Optimizing Steel Melt Shop Operations using an Iterative Hierarchical Decomposition based Discrete Event Simulation Model

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Abstract: Maximizing productivity in a steel melt shop requires appropriate equipment and facility design and the synchronization of production across units like iron making, steel making, holding furnaces and casting of the molten metal. This requires that blockages and bottlenecks in the production chain be identified and overcome and the logistics in terms of equipment and facilities to move the materials appropriately designed. Removal of blockages and bottlenecks requires a combination of process redesign and investments in facilities and equipment in the production units supported by potential logistics redesign in terms routing and scheduling of equipments like cranes, ladle cars hot metal ladles and steel ladles used in the production shop . This approach addresses the system-wide bottleneck removal problem such that congestions, interferences, delays, stoppages and idle times coupled with process and cycle time variations; do not limit the end-to-end production. This paper presents how we improved the productivity in a melt-shop by using an iterative hierarchical decomposition based modelling and simulation approach to help identify the bottlenecks causing capacity loss, and experiment with options to redesign the system by suggesting mechanisms for improvement and additional facilities and logistical resources. The implementation of the system has resulted in a 28% increase in melt-shop throughput and increase and significant increase in profitability by decreasing hot metal diversions to alternative casting facilities.

1 INTRODUCTION

Steel is produced from iron and ferrous ores and scrap through two major processes – Iron-making and Steelmaking. Figure 1 shows the overview of the process of producing steel in an integrated steel plant.

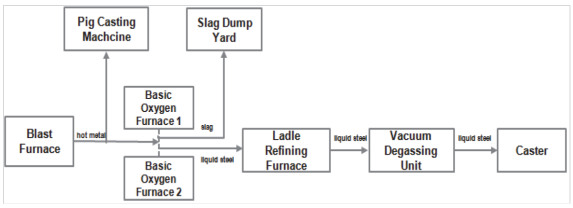

Figure 1: The steel production process overview.

The first phase in steel production is iron-making where oxygen and impurities are removed from iron ore using other raw materials through a process in a counter-current heat exchanger known as the blast furnace. A Blast Furnace (BF) produces molten iron/pig iron, termed as Hot-metal. In an iron-making unit of a steel plant, the hot-metal from the blast furnace is tapped in the cast house either in open top ladles or in torpedo ladles. These ladles are then moved to the Steel-making unit, also called Steel Melting Shop (SMS) by locomotives to be fed to the Basic Oxygen Furnace (BOF). The BOF converts liquid iron from BF and scrap steel into liquid steel which is then refined in ladles and finally cast at the casters. In case the BOF is not ready to accept hot metal due to production bottlenecks or capacity mismatches it is sent to Pig Casting Machine (PCM) to be cast into saleable iron ingots.

The goal of a steel plant is to synchronize operations across the iron and steel making units such that throughput is maximized. This translates into specific unit optimization goals along with synchronization and coordination requirements cross the units. From a unit optimization perspective, it is essential that the BOF does not have any wait time other than the preparation time. This means that the optimal number of ladles, the optimal number of cranes and the optimal movement algorithm of cranes needs to be determined such that the hot

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metal feed to the BOF is synchronous and without wait. Also, timely arrival of hot metal from the iron-making-unit needs to be ensured.

In the steel-melting-shop unit, the liquid steel from the BOF is taken to the Caster where the liquid steel is molded via secondary refining units comprising of Ladle Refining Furnace (LRF) and/or Vacuum Degassing (VD) units. The BOF should be synchronized with the Casters such that the heat sequences for different grades are maintained while maximizing the utilization of the equipment to ensure the highest throughput from hot-metal charging to casting. It is always preferred to have uninterrupted sequence during continuous casting to achieve higher production and yield.

Our study was based on an integrated steel plant having two BOFs, with one working and one standby mode, one LRF, one Vacuum Degassing unit and one three-strand Caster (operated with two strands). The existing operations needed to be studied and analyzed in detail and additional facilities/ improvements in the system needed to be proposed to utilize the Caster, LRF and BOF fully and thereby increasing the overall throughput of the system. It was also needed to suggest the number of hot metal ladles and steel ladles in active circulation required for the suggested production.

2 THE PROCESS AND OPERATIONS

Hot metal in the Blast Furnace (BF) is cast as per BF cast schedule into open top ladles placed in transfer cars on railway tracks. The ladle transfer car is carried to SMS or PIG Casting Machine (PCM) by captive locomotive depending on the readiness of the converter to accept the hot metal.

At SMS the full ladle is picked up from the transfer car by an overhead crane and carried to the sampling point. In case an empty ladle is ready for return to BF, the full ladle is picked and kept on the pit, the empty ladle placed on the transfer car and then the full ladle is picked up again by the overhead crane. Once the sampling is complete, the ladle is carried to the BOF. In the mean time scrap is charged to the BOF by scrap charging crane. On completion, the hot metal is charged to the BOF and blowing starts. Near the end of the blowing cycle, temperature is measured and samples are taken for analysis. After pouring of the hot metal to the BOF, the ladle is carried to the pit by overhead crane for sending back to the BF.

Steel ladle on steel transfer car gets under the BOF vessel and steel is tapped into the ladle through the tap hole. Once tapping is complete, slag pot car gets under the BOF vessel and slag is poured into the slag pot through the BOF vessel mouth.

After processing of 8 heats in the BOF, maintenance operations, also known as dozing and mouth jam cleaning are carried out. After 15 heats of BOF operation the maintenance operation of tap hole changing is performed. And after 75 heats, other maintenance works on the vessel are carried out. The numbers are varied depending on the status and completion of the casting sequence.

After tapping of steel into the steel ladle, it is transported to the ladle refining aisle by the ladle transfer car, picked up by overhead crane and placed on the LRF transfer car. The purging lines are fixed and the transfer car goes into the LRF. The steel is further refined in the LRF by adding alloying materials to give it special properties as required. Once the LRF processing is complete, the ladle transfer car brings out the ladle and the purging lines are removed. The ladle is also moved to the VD unit by overhead crane, and further treatment done.

The ladle is transported to the caster turret from the LRF or VD by overhead cranes. The ladle sits in a rotating turret at the casting machine. One ladle is in the 'on-cast' position (feeding the casting machine) while the other is made ready in the 'off-cast' position, and is switched to the casting position when the previous ladle is empty. Once casting of one ladle is over, and the turret rotates, the empty ladle is transported from the turret to the slag dumping area and slag is dumped. After slag dumping, the ladles are sent to the ladle preparation area and placed back on the transfer car for the next tapping from the BOF.

3 OVERALL THROUGHPUT IMPROVEMENT

The process of steelmaking and casting, from BOF to Caster, may be categorized into three distinct stages, viz. primary steelmaking, secondary steelmaking and casting. Primary steelmaking is concerned with the production of liquid steel, which is subsequently refined in terms of both its composition and its cleanliness through a host of secondary steelmaking processes. Molten steel with desired composition, cleanliness and temperature is finally transformed into solid products through continuous casting. Figure 2 shows the categories of the steelmaking process.

Figure 2: The steelmaking process categories.

The overall throughput of the steel making process depends on the functioning of each of these units at efficiency levels which maximizes the total output. The functioning of these units at their required efficiency levels which maximizes output, depends on:

- Design or rated capacity of the unit
- Operating efficiency
- Overall shop logistics

The units can be operated at their design or rated capacity by improving operating efficiency of unit or shop logistics. Related work in the area of logistics optimization (McGinty et al., 2008) and hidden capacity discovery (Mukherjee et al., 2012) has been carried out to address specific improvement goals around this area. Our approach is an integrated holistic approach to plant operations improvement through simulation so as to include unit operations, logistics, cycle times and their interactions.

4 APPROACH OF ITERATIVE AND HIERARCHICAL DECOMPOSITION

A large number of problems in production operations can be initially analyzed using simple relationships that do not require assumptions about the distribution of service times and inter-arrival times in a queuing network. Several such relationships, called *operational laws* (Buzen, 1976) (Jenning and Buzen, 1978) are useful in looking at the starting point for the analysis. For example, the melt-shop operations is a form of the queuing network where the job flow balance is maintained and obeys the *forced flow* law. Each unit operation (BOF, LRF, Casting etc.) in such a system has a service time and the unit utilizations are proportional to their service times. The unit with the highest total service time has the highest utilization and is called the bottleneck unit. This unit is the key limiting factor in achieving higher throughput to start with. Identification of the bottleneck unit was the first step in operations performance improvement of the system. Using baseline simulation we can estimate the highest service demand in the operation chain. So the approach was to see the opportunity for cycle time /service time reduction and hence capacity improvement in the BOF, Caster, LRF or VD.

Once we could reduce the cycle time to the minimum level possible at the bottleneck unit, we again simulated the model and stack-ranked the service times in the production chain and looked at how the bottlenecks shift across the production units. Frequently, the bottlenecks shift in the production chain during iterations of improvement. If there is an opportunity for improvement in the other unit cycle times/service times as the bottlenecks shift we continue iterating till there is no further opportunities for practical cycle time improvement across the production chain.

Once we exhausted the opportunities for cycle time improvement we argued that given the difference in variability in the service times in each of the units and their distributions, there might be further scope for improvement. This led us to observe the behavior of capacity utilizations across the downstream units which could potentially create a bottleneck so as to give us further insights. We hypothesized that if indeed the capacity utilizations of some of the units changed and tended to move in a way which would affect the performance of that unit, there could be opportunity for further improvement in system performance by adding capacity. Addition of that unit capacity needs to be guided by the economics and the cost benefit of such an option. Typically as a thumb rule, buffering units like the holding furnace (LRF) are good candidates for capacity addition to improve performance. We would similarly iterate and exhaust all capacity addition options till there are no further opportunities for overall improvement in the system.

This progressive hierarchical decomposition of the chain and iterating based on the two heuristics drives the simulation towards an optimal solution. We think that this method can be applied to large scale manufacturing scenarios with many units and can be a useful method for analyzing and potentially optimizing large scale systems through simulation.

5 BASELINE SIMULATION MODELING AND ANALYSIS

A baseline simulation model was built using the Promodel software to simulate the operations of SMS with the existing service times of the units. The service time for each unit operation (also referred as cycle time) included processing time, downtimes due to maintenance, preparation times and transfer times. Logistics movements including rail movement of the transfer cars and the crane movements was modeled in the software using its feature of network path and entity driven simulation.

The approach followed in the model building was LEAP (Locations, Entities, Arrival, and Processing). The first task in building the model was to identify the locations which included source locations, destination locations and intermediate locations where the entities will arrive at and exit from during the movement in the system. It was also necessary to identify the entities which will originate at the BF and BOF and exit from Caster; and the entities like hot metal ladles and steel ladles which will keep on moving in the system to facilitate movement of other entities. Also, resources like transfer cars, cranes, locomotives were created which will move the entities from one location to the other. Once the entities were identified and created, the arrival of the entities had to be modeled as per the arrival schedule. That included hot metal at BF; Scrap at scrap yard for charging to BOF; and Steel and Slag at the BOF for tapping. The next task was to create the appropriate network path for transfer car movements and crane movements. The final step was to create the processing logics for the entities at a particular location and thereafter creating the routing logics for moving to the next location using the required resources. Figure 3 shows a screenshot of the simulation model.

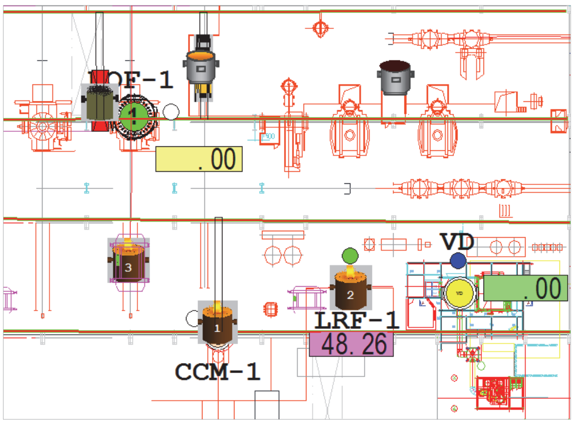

Figure 3: The model screenshot.

To model the behaviour of various operation parameters, one year operation data was collected for the BOF, LRF, VD and Caster and were fitted into various distributions and best fit distribution was selected with the help of goodness of fit tests. The model was run with the existing operation parameters taking into consideration the stochastic behaviour of the parameters involved in various processes like blowing time at the BOF, tapping time, LRF process time, VD treatment time, crane availability etc. The transient response of the model stabilized after 30 days of simulation time. The results yielded are as shown in the Table 1.

Table 1: Results of simulation runs for 10 days with existing parameters after attaining stabilization.

	Results
Total heats	217
Average BOF tap-to-tap time	65 mins
LRF utilization	79.83 %
Caster utilization (using 2 strands)	52.60 %
VD utilization	47.60 %
Caster heat sequence	Maintained

Also the behavior of the BOF tap-to-tap time turned out to be as shown in Figure 4.

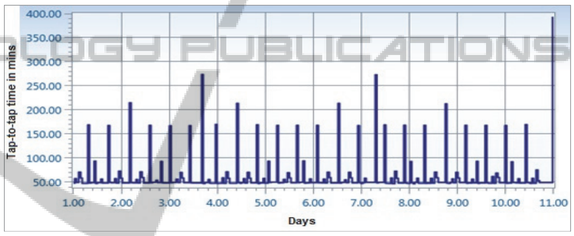

Figure 4: BOF tap-to-tap time with the existing maintenance downtimes.

6 THE BOF PROCESSING AND UTILIZATION ANALYSIS

The BOF converter unit being the generation point in the steelmaking process, it was envisaged that improving the cycle time by reducing downtimes at the BOF will increase its throughput and hence the overall throughput. Table 2 shows the various basic activities involved in the BOF operations.

Table 2: Basic time components in BOF process.

Activities	Time in minutes
Scrap charging	1 to 2
Hot metal pouring	4
Blowing	16 to 18
Deslagging	2 to 3
Temperature & Analysis	5
Tapping	4 to 6
Slagging off	2
Slag coating	5
Total	45 (max)

In addition to the above, currently there also exists recurring events of dozing, mouth jam cleaning, tap hole changing and other maintenance operations as shown in Table 3 which contributes to the BOF tap-to-tap time thereby reducing the BOF throughput.

Table 3: Current BOF maintenance downtimes.

Event	Time in minutes
Mouth jam cleaning and dozing after every 8 heats	90
Tap hole changing after 15 heats	45
Other maintenance after 75 heats	180

With these BOF processing times the overall steelmaking process behavior needed to be studied and analyzed. Simulation has been used for studying and analyzing systems operations previously and the methodology applied has been 'highly efficient' when applied in complex logistic systems. Considering the complexity of operations, criticality of sequencing activities and the interdependencies of the logistics parameters, it was decided to develop a discrete event simulation model of the system and evaluate the improvement options.

7 IMPROVEMENT STRATEGY AT THE BOF

The baseline simulation results showed that the number of heats from the BOF is constrained by the higher tap-to-tap time caused by recurring maintenance delays. It was evident that if these delays can be reduced, the number of heats from the BOF can be increased. Based on the technology available it was envisaged that these delays could be reduced using tap hole sleeves in the BOF vessel which will allow a minimum corrosion and erosion during the operation of the BOF and improving operating efficiency. With the above measures the maintenance downtimes was envisaged to be brought down as shown in Table 4.

Table 4: Proposed BOF maintenance downtimes.

Event	Time in minutes
Mouth jam cleaning and dozing after every 15 heats	90
Tap hole cleaning and other maintenance after 75 heats	180

However the envisaged maintenance downtimes would affect the entire sequencing of activities from the BOF to the Caster and needed to be evaluated and validated using the model built. The model was run again with the changed maintenance delays and results were obtained as shown in Table 5.

Table 5: Results of simulation runs of 10 days with proposed parameters after attaining stabilization.

	Results
Total heats	237
Average tap-to-tap time	59 mins
LRF utilization	92.27 %
Caster utilization (using 2 strands)	60.29 %
VD utilization	54.88 %
Caster heat sequence	Maintained

The behavior of the BOF tap-to-tap time with proposed maintenance operations was found to be as shown in Figure 5.

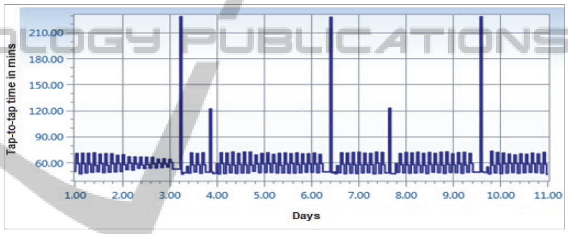

Figure 5: Tap-to-tap time with proposed operations.

It is clear that with the frequency of downtimes reduced in the proposed mode of operation, the surges in the tap-to-tap time are lesser resulting in a lower average tap-to-tap time and hence higher number of heats would be possible from the BOF. According to the results, the average BOF tap-to-tap time could be reduced from 65 mins to 59 mins as shown in Figure 6, considering the reduced downtimes at the BOF and the constraints in the upstream and downstream facilities, with 45 mins of minimum tap-to-tap time required in the BOF, thereby increasing the overall throughput of the system. Individually, the BOF had the potential to reduce its tap-to-tap time further.

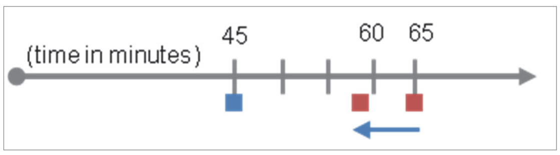

Figure 6: Reduced BOF tap-to-tap time.

However the additional component in the tap-to-tap time over and above the basic BOF processing time is not only due to BOF maintenance downtimes, but also is probably due to contributions from downstream blockages like the LRF. The utilization of the LRF being on the higher side points to a probable blockage in the LRF (as per the result). So if the downstream blockages can be removed it was envisaged that the average BOF tap-to-tap time can be further reduced to increase the throughput while maintaining the synchronization between the BOF and the caster.

Our next goal was to find out as to how much of further reduction in tap-to-tap time is possible by removing the downstream bottlenecks. So the next step was to find a strategy to remove the downstream blockage through additional buffering thereby reducing the converter tap-to-tap time and improving the overall throughput.

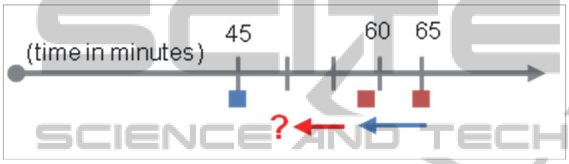

Figure 7: Further reducing the BOF tap-to-tap time.

It was further reasoned, that with higher LRF utilization it would not be feasible to accommodate more heats from the BOF and transport to the caster at a higher rate. Hence the bottleneck was in all likelihood the existing capacity of the LRF. It was suggested that an additional LRF could be a probable solution to make use of the additional BOF capacity as well as the additional caster capacity with three strands in operation. The modified operations of the iron making and steel making unit of the plant can be outlined by the schematic as shown in Figure 8:

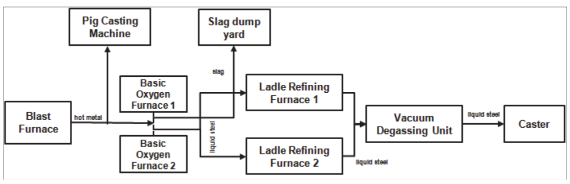

Figure 8: The steelmaking process with additional LRF.

8 SIMULATING WITH ADDITIONAL LRF CAPACITY

Engineering of the additional LRF led to modified layout with provision of transfer cars and crane accessibility to the additional LRF. The sequencing of heats with the additional LRF and operations using three strands of the caster needed to be validated to ensure proper synchronization of the BOF with the Caster such that the heat sequences for different grades are maintained while maximizing the utilization of the Casters. It was also required to find the maximum possible heats keeping in mind when a heat sequence has started in a Caster, it should complete the cast sequence without interruption due to the unavailability of heat.

The model was run with the additional LRF and appropriate sequencing of heats at the LRFs. The results found were as shown in Table 6.

Table 6: Results of simulation run with additional LRF for 10 days after attaining stabilization.

	Proposed Operation
Total heats	278
Average tap-to-tap time	51 mins
LRF-1 utilization	45.86 %
LRF-2 utilization	45.78 %
Caster utilization	71.60 %
VD utilization	64.63 %
Caster heat sequence	Maintained

The simulation results showed that with additional LRF and the envisaged BOF maintenance downtimes, the average BOF tap-to-tap time could be brought down to 51 minutes and the caster could be operated with three strands; as a result the number of heats will increase substantially. The simulation results also suggested that there needs to be 4 hot metal ladles in active circulation and 4 steel ladles in active circulation to support the logistics and achieve the desired production.

9 COST BENEFIT ANALYSIS

A cost-benefit analysis was performed to analyze the return on investment. Improving the overall throughput increased the production of saleable steel in terms of billets which otherwise was being diverted to the pig casting machine for casting iron ingots. The price of billets is generally higher than price of iron ingots on a per ton basis. The marginal cost of producing steel through caster or the pig casting machine is minimal and is assumed to be zero. The marginal cost of processing of steel in the LRF was non-trivial. Additional operational costs for BOF tap-hole sleeves were also non-trivial. It was assumed that all the billets or pig cast ingots that were produced were sold in the market at average market prices. Investments in additional buffer and processing capacity were in the form of a 35 ton LRF.

Table 7 shows the CAPEX, OPEX, revenue and payback period based on the proposed modifications in terms of capacity expansion and operating practices.

Table 7: Cost benefit analysis.

Unit Costs & Operational Parameters	
Tap hole sleeves 200 mm, 10 sleeve pack	$3000
Sleeve change interval	75 heats
Electrode consumption in LRF	12 gm/KWH
Electricity consumption in LRF	0.5 KwH/Degree Celcius/ton
Average heating in LRF	5 Degree Celcius
Cost of Electricity	10 C/ KWH
Investments	
1X35 Ton LRF	8 MM$
Product Price	
Average Billet Price	$480 /ton
Average Pig Iron Price	$ 400/ton
Marginal Revenue △R	5.3 MM$/year
Marginal Cost △C (Sleeve Cost + △Electrode Consumption + △ Power Consumption)	~$400,000
Additional profit , △P	4.9 MM$
Payback Period for Investment	**1 Year and 7 Months**

10 CONCLUSIONS

The paper presents an approach for increasing the overall throughput of a steel melt shop in an integrated steel plant constrained by unit operations' service times and capacity of facilities with the help of simulation. Global optimization of the steelmaking process has many interdependent variables which are also probabilistic in nature making the analysis intractable through traditional analytical methods. Discrete event simulation with a hierarchical iterative approach allowed us to progressively analyze and re-design cycle time, logistics and capacity improvement across the operating units in the steel melt shop for better throughput. The result showed that only reducing downtimes at the BOF was not effective in increasing the shop production and an additional LRF was also necessary to obtain the benefits. The recommendations resulted in effective utilization of all the units so that the overall throughput was maximized. Based on our recommendations the number of heats processed increased from an average of 21 per day to an average of 27 per day resulting in an increase of 28%. The increased overall steel production and reduced converter wait times decreased the diversion of hot metal to the pig casting machine improving the profitability of the melt shop. The proposed system design and recommendations is currently being implemented.

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