUCTION

On an annual casting production of 95 million tonnes with a very conservative cost of US$1.2 per kg for ferrous alloys, the total foundry market is well in access of US$100 Billion. Approximately 15% of these costs are energy costs (US$ 15 Billion) and 75 to 80% of the costs are in the melting process alone. A 10% saving in energy efficiency is equivalent to a saving of US $1.5 Billion along with substantial reduction in harmful greenhouse gas emissions.

A quick Google search will discover that the foundry industry is on various government agencies radar across the globe in order to meet emission targets set by them. For example, European Union has come up with 20-20-20 targets by 2020[1]. The policy is to reduce greenhouse emissions by 20% of 1990 levels as well as increase energy efficiency by 20%. Similar targets are also announced by the US Environmental Protection Agency[2]. In the recent UN Climate Summit even China has given its commitment to reduce harmful emissions[3].

US department of energy has compiled examples or suggestions on best practise energy use in metal casting industry[4]. European commission has also funded complementary projects and the findings[5,6] are available on internet along with number of guidelines and suggestions. Some of the guidelines require substantial capital investment that may not be an option for every foundry.

7EPSILON AND ENERGY EFFICIENCY

This paper presents a case study in a foundry where the foundry planned energy improvement solutions as part of a much wider activity. The foundry was introduced to the 7Epsilon[7] philosophy on process improvement. The 7Epsilon initiative, led by Swansea University, has bought together a consortium of European foundry experts, process engineers, trade associations, universities and institutions to develop a philosophy that would take us beyond six sigma thinking on knowledge management and in-process quality improvement projects. Since 2012, the second and third author have conducted numerous roadshows and personally trained over 175 foundry process engineers from UK, Spain, Poland, Sweden, Belgium, Ireland, India and USA[7]. The first author has actively campaigned for the 7Epsilon initiative in India. The 7 steps of 7Epsilon to ERADICATE defects were implemented in a US steel foundry and the case study was presented as an official UK exchange paper to the recent World Foundry Congress[8]. A chemical composition optimization case study related to a European investment casting foundry is being presented at the 61st annual ICI conference[9].

The objective of this paper is to discuss the experience of implementing energy optimization example in a foundry by adopting 7Epsilon principles.

AN ENERGY SAVING CASE STUDY

The foundry is a gray iron foundry in India producing cylinder blocks and heads with a monthly output of 2500 tonnes of good castings. The foundry had induction furnaces based on heel melting principle as a result of low powered (mains frequency) requirement. The foundry had energy meters installed with continuous monitoring of energy data with a web based communication system (Fig. 1.) offered by Customized Energy Solutions[10]. The company maximizes value of existing and emerging electric infrastructure through active resource management for over 300 clients in all 7 competitive electricity markets in USA and India.

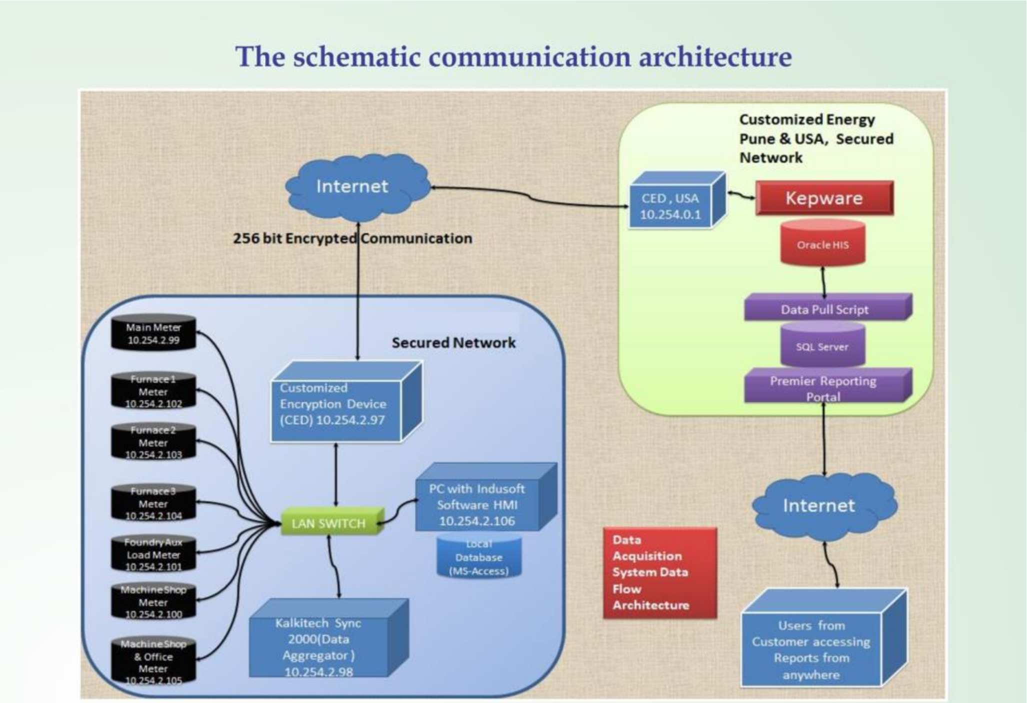


Fig. 1. Schematic diagram of a typical web based communication system for energy audits.

The web based communication system allowed comparing energy consumption with respect to process output as well as production shifts. The typical load curve is shown on the graph (Fig. 2.). The objective as described in the graph is to ensure that there are no peaks or valleys and the optimized power demand is fairly constant. The Specific Energy Consumption (SEC) variation in kWh/ tonne of melt for three furnaces is shown in Figure 3 for three shifts over a three day period. It is observed that the variation in one furnace is higher than others. Further optimization opportunities can be discovered if the energy consumption is monitored at much shorter durations e.g. every 30-90 minutes (Fig. 4) and is related to in-process observations. In this example, the graph shown in Figure 4 is used to discuss a roadmap to lower energy consumption. The average value over the 3 day period was 683 kWh/tonne of melt and the monthly average value was 660 kWh/tonne of melt.

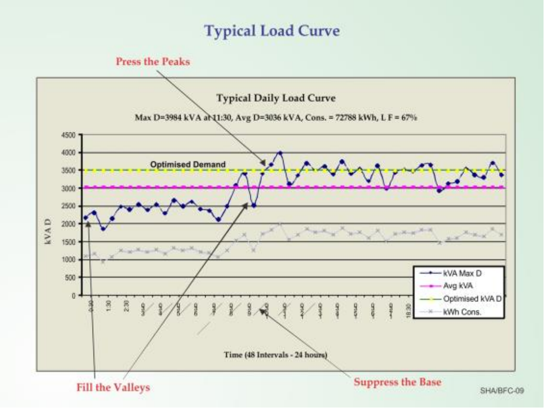


Fig. 2. Schematic of a typical daily load curve

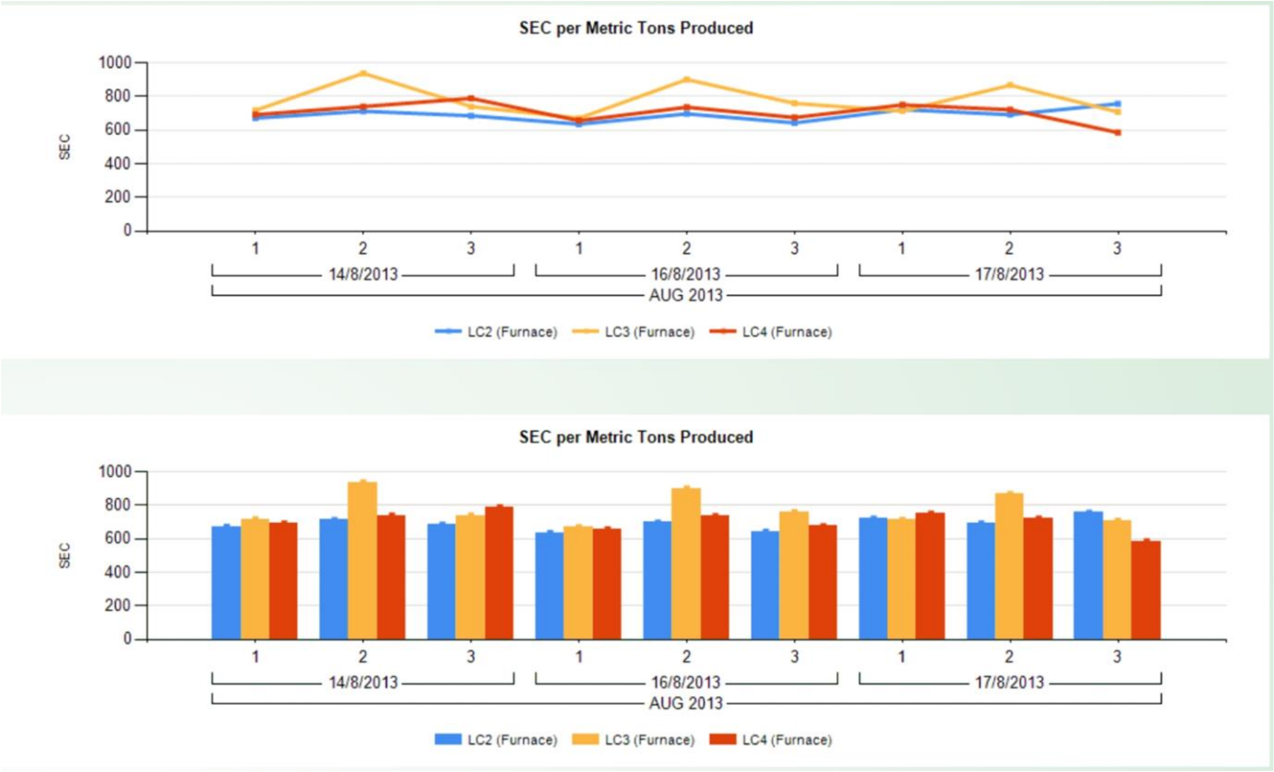


***Fig.3. Specific energy consumption per tonne of melt produced is compared for three furnaces for a period of 3 days*.**

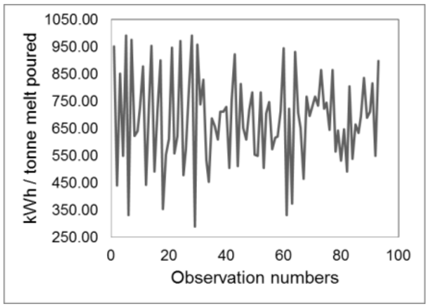


Fig. 4. A typical energy consumption (kWh) for an induction furnace continuously monitored at approximately 30-90 minutes intervals for a period of 3 working days.

7EPSILON STRATEGY

The top management of the concerned foundry chose to make any future investments necessary as part of a wider 7Epsilon strategy of changing the work culture towards in-process quality improvement and creating an environment where the organisational knowledge is continuously captured and reused by its employees in order to make foundry specific improvement decisions. The foundry categorised the improvement process into three phases:

1. Solutions that do not require any investment: The objective of this phase is to proactively engage with the staff in changing the work culture and right practices so that they participate in new development and are ready for addressing changes in the working environment. The exercise also focuses on continual process improvement strategies and achieves savings that pay for the costs of small investment decisions.

2. Solutions requiring small investment: Small investment decisions focus on acquiring new tools and instrumentation, safe and efficient electrical installations etc. The process continually develops improvement opportunities, retains engagement with the staff, creates organisational knowledge and the money saved can partly pay for the necessary large capital investments.

3. Solutions requiring large capital investment: These decisions include potential changes to the material handling systems, modifications in plant layout, energy efficient electric motors or furnaces etc. The advantage to the top management is that the interdisciplinary process improvement team suggests solutions after conducting a series of self-funding improvement projects and undertaking their own research on published best practise guidelines rather than the management making a top down decision early on in the process and losing the opportunity of creating a much wider impact and involvement of its staff in the decision making process.

The 7 Steps of 7Epsilon to **ERADICATE** defects or non-conformities are:

Step 1: **E**stablish process knowledge [x’s], [y’s]
Step 2: **R**efine process knowledge [y = f(x’s)]
Step 3: **A**nalyse data
Step 4: **D**evelop hypotheses (potential solutions)
Step 5: **I**nnovate using rootcause analysis and conducting confirmation trials
Step 6: **C**orrective actions and update process knowledge
Step 7: Build **A**spiring **T**eams and **E**nvironments by monitoring performance

The step 0 has been implicitly designed in that it defines a project goal. This step is similar to any Six Sigma project. The major difference in a Six Sigma and 7Epsilon project is that the DMAIC cycle focuses measuring the data on critical process variables. Six sigma techniques focus on creating new knowledge by discovering new combinations of process inputs with significantly different tolerance limits (design of experiments philosophy). 7Epsilon’s in-process quality improvement philosophy focuses on making small adjustments to several process inputs.

STEP 1: ESTABLISH PROCESS KNOWLEDGE [X’S], [Y’S]

An interdisciplinary team is formed to gather process knowledge. Typically, [y’s] are process outputs or responses and [x’s] are process inputs or measurable factors. The traditionally used brain storming sessions can be employed for creating process maps.

For the energy case study, the process response was energy consumption in kWh/tonne charge and / or kWh/tonne of liquid metal poured. In this example, the team involved process engineers, plant engineers, operators and supervisors from the melt room, foundry managers as well as the maintenance team. The operational constraints were understood from them and every one was encouraged to provide valid suggestions.

The operating cycle was studied (e.g. charging time, charge density, deslagging time, sample taking time, temperature measurement time, holding time, tapping temperature, tapping time, furnace metal heel, position of furnace cover and facilities on charging platform).

The team was directed to undertake a literature review. Best practise examples for induction melting process available on Google were studied and notes were made.

1. Advanced melting technologies: energy saving concepts and opportunities for the metal casting industry[11]
2. Theoretical/Best practice energy use in metal casting operations[12]
3. Metalcasting industry: energy best practice guidebook[13]
4. Guide to energy efficiency opportunities in Canadian foundries[14]
5. IPPC reference document on best available techniques in the smitheries and foundries industry[15]
6. Foundrybench: Good practise guides for European foundries (reports D19 and D21) [16]
7. Effective energy management presentation given by AFS technical director[17]

As discussed before the objective of this study was to discover solutions that do not require investments. As shown in Figure 4, there was considerable variation in the energy consumption measured at much shorter durations and the goal was to discover continual process improvement opportunities that may result by slightly adjusting one or more process inputs. The in-process data for the following 25 process parameters was collected (Table 1).

Table 1: Process inputs monitored for a 7Epsilon in- process quality improvement project

Heel metal at start (kg)	Charge Mix – Boring (kg)	Density of material (I: closely packed, III: lose)	Charging excluding heel metal (kg)	Metal above active coil (Yes/No)
Charge Mix –Mild Steel (kg)	Time interval used for monitoring (min)	Quality of boring (I: Good, III bad)	Tapping Temperature (^{o}C)	Slag buildup (Less, Heavy)
Charge Mix – Pig Iron (kg)	Energy consumed in the given time (kWh)	Quality of Mild Steel (I: Good, III bad)	Power quality (V) at full level	Deslagging time (min)
Charge Mix – Runner Riser (kg)	Total Charge used (kg) in the given time	Quality of Runner Riser (I: Good, III bad)	Shift I/II/III	% of full power rating used.
Charge Mix – Cast Iron (kg)	Melt poured in the given time (kg)	Size of material	Operator skill	Holding of metal

In this example, the team monitored a furnace in continuous production (all three shifts) for a period of 3 days and took readings for all 25 process inputs averaged over the time interval of 30-90 minutes e.g. the heel metal at the start of the interval was measured. The charge added, average tapping temperature and the energy consumption in kWh for the same interval was noted. However the molten metal poured or charge added included the total metal poured or charge added in the given time frame. The response values of specific energy consumption of kWh/tonne of melt poured and kWh/tonne of charge were calculated for each time interval. The resulting graph of kWh/tonne of melt poured is shown in Figure 4 and the corresponding scatter variation is shown in Figure 5a.

STEP 2: REFINE PROCESS KNOWELDGE [Y=F(X'S)]

This step requires the interdisciplinary team to make their own notes relating how process inputs affect process outputs. This helps the team to visualise the process e.g. compare and contrast heel melting process with a batch melting process for induction furnaces. E.g in this example, it was noted that the constraints of matching mould line capacity and metal handling equipment has made compulsion to have heel metal in crucibles. The team understood the heat loss process due conduction and radiation and related to the potential causes identified in the first step. They studied operating conditions, limitations, advantages and disadvantages and made notes from the literature reviewed. The logic for the sampling rates for responses and process inputs (factors), their tolerance limits and target values were noted for future reference. This process helps to create, capture and if necessary update, foundry and product specific process knowledge. This knowledge normally remains confidential to the foundry.

STEP 3: ANALYZE DATA

This step defines limits for acceptable and unacceptable process variation (e.g. energy consumption in kWh/tonne of liquid metal) as described in Figure 5a and b. The bench mark review for foundries undertaken in Europe and North America suggests wide variation for heel melting process. A study, undertaken for US department of energy for induction furnaces, shows an average energy consumption value for well-run heel melters up to 800 kWh/ton as compared to batch melters (530 kWh/ton)[12]. European best available techniques guideline gives a value of 600 kWh/tonne melt for molten metal heal with a range from 550 to 650 kWh/tonne melt[15]. A survey with Canadian foundries suggested a much larger variation from 595 to 1290 kWh/tonne of melt with an average value of 772 kWh/tonne[14]. The penalty matrix approach of 7Epsilon develops penalty function quantifying acceptable and unacceptable response. In this example, acceptable response values below 650 kWh/tonne of melt were given zero penalty and unacceptable response values above 725 kWh/tonne of melt given 100 penalty (Fig. 5b). The values in between were scaled linearly. The novelty in the approach as compared to the traditional statistical techniques is that the response penalty values are transferred onto the factor scatter diagram as shown in Figure 6 a which turns it into a bubble diagram as in Figure 6b for a factor heel metal at start. Figure 7b converts the same information in a penalty matrix format with each cell indicating number of observations per quartile of the factor range [Q1= Bottom 25% range, Q1+Q2 = Bottom 50% range, Q4 = Top 25% range, Q3+Q4 = Top 50% range and Q2+Q3 = Middle 50% range of factor heel metal at start] with corresponding response penalty values. An interaction bubble diagram between two process inputs: heel metal at start and melt poured in a given time period is shown in Figure 8a along with its corresponding interactions penalty matrix (Fig. 8b) showing optimal region when both factor ranges are occurring together (F1:F2), as opposed to one factor range at a time (F1:~F2 and ~F1:F2) or both factor ranges not occurring together (~F1:~F2). Figures 7 and 8 are plotted using commercial penalty matrix data visualizer software[7]. The software has ability to generate penalty matrices and rank them in an order of importance[18-20].

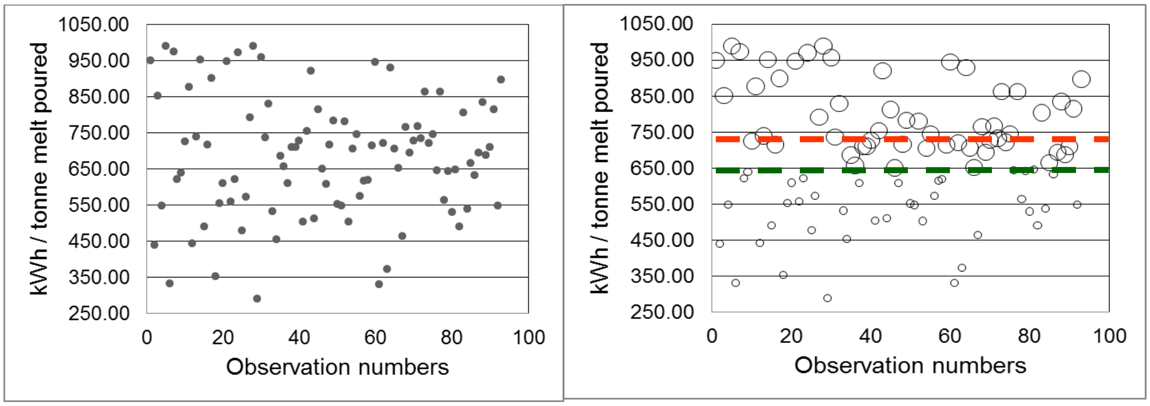


Fig. 5 a (left): Scatter diagram of specific energy consumption of data shown in Figure 4. Fig. 5 b(right): Conversion of the scatter diagram with a corresponding bubble diagram defining acceptable (zero penalty values) and unacceptable (100 penalty values) process responses.

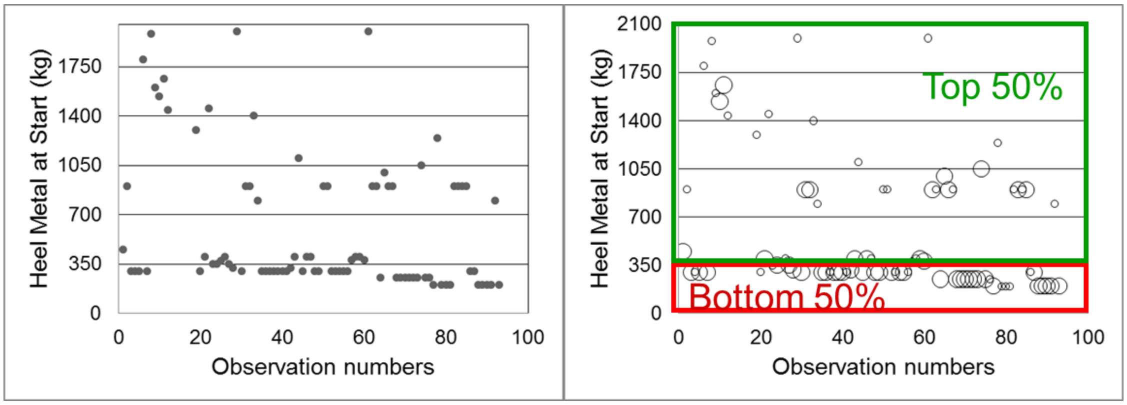
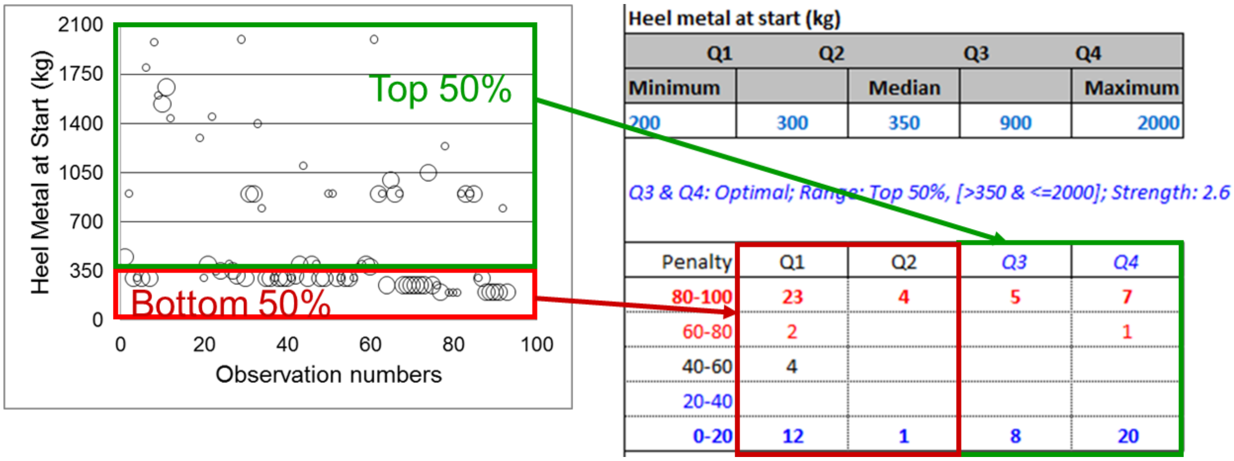


Fig. 6 a (left): Scatter diagram of process input heel metal at start. Fig. 6 b (right): Conversion of the scatter diagram with a corresponding bubble diagram defining acceptable (zero penalty values) and unacceptable (100 penalty values) process responses.



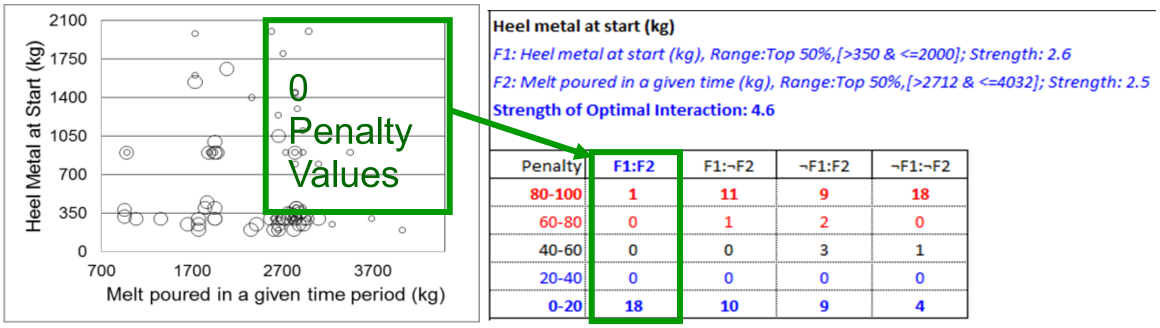
Heel metal at start (kg)

Q1		Q2		Q3		Q4
Minimum		**Median**		**Maximum**
200	300	350	900	2000

Q3 & Q4: Optimal; Range: Top 50%, [>350 & <=2000]; Strength: 2.6

Penalty	Q1	Q2	Q3	Q4
80-100	23	4	5	7
60-80	2			1
40-60	4			
20-40				
0-20	12	1	8	20

Fig. 7 a (left): Bubble diagram of process input heel metal at start. Fig. 7 b (right): Representation of the bubble diagram with a corresponding main effects penalty matrix for the process input heel metal at start.



Heel metal at start (kg)

F1: Heel metal at start (kg), Range:Top 50%,[>350 & <=2000]; Strength: 2.6

F2: Melt poured in a given time (kg), Range:Top 50%,[>2712 & <=4032]; Strength: 2.5

Strength of Optimal Interaction: 4.6

Penalty	F1:F2	F1:¬F2	¬F1:F2	¬F1:¬F2
80-100	1	11	9	18
60-80	0	1	2	0
40-60	0	0	3	1
20-40	0	0	0	0
0-20	18	10	9	4

Fig. 8 a (left): An interactions bubble diagram for process inputs heel metal at start and melt poured in a given time period. Fig. 6 b (right): Representation of the interactions bubble diagram with a corresponding interactions penalty matrix.

STEP 4: DEVELOP HYPOTHESES (POTENTIAL SOLUTIONS)

The correlations identified in Step 3 are hypotheses or potential solutions for process improvements. These hypotheses are evaluated with the process knowledge identified in Step 2. E.g. avoiding lower quartile of heel metal at start and achieving high values of melt poured were considered for further investigation as they highlight opportunities for further process improvement. High heel metal at start may result in better electromagnetic coupling between the melt and the coil and can help to increase production rates or lower energy consumption. The 7Epsilon approach helps to create foundry specific optimal tolerance limit for each process input.

STEP 5: INNOVATE USING ROOTCAUSE ANALYSIS AND CONDUCTING CONFIRMATION TRIALS

In this step the tolerance limits for the chosen process parameters are slightly adjusted to test the potential improvement in process. This step is different to the design of experiment stage where the limits used would normally be much wider than considered in 7Epsilon projects. However, steps 3-5 can be engaged in an iterative way in conjunction with design of experiments if necessary. In this example, the operating limit of heel metal at start was modified and the melt poured in the given time period was increased by minimizing holding time with an optimized production schedule.

STEP 6: CORRECTIVE ACTIONS AND UPDATE PROCESS KNOWLEDGE

The trial showed an average saving of 60kWh/tonne of melt per month. The automatic and optimised feeding of charge ensured optimised level of heel of metal at start. The variation in the specific energy consumption shown in Figure 5a was minimised (Fig. 9). With average 2500 tonnes of liquid metal production per month the savings are approximately US$ 12,000 every month.

STEP 7: BUILD ASPIRING TEAMS AND ENVIRONMENTS BY MONITORING PERFORMANCE

The 7Epsilon process helped the top management to develop an active and enthusiastic team that discovered solutions in a bottom up approach and developed a convincing report seeking further modifications and investments. After exploiting the benefits of making changes that require no investments, the management was able to take the team systematically to the next stage of implementing solutions requiring small and large investments.

FURTHER RECOMMENDATIONS

The team developed a further list of action plan and made following recommendations:

1. Metal should not wait for moulds (unless the management invests in a holding furnace)
2. Achieve perfection in charge mix and alloying elements to minimise correction time.
3. Always fill the crucible and keep the power at maximum.
4. Remove slag regularly however minimize the radiation loss that may result from exposing the melt to the atmosphere.
5. Use preheated ladle.
6. Use covers for ladles to avoid radiation losses.
7. Ensure that the pouring is done in least time.
8. Keep maximum possible bunch weight in mould box.
9. Maintain the temperature of circulating soft water for furnace coils as prescribed by furnace manufacturer.
10. Keep the lining thickness as recommended by the manufacturer.
11. Constantly look for opportunities to minimize the pouring time and pouring temperature. Ensure that the acceptable quality level is NEVER compromised.

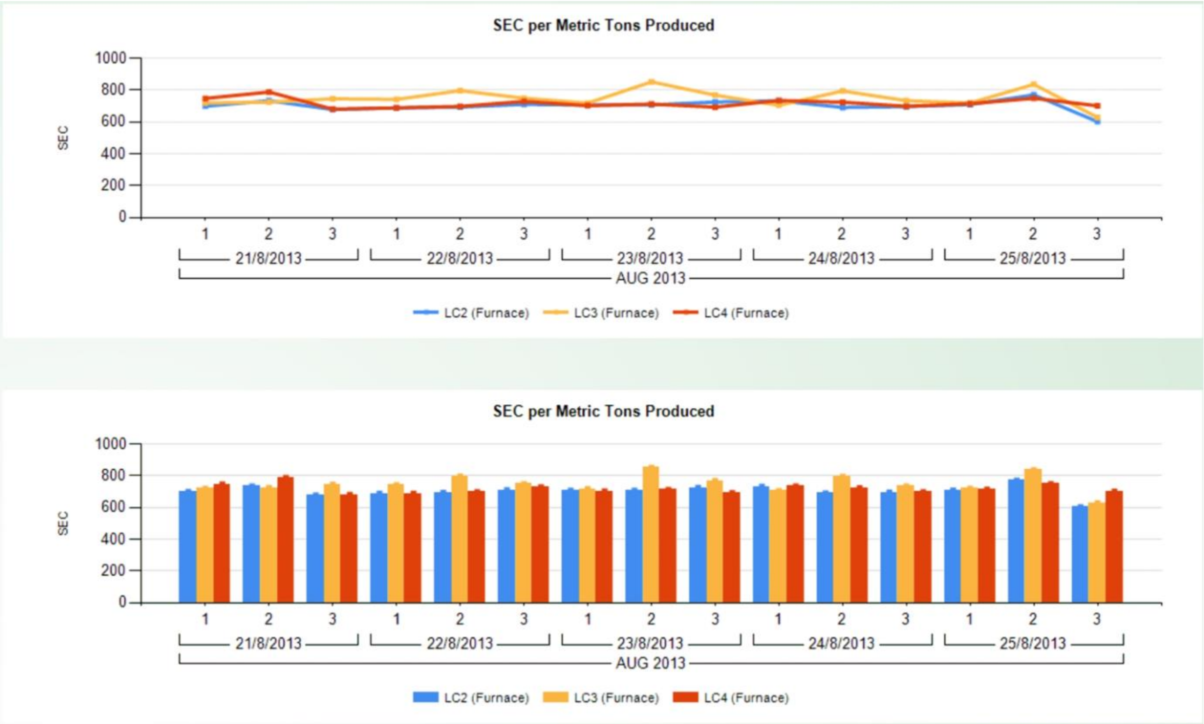


Fig. 9. The specific energy consumption for furnace 3 was lowered as seen in the data monitored for the subsequent three days. The energy savings were sustained resulting into financial savings for the foundry.

In addition to the guidelines and best practise advice as referred early in the paper, the following best practise examples were identified for achieving sustainable results.

1. Check harmonics levels at furnaces and compensate with installation of active monitoring and conditioning component such as filters, capacitors etc. This helps to avoid breakdowns and maintenance hassles of the furnace installations, and also accelerates the melting process.
2. Check for total electric installation of the plant for safety and current leakages etc and plan for corrective steps.
3. Buy cheaper power through power trading companies

4. Evaluate feasibility of grid scale energy storage batteries now available in kW, MW scale[21] to optimise time of use tariff and peak demand reduction.
5. Check for feasibility for integration of renewable energy.

It was also decided to explore the following additional Energy Saving Opportunities (ESO's):

1. The regular maintenance of sand plant including intensive sand mixers.
2. Check for sand parameters and set the timing for mixing cycle.
3. Check for compressor efficiencies and air leakages.
4. The maintenance, housekeeping and material flow are important in fettling shop. The pollution control equipment has to be in place at shot blasting and other activities of fettling shop.
5. Check for core paints application and efficiency of core ovens.
6. Furnace mapping/ calibration is essential for all the furnaces including heat treatment furnace on regular basis.

CONCLUSIONS

Most foundries have ISO9001:2008 or equivalent quality standard and record variety of in-process data. It is well known in the foundry world that each foundry has developed its own optimal range of tolerance limits for its process variables and is often a closely guarded trade secret. Most precision foundries record lot of data. However, it is surprising that case studies relating real time energy consumption data with associated in-process data to continually enhance the energy efficiency of foundry by adjusting the tolerance limits of process variables have not yet been discussed or reported in the literature. The most commonly used studies are based on traditional design of experiments. These techniques have limited value in making small adjustments to several process variables at once.

The 7Epsilon approach refines Six Sigma's DMAIC steps with a focus on reusing foundry and product specific process knowledge for in-process quality improvement. The innovative penalty matrix based approach has been used to visualize energy consumption data on a furnace collected over a period of three days with corresponding in-process data on 25 process variables. The paper described 7 steps of 7Epsilon to ERADICATE defects with reference to an energy efficiency improvement case study. It is shown how a foundry has been able to make small adjustments to the tolerance limits of multiple process variables and make a saving of 60kWh/liquid metal tonne resulting in an annual saving of US$ 144,000 in operating costs of furnaces.

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