Ladle circuit optimization through simulations for reduced refractory wear, energy consumption and carbon emissions

Saikat Chatterjee, Anand Senguttuvan, Amiya Biswal, Arnab Adak, Tanmoy Mandal, Raghav Mittal, Pramod Kumar Ishwar, Kaushal Kumar Sinha, Atanu Mukherjee

S. Chatterjee, A. Senguttuvan, Dastur Innovation Labs, Canada and M. N. Dastur & Co. (P) Ltd., Canada;
A. Biswal, A. Adak, T. Mandal, R. Mittal, P. K. Ishwar, K. K. Sinha, A. Mukherjee, M. N. Dastur & Co. (P) Ltd., India

Contact data

Saikat Chatterjee, Dastur Innovation Labs, 250 Yonge Street, Suite 2201, Toronto, ON M5B 2L7, Canada,
Phone: +(1) - 647-6-DASTUR, +(1) - 647-632-7887
Email: Chatterjee.Saikat@dastur.com

Summary

The continuity in ladle circulation across various steelmaking unit operations is critical for the attainment of operational efficiency of a plant. Every steel plant, with a certain capacity, process flow, operations philosophy and product mix, has a certain velocity of flow across the steel circuit. Disruption in the flow velocity due to external and internal events leads to suboptimal operations in terms of throughput, quality, costs, energy and emissions. Any delay event, such as purging failure, ladle puncture, extended nozzle/porous plug cleaning amongst others, can cause major roadblocks to smooth steelmaking operations. These events disrupt ladle circulation leading to increase in steel residence time, steel/slag/refractory interaction, refractory and energy consumption, temperature drop, carbon emission as well as decrease in productivity and yield, which makes it important to identify and minimize 'delays'. A simulation-based framework, consisting of an extensive process and operations database along with embedded heat transfer and logistics models, has been developed to evaluate impact of delays and to predict production, ladle holding times, ladle turnaround time, percentage utilization of resources, temperature drops, energy and refractory consumption, carbon emission and associated cost impact. The results allow formulation of operating recommendations that help achieve the target levels of refractory consumption, energy consumption and carbon emission that are possible for a certain plant configuration while maintaining the flow through the steel circuit at its optimum level.

Key Words

Ladle circuit, steelmaking, continuous casting, productivity, consumables, carbon emission, process simulation, temperature control, logistics, heat transfer

Introduction

The extent of operational efficiency achieved by a steel melting shop (SMS) directly depends on how well its resources are utilized. The main levers determining operational efficiency include:

- number of ladles in circulation (also known as ladle fleet size)
- productivity and yield
- consumable life
- energy consumption
- CO_2 emission

In the steel making process, ladle is one of the most important resources as it acts as a connecting link between various unit operations. It traverses from:
(1) the preparation area to
(2) primary steelmaking (BOF/EAF) to
(3), (4) secondary steelmaking (LRF/VD/RH) to
(5) caster
and then keeps on repeating the cycle until it is taken out for relining/maintenance. The process is schematically depicted in Figure 1. Synchronization of operations across the various unit operations is necessary to maximize the productivity or throughput. For instance, when a heat sequence is started in a caster, it should be completed without any interruption due to unavailability of liquid steel from primary/secondary steelmaking units.

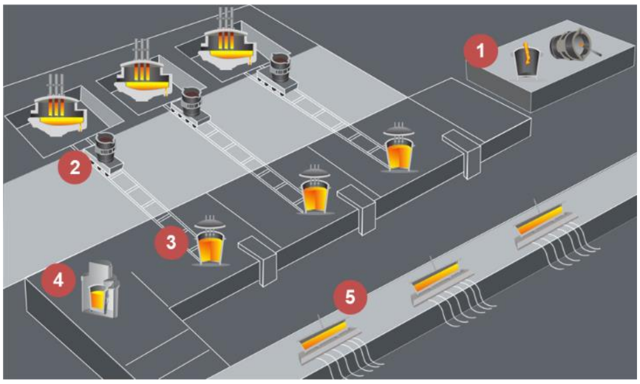


Figure 1: Ladle circuit in a steel melt shop
Note: 1. Preparation area, 2. BOF/EAF, 3. LRF, 4. VD/RH, 5. Caster

A delay, during or between any of the unit operations depicted in Figure 1, breaks the ladle circuit and results in decrease of productivity and yield on one hand and increase of energy and consumable consumption along with carbon emission on the other hand. Ladle Circuit Optimization (LCO) is a complex problem and it impacts on the levers stated earlier *viz.*, ladle fleet size, productivity/yield, consumable life, energy consumption and carbon emission.

In the past, DASTUR has successfully carried out multiple ladle circuit and steel melt shop optimization projects [1]. Using our prior experiences, a comprehensive simulation-based framework named *LADSIM^{TM}* (Ladle Simulator) has been developed which can consider the effect of various process/operational changes on the levers stated above with the objective of optimizing the ladle circuit. This platform creates an easy to understand way for:

a) *steelmakers* to:
   - perform various scenario analyses for optimization of resources, energy and consumables to achieve cost savings
   - quantify the impact of suboptimal operations and select the right combination of consumables and standard operating procedures (SOPs) that will mimimize their operating expenditures
b) *refractory suppliers* to
   - portray advantages of their advanced products to their clients
   - find out root cause of suboptimal operations and resolve penalty charges
c) *steel plant management* to have better informed decisions on investments for higher returns.

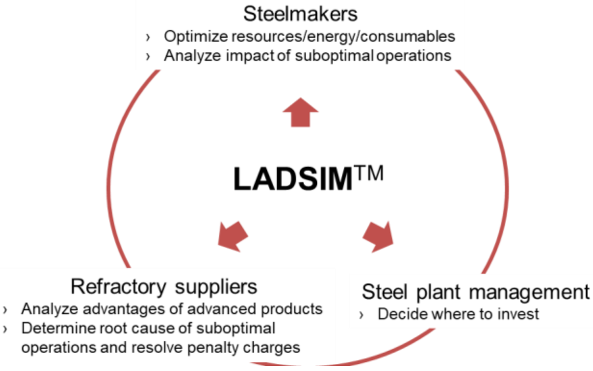


Figure 2: Potential users of *LADSIM^{TM}*

Steel plant operational issues leading to suboptimal outputs

Every steel plant, with a certain configuration (capacity, layout, process units, consumable types), operations philosophy and product mix, has a certain steel flow characteristic resulting in a specific throughput, yield, carbon emisssion, energy and consumable consumption along with ladle fleet size. Any disruption in the flow due to external/internal events is termed as a 'delay event'. An indicative list of various 'delay events' is provided in Figure 3. These delay events lead to suboptimal operations primarily due to increased and variable residence times of steel (and slag) in ladle. Higher and variable residence times cause:

a) Lower throughput and loss in productivity
b) Higher steel/slag/refractory interaction leading to higher refractory wear
c) Higher temperature drops and energy loss
d) Higher carbon emission
e) Inappropriate ladle fleet size
f) Higher operating costs

These suboptimal outputs, as depicted in Figure 4, makes the plant operations highly inefficient and thus, it becomes important to identify the impact of 'delays' and thereby aid in prioritizing corrective actions. Smooth non-blocked flow of steel (without delays) across the ladle circuit is ideal for maximizing the productivity of steel operations. Hence, the closer the operations are to the ideal one, better the productivity and cost optimization will be. Based on the SMS configuration, operations philosophy and product mix of a specific plant, *LADSIM^{TM}* can determine its ideal/optimum circuit and flow, target levels of refractory consumption, energy consumption and carbon emission.

LADSIM^{TM}: A simulation and process modeling framework for Ladle Circuit Optimization (LCO)

As depicted schematically in Figure 5, *LADSIM^{TM}* consists of three components:

I. Process Time Simulator (PTS)
II. Delay Event Tracker (DET)
III. Energy and Refractory Life simulator (ERLS)

The functionalities of these components will be discussed in the next section. The inputs and outputs of individual components are shown in Figure 5. The embedded heat transfer and logistics models along with DASTUR's embedded proprietary process and operations database, can be used to:

a) build and validate baselining operations
b) perform *operational sensitivity analyses*

a) <u>*Build and validate baselining operations*</u>: The first and foremost objective is determining and validating the baseline of the plant operations accurately. A plant with a specific configuration (layout, production capacity, grades produced, ladle fleet size and refractory products), can attain specific KPIs such as productivity, CO_2 emission, ladle circulation time, refractory and energy costs based on the operating practices being followed.

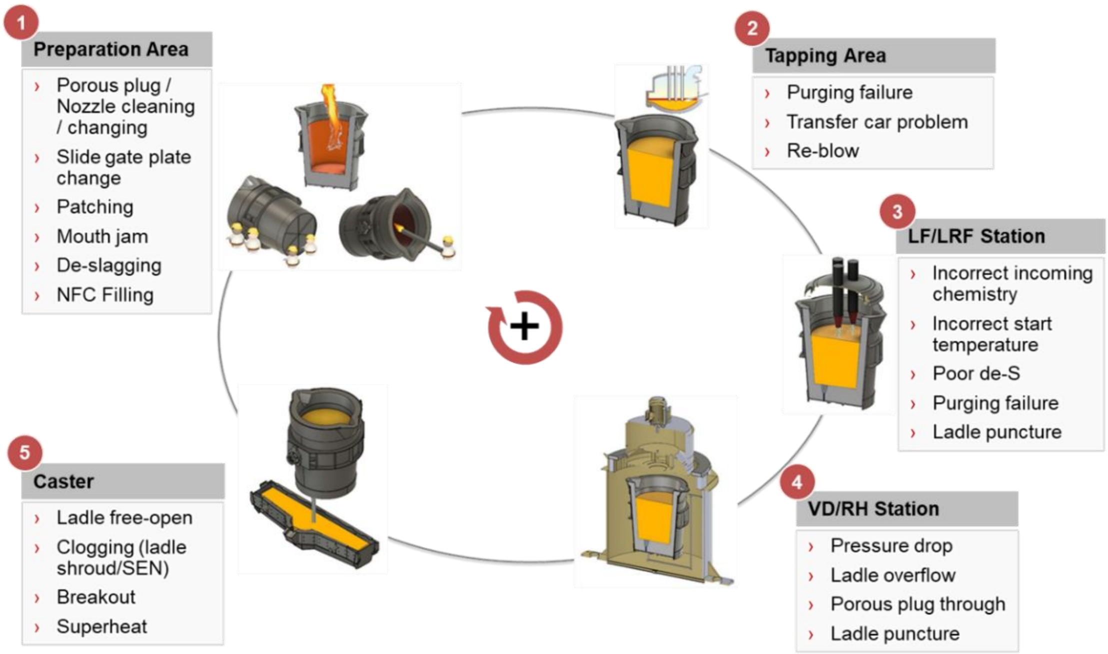
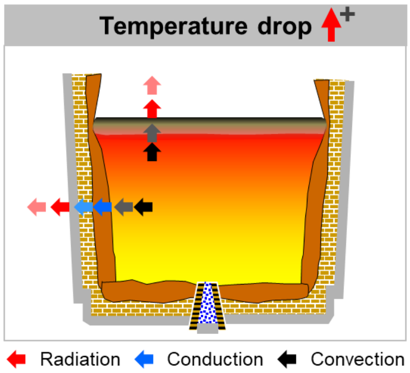
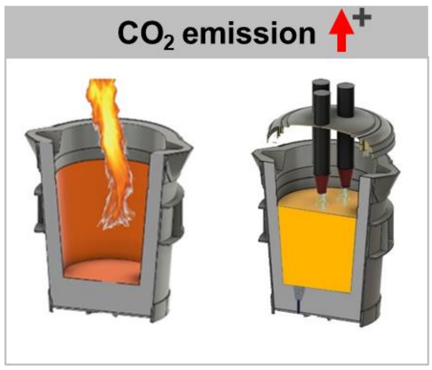


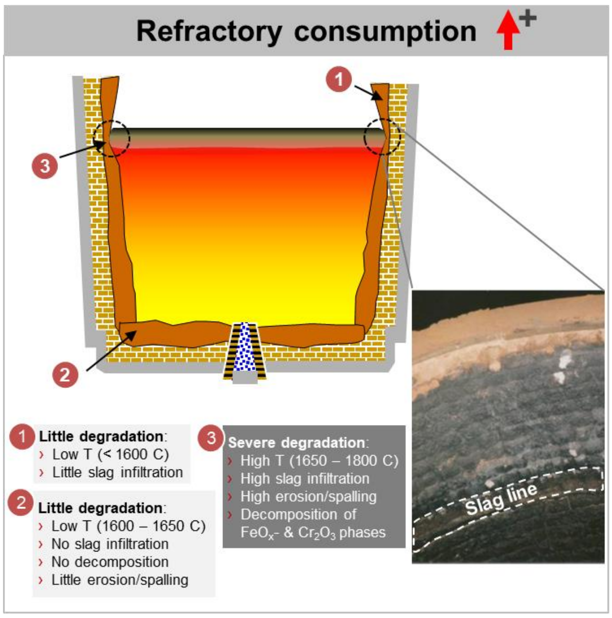
Figure 3: Delay events across various process units that cause major roadblocks to smooth steelmaking operations (*NFC: Nozzle Filling Compound; SEN: Submerged Entry Nozzle*)



(a) Temperature variation



(b) Carbon emission



(c) Refractory consumption

Figure 4: Ladle delay events leading to suboptimal outputs

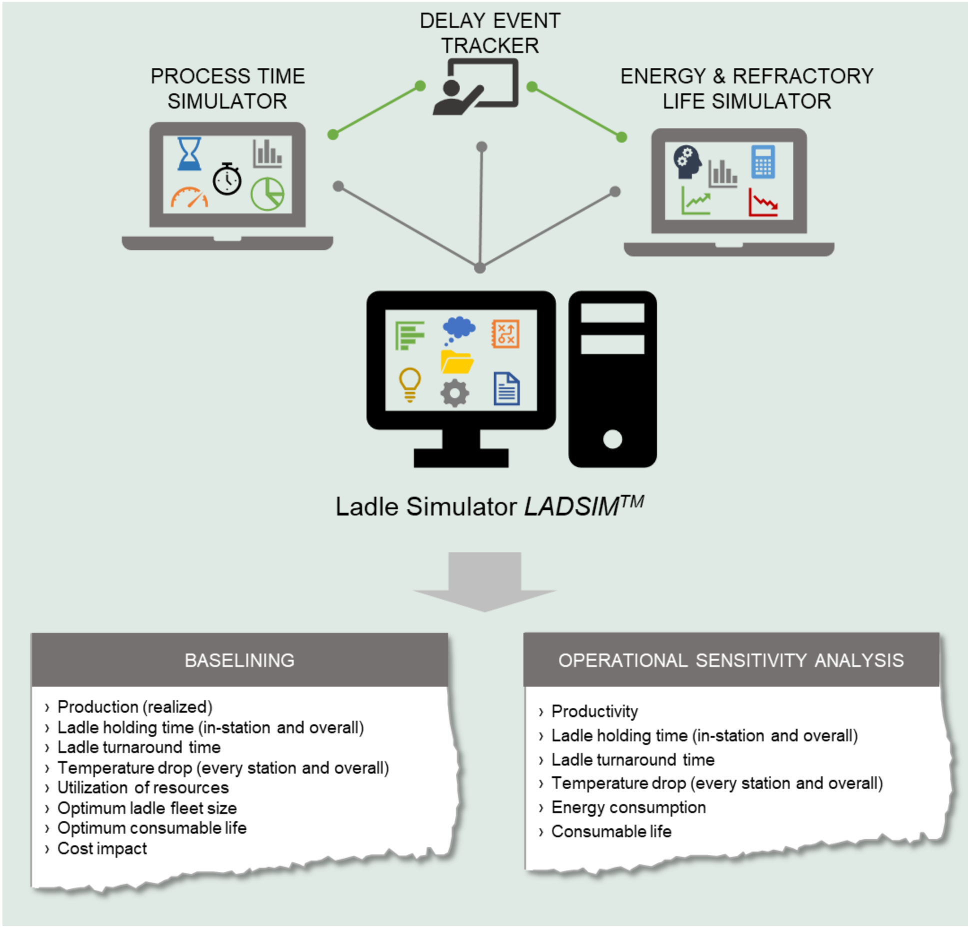


Figure 5: *LADSIM*^{TM} architecture

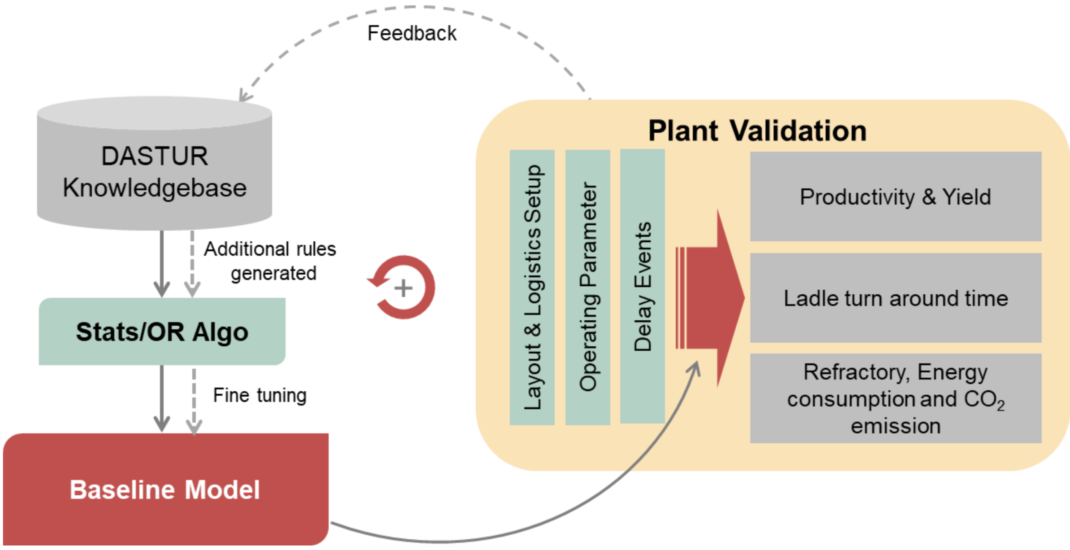


Figure 6: Methodology of baseline validation

The objective in this step is to reproduce these KPIs (at good confidence levels) through the framework of *LADSIM*^{TM}. Long-term performance of the plant can be predicted by simulating the operations for a long enough period (say few months).

The preliminary baseline model, thus determined, has to be validated by considering plant operational data.

Since every plant is different, having its own operating practices, fine-tuning of the baseline is a necessary step. The procedure for baseline validation is schematically depicted in Figure 6. This allows the user to reach to a consensus with the plant operators.

b) *Operational sensitivity analysis* (day-to-day basis): The next step after establishing a 'baseline' is to perform sensitivity analysis, i.e. evaluating operational and cost impact of a particular event or multiple events in conjunction. A typical example of a suboptimal operation is failure to prevent temperature loss. Its operational and cost impacts, determined from DASTUR's operational expertise, are depicted in Figure 7. Usually, it is difficult to envision the 'real' impact of a suboptimal operation since most of it is hidden under 'opportunity cost'. DASTUR's database considers all the possible operational and cost impacts, which allows precise determination of the effect of these events.

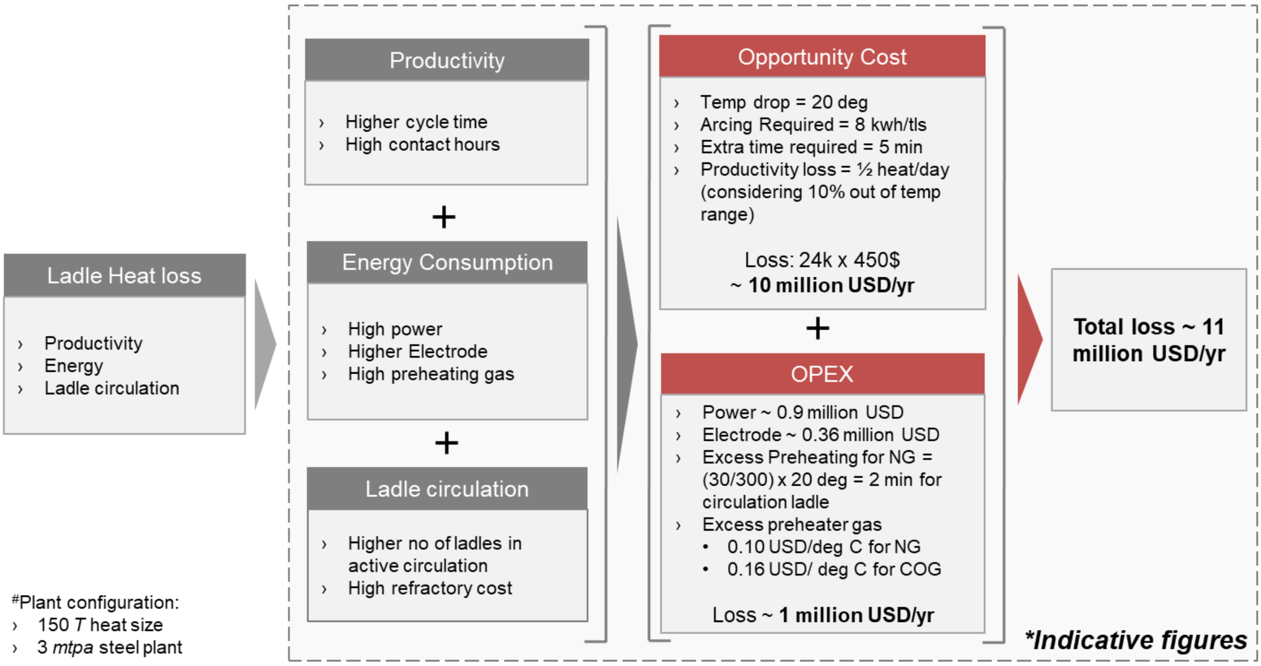


Figure 7: Typical example of impact of a suboptimal operation. In this case, the operational and cost impact of failure to prevent 20 degrees temperature loss from ladle is depicted.

Capturing the stochasticity of steel plant operations through process simulation

There are a multitude of events taking place in a melt shop and interestingly all these are very stochastic and can occur simultaneously. So it is important to consider the interaction of these events and not just the individual events, which is exactly what Process Time Simulator (PTS) does. PTS captures the stochasticity of the events and their associated uncertainties in the melt shop

Apart from capturing the stochasticity, usage of a strong database is critical. Using DASTUR's global operational database, and process and operational knowhow, the frequency of occurrence of the delay events and their average duration are considered in *LADSIM^{TM}*. Different kinds of statistical distributions are considered to take into account the stochasticities in the database wherever applicable. Similarly, the operational knowhow stored as an extensible rules library is used to form the heuristics that drive the progressive optimization in *LADSIM^{TM}*. These inputs can be customized, as and when required, to calculate for instance, the impact of a specific event or any combination of events.

For a specific set of operating conditions, the PTS determines production volume, resource utilisation and ladle turnaround times (LTT) directly. However, its main objective is to determine the optimum resources, such as ladle fleet size, number of cranes and transfer cars, by iteration.

Delay Event Tracker (DET) is a repository of all possible delays affecting ladle circuit. An indicative list of these events is depicted in Figure 3. Inputs from the DET into PTS allows sensitivity analysis (evaluating the effect of one or combination of events). The results from PTS are used by Energy and Refractory Life simulator (ERLS) to determine temperature drop, CO_2 emission, energy and refractory consumption.

Embedded heat transfer model

The heat transfer model is based on the balance between the heat gains and losses performed at every time step. While the heat gains are due to ladle pre-

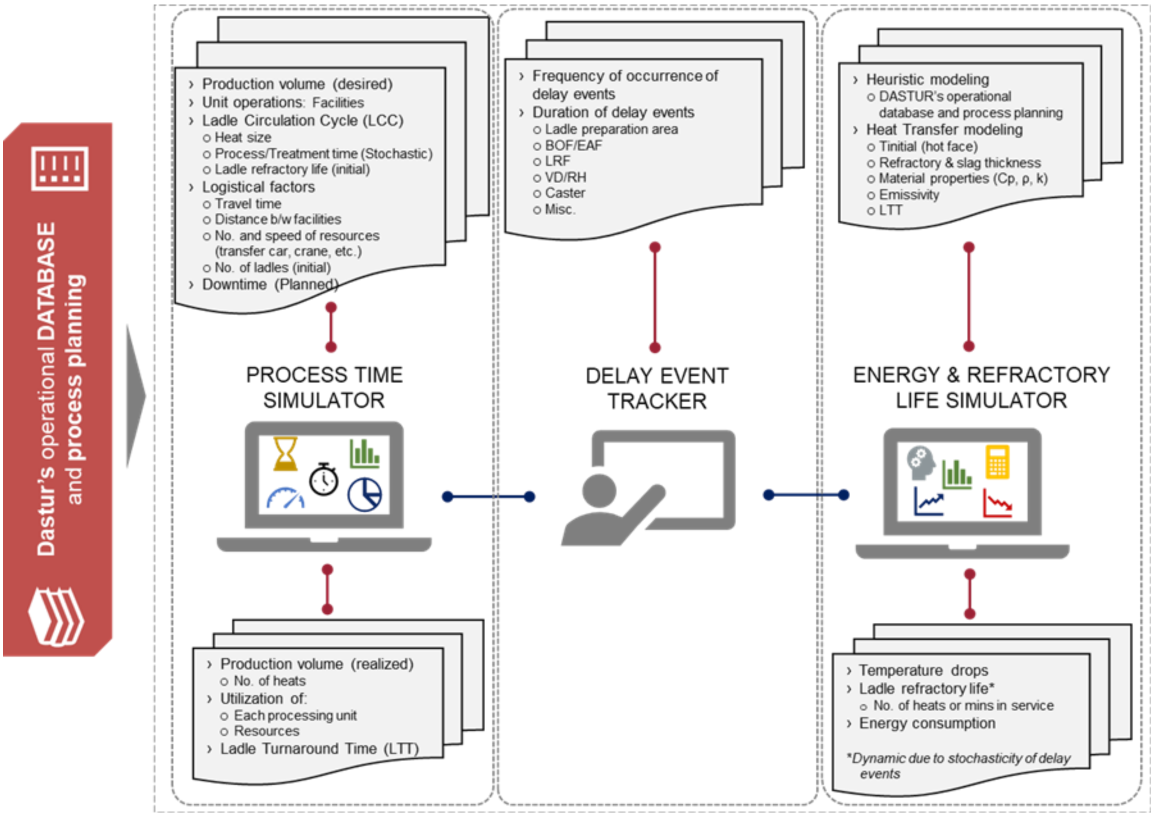


Figure 8: Inputs and outputs of each component of *LADSIM*^{TM}

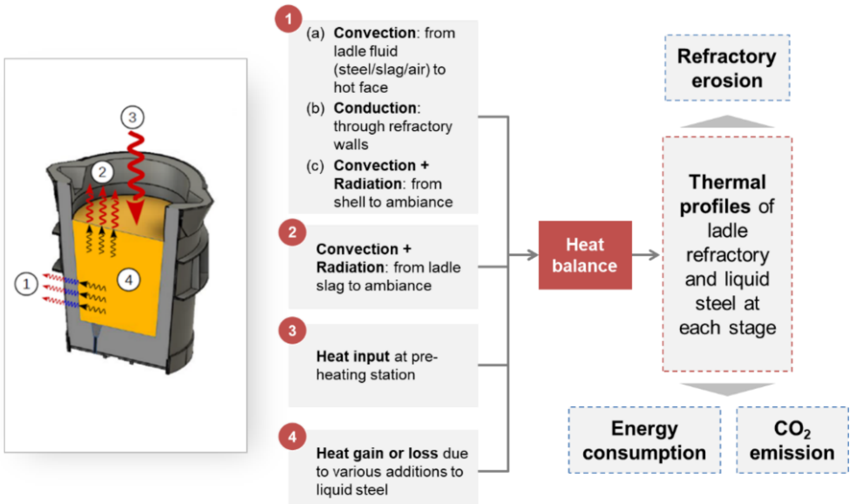


Figure 9 (a): Basis of the heat transfer model and ERLS

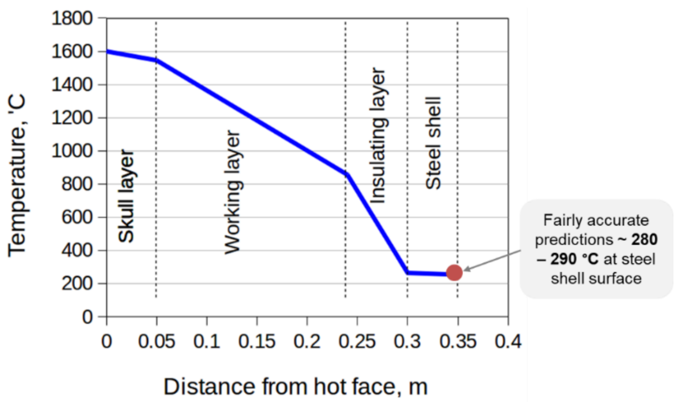


Figure 9 (b): Sample ladle temperature profile calculated during its operation heating, exothermic reactions and arc heating in the ladle refining stage, the radiative, convective and conductive heat losses to ambiance are incurred during gas stirring, holding, empty waiting, cleaning and preparation of the ladle [2, 3]. The basis of the heat transfer model is depicted in Figure 9 (a).

The major assumption is that uniform temperature prevails on each face of the ladle and within the liquid steel as well as liquid slag. This simplification allows for a one-dimensional heat conduction model for heat transfer across the ladle wall, calculation of heat loss through radiation and convection based on one temperature value for each ladle faces, calculation of the heat loss and gain by the liquid steel and liquid slag based on one temperature value for each phase and therefore allows a rapid calculation of thermal profiles. The inner faces of ladle is assumed to achieve equilibrium with the liquid steel. A sample temperature profile of a ladle calculated using the present heat transfer model (Fig. 9(b)) shows close correspondence to reality.

Erosion of ladle refractories are strongly influenced by the intensity of liquid flow in the ladle during various operations such as furnace tapping, gas stirring and RH degassing. Erosion rate prediction based on first principles modeling are cumbersome and therefore empirical models are developed based on DASTUR's operational database. Instead of erosion rate, the empirical model estimates the life of each refractory zone in the ladle based on the stirring intensity-weighted duration of various process steps in each cycle, for several cycles.

Functionalities of *LADSIM*™ through a couple of case studies

As described earlier, *LADSIM™ 1.0* consists of two main modules:

(A) BASELINING
(B) SENSITIVITY

(A) BASELINING

<u>Home window</u>:

The main menu window of *LADSIM™ 1.0* is depicted in Figure 10 (a). Under the 'Home' window, the steel plant name has to be selected, as shown in Figure 10 (b). As an example, a hypothetical plant named XYZ Steel has been illustrated. The default data, which is plant-specific, appears on the required fields from the in-built DASTUR database. If the user wants to modify certain fields, that is possible by making changes in the subsequent windows. The settings window, as depicted in Figure 10 (c), has the following fields that can be modified:

(i) Production capacity
(ii) Grades produced
(iii) Tapping temperature / Casting temperature / Superheat
(iv) Ladle fleet size
(v) Labor for preparation area
(vi) Consumable life

<u>Configuration window:</u>

Next comes selection / modification of facilities / unit operations such as BOF/EAF/LF/RH/caster under the 'Configuration' window, as depicted in Figure 10 (d). The following parameters can be modified:

(i) Number of stations
(ii) Heat size
(iii) Processing / Treatment time
(iv) Travel times

<u>Operational events window:</u>

Area-wise operational events are considered in the *LADSIM™* framework. A snapshot of the events that need to be considered for the 'ladle preparation area' such as de-slagging, mouth jam, gunning/patching, preheating, etc. is shown under the 'Operational events' window in Figure 10 (e). The parameters that can be modified include:

(i) Recurring time of event
(ii) Duration of event

<u>Options window:</u>

After making all the changes, the user needs to select the time for which the entire process has to be simulated. This is depicted under the 'Options' window (Figure 10 (f)). For the ease of understanding and carrying out simulations, two options are included:

(i) Absolute time (in hours)
(ii) Calendar (dates)

<u>Results window:</u>

The simulation results are grouped into to two sub-sections:

(i) Key Performance Index (KPI) – Both cost and process parameters are displayed in the results window, as shown in Figure 10 (g). Some of the parameters are as follows:
   › Productivity
   › Ladle turnaround time
   › Delay (total ladle holding time)
   › Energy consumption
   › Refractory consumption
   › Energy cost
   › Refractory cost

These parameters may need to be fine-tuned based on the inputs from the steel plant operators. Once completed, this data set will form the baseline for the current plant operations.

(ii) Impact Analysis – The effects of each of the operational event (such as de-slagging, mouth jam, preheating, etc.) considered in the simulations are determined, as shown in Figure 10 (h). The parameters displayed are as follows:

› Productivity
› Ladle turnaround time (per ladle)
› Temperature drop
› Energy consumption
› Refractory consumption

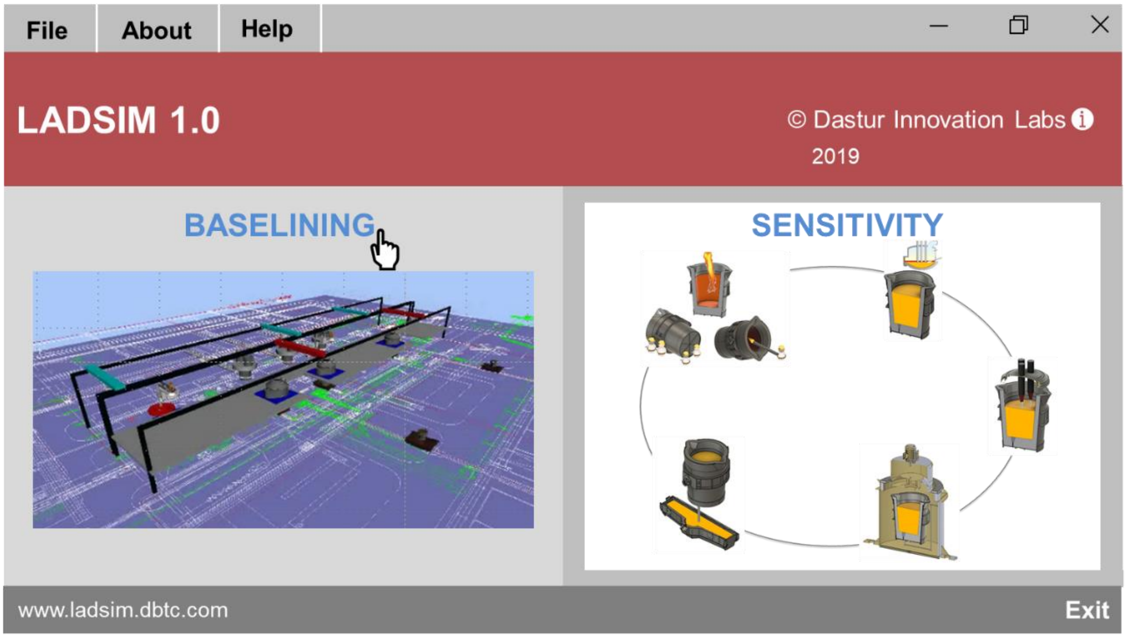


Figure 10 (a): *LADSIM^{TM} 1.0* main interface – Baselining of plant operations

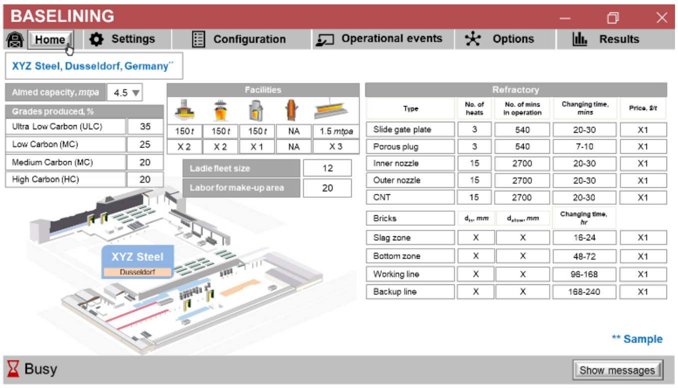


Figure 10 (b): *Home* window of XYZ steel plant – plant specific data obtained from in-built DASTUR database

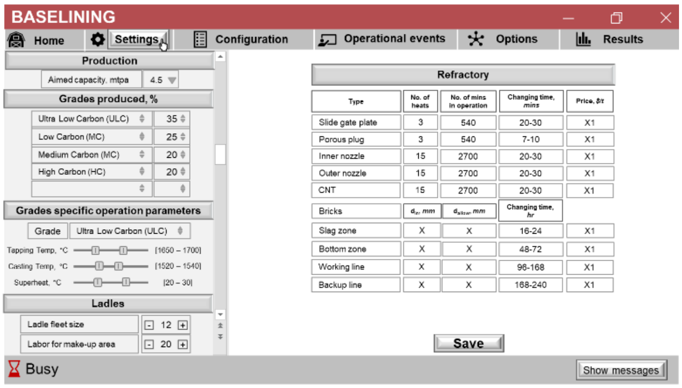


Figure 10 (c): *Settings* window – modification of production, grades, ladles and refractory data

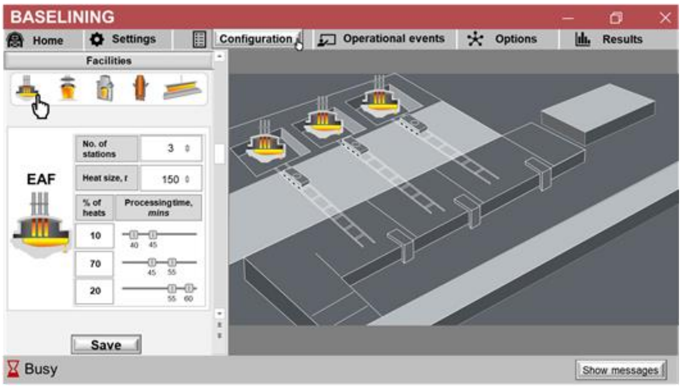


Figure 10 (d): *Configuration* window – modification of facilities data

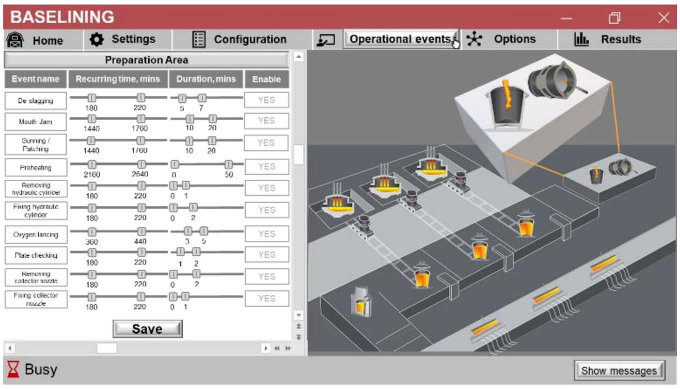


Figure 10 (e): *Operational events* window – modification of duration and frequence of occurrence data

Figure 10 (f): *Options* window – selection time for which process has to be simulated

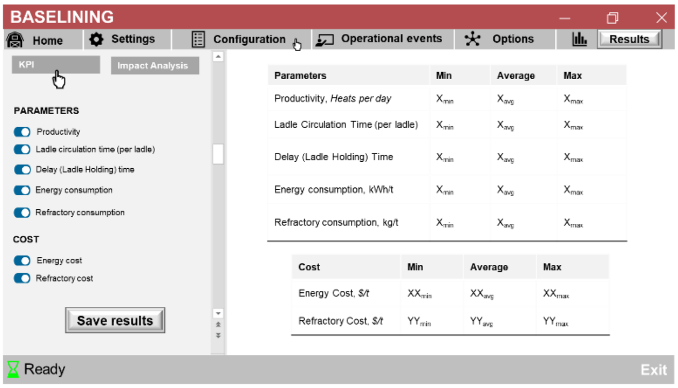


Figure 10 (g): *Results* window – Key Performance Indices

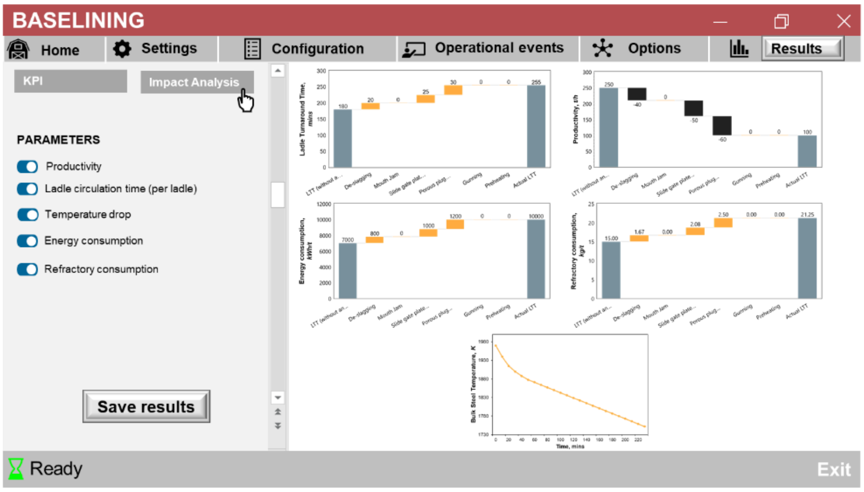


Figure 10 (h): Results window – Impact Analysis

***Note: All data used here are indicative and should not be referred to*

(B) SENSITIVITY

Once the baseline is validated and saved, various sensitivities can be performed on the operating parameters. The results of the simulation runs with the changed parameters can give a comparison with the baseline to show if there is an improvement or deterioration in the system with quantified values and in terms of:

- Productivity
- Ladle turnaround time (per ladle)
- Energy consumption
- Refractory consumption
- Energy cost
- Refractory cost

For example a snapshot of the process parameters for (a) the baseline operations and (b) with extended oxygen lancing is depicted in Figure 11(d). While ladle turnaround time, energy and refractory consumptions are seen to increase, productivity decreases with increase in duration of oxygen lancing.

These sensitivities also guide to identify the bottleneck units/areas of the system. The effect of debottlenecking measures on those areas can be further verified through simulation runs. Analysis of the debottlenecking measures of one unit/area and performing sensitivity on those might lead to reveal other debottlenecking unit/areas and further sensitivity analyses can be performed on those. This is an iterative cycle and needs to be performed till the system reaches a stable state with the desired productivity, cost and other governing parameters.

Figure 11 (a): LADSIM™ 1.0 main interface – Sensitivity Analysis

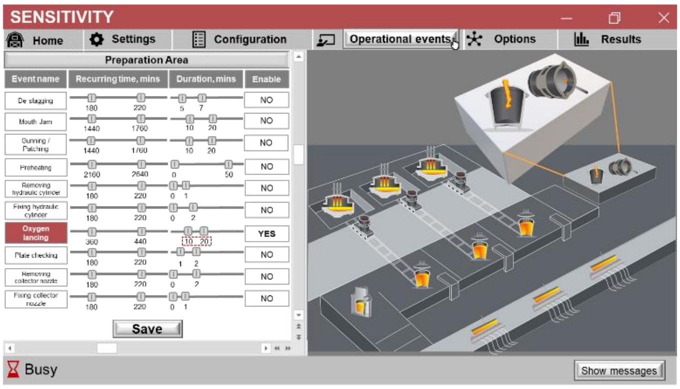


Figure 11 (b): Effect of a delayed ‘individual’ event (oxygen lancing)

Figure 11 (c): *Options* window – selection time for which process has to be simulated

Figure 11 (d): Results window: Comparative analysis showing the impact of one delay event (oxygen lancing) on normal operations

***Note: All data used here are indicative and should not be referred to*

Conclusion

Ladle Circuit Optimization (LCO) can greatly impact a steel plant's EBITDA by maximizing the productivity and yield on one hand, while minimizing energy wastage, consumable consumption and carbon emission on the other. A process simulation based framework has been developed for LCO, taking into consideration the complexities and stochasticities of plant operations. Making use of a strong operational database, plant specific configurations and operations can be simulated to predict the impact of one or multiple events on ladle turnaround time, productivity, energy and consumable consumption. Bottlenecks can be identified and various what-if scenarios can be tested to determine the most efficient debottlenecking measure for a specific problem. It can turn out to be a very useful tool for:

(a) steelmakers, who can use it to optimize their operations
(b) steel plant management, to make decisions on investments
(c) refractory suppliers, who can use it to showcase the advantages of their advanced products in addition to resolving penalty charges on account of suboptimal operations.

References

[1] Mukherjee A.; Adak A.: Optimizing Steel Melt Shop Operations using an Iterative Hierarchical Decomposition based Discrete Event Simulation Model; Proceedings of 5th International Conference on Simulation and Modeling, SIMULTECH, (2015), P. 1-8.

[2] Tripathi A.; Saha J.K.; Singh J.B.; Ajmani S.K.: Numerical Simulation of Heat Transfer Phenomenon in Steel Making Ladle; ISIJ Int., (2012), P. 1591-1600.

[3] Gupta N.; Chandra S.: Temperature Prediction Model for Controlling Casting Superheat Temperature; ISIJ Int., (2004), P. 1517-1526.