Auction Based Approach to Resolve Scheduling Problem in Steel Making Process

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Abstract

Steel production is an extremely complex process and finding its coherent schedules for the wide variety of production steps in a dynamic environment, where disturbances frequently occur, is a challenging task. In the steel production process, the blast furnace continuously produces liquid iron, which is transformed into liquid steel in the melt shop. The majority of the molten steel passes through a continuous caster to form large steel slabs, which are rolled into coils in the hot strip mill. The scheduling system of these processes has very different objectives and constraints, and operates in an environment where there is a substantial quantity of real-time information concerning production failures and customer requests. The steel making process that includes steel making followed by continuous casting is generally the main bottleneck in steel production. Therefore, comprehensive scheduling of this process is critical to improve the quality and productivity of the entire production system. This paper addresses the scheduling problem in steel making process. The methodology of winner determination using combinatorial auction process is employed to solve the aforementioned problem. Combinatorial auction based approaches are capable of minimizing large search space, discontinuity, and noise in order to obtain near optimal solutions. Hence in the proposed work the authors have adopted its splendid characteristics to enhance the quality of the solution in such complex scenarios. In the combinatorial auction, allowing bidding on a combination of assets, offers a way to enhance the efficiency of allocating the assets. In this paper, scheduling problem in steel making has been formulated as a linear integer program to determine the scheduling sequence for different charges. Then bids are obtained for sequencing the charges. Next, a heuristic approach is used to evaluate the bids. The computational results show that our algorithm can obtain optimal or near-optimal solutions for combinatorial problems. The proposed algorithm has been verified by a case study.

Key words: combinatorial auction, charges, coherent scheduling

1. INTRODUCTION

For decades, the steel industry has been a powerful symbol of an increasingly global market economy, providing one of the most primary materials for many other industries that include automobile, aircraft, construction, machinery production, food services, beverages industries etc. Modern iron and steel companies are heading towards continuous, fast and automated processes along with large infrastructure to attain high quality, and low cost products, just-in-time delivery and small lot sizes with variety of products. Development and use of the Computer Integrated Manufacturing System (CIMS) can improve the productivity, decrease waiting time between two processes, enables efficient material and energy utilization, and also cuts the production costs down (Balakrishnan and Brown, 1996). The iron and steel production includes several processing stages viz. iron making, steel making, continuous casting, and steel rolling, and is very extensive in investment and energy consumption. The most important characteristics of these processes are high temperature, high weight material flow with complex technological process.

To accommodate customer requirements for different types of finished products having varying demand, various rolling mills with sufficient production capacity in steel rolling phase are designed. Since steel making process include complicated technological processes that needs expensive and energy-extensive equipment and runs in continuous mode, its capacity is always below the actual capacity of the rolling stage. Thus, effective scheduling of steel making resources is therefore key component, especially in highly competitive global steel market of today, to meet the customer requirement and improve productivity of the entire production system.

Scheduling problems associated with steel making-continuous casting production, are aimed to determine at what time, on which device and in what sequence molten charge should be arranged at various production stages from the converter (steel making) to continuous casting. Three important aspects for a system to be applied in a real scheduling environment are as follows:

- Representation of the Problem environment
  Due to dynamic nature of demand, resources and organization are frequently changing. Therefore, environments and constraints pertaining to the problem should be modeled that can be easy to represent and modify.

- Different evaluation criteria

  A schedule is assessed according to many conflicting criteria. These criteria vary for different cases.

- Efficient solution generation

  It is not only necessary but imperative to generate scheduling sequence pertaining to different charges, without machine conflicts. Rescheduling capacity is also crucial while dealing with mechanical problems.

The whole scheduling problem of Steel Making-Continuous Casting (SMCC) consists of four steps

- Cast sequencing.
- Scheduling of individual charge sets.
- Merging of individual charge sets scheduling to make rough scheduling.
- Optimal scheduling that eliminates machine conflicts.

The first three steps are mainly dependant on the operational relationships and relatively can be done very easily. The last step is crucial and needs to follow resource and machine constraints to ensure practical feasibility of the resulting schedule. This paper focuses on determining this optimal scheduling step.

Hence, it is essential to develop an efficient and effective scheduling algorithm for such a system. The problem addressed in this paper is the Steel Making-Continuous Casting production (SMCC) scheduling problem encountered in practice. However, due to its complexity, no efficient optimization algorithms can solve the problem in polynomial time. Iterative algorithms are good alternatives, but robustness, an important criterion in practical situations, is usually unattainable. The comprehensive literature review in the field of scheduling of steel making processes revealed the necessity of a robust approach that can efficiently handle the complexities prevailing in such scenarios. In recent years application of distributed computing and agent technology have attracted the attention of researchers and practitioners, and a few notable contributions have been successfully reported with regard to there adoption in planning and scheduling problem in automated manufacturing systems. Negotiation based methodology has been used prominently to reveal interaction among agents which characterizes several features related to autonomy and functionality, and behavior. The multi-agent based shop floor manufacturing schedulers, agent based architecture to support distributed manufacturing systems, are some of the logical research output found worth recent years (Ryu and Jung, 2003, Khoo *et al.* 2001, McDonnell *et al.* 1999 etc.). Dewan and Joshi (2002) advocated auction based distributed scheduling to match the requirements of needs of a dynamic job shop environment. Furthermore adoption of e-manufacturing and e-business themes where internet is an indispensable ingredient, advocates for bidding based system to hammer out resource sharing among different agents. Narahari and Dayama (2004) outlined the need of combinatorial auction for electronic business in which they have covered different areas where paradigms of combinatorial auction have been used successfully to tackle job shop scheduling, supply chain coordination, band width changer, electronic procurement etc. In this paper we developed a combinatorial auction based approach to resolve the scheduling problem in SMCC. In combinatorial auction, bidders bid on set of items via different bidding languages and the auctioneer allocate the set of items to highest paid bid. Present study uses this property to determine the charge sequence. Steel making system acts as an auctioneer and all possible sequences of different charges act as bidders. A bid is the demand for certain position in the charge sequence. Thus the bids determine the order in which the charges are to be processed on different machines. Then each bid is evaluated using a heuristic approach. A bid is feasible till it satisfies the various constraints related to SMCC scheduling problem. Finally, system allows that bid for steel production which gives minimum waiting time and maximum throughput. The computational results show that our algorithm can obtain optimal or near-optimal solutions for large-sized problems in a reasonable computation time. Therefore, the proposed algorithm may be implemented in real-life production systems.

Rest of the paper is organized as follows. Section 2 briefs review of the related work. Section 3 illustrates the scheduling problem in SMCC production. Section 4 deals with the combinatorial auction with different bidding rules. Section 5 presents the mathematical formulation of the problem and evaluation of objective function. Section 6 presents the results and discussions explained through a case study. Finally, the general conclusions follow in section 7.

2. BACKGROUND AND RELATED WORKS

The main difficulties while dealing with scheduling problem are combinatorial explosion which is characterized by n machine, m job problem having $(m!)^n$ possible schedules and the diversity of conflicting constraints. Due to combinatorial explosion, a prohibitively large number of cases must be checked without elaborate and intelligent methods. A scheduling problem is usually constrained by due date, cost limits, production levels, machines, demand, resources and other factors.

Scheduling problems have been comprehensively studied by Artificial Intelligence (AI) technique to obtain near optimal solutions. Scheduling problems have been also extensively studied by OR technique which is an analytical method for getting optimal solutions by modeling. Johnsan (1954) presented an algorithm for obtaining optimal solution for two machines with the same order of jobs. Heller (1960) and Little *et al.* (1963) studied scheduling problem using simulation and a branch-bound method. Fox and Smith (1984) and Smith *et al.* (1986) presented a knowledge-based system for factory scheduling.

Steel production scheduling has been recognized as a difficult industrial scheduling problem (Cowling and Rezig, 2000; Tang *et al*., 2002). It involves a variety of complex technological processes, each of which has many critical production constraints, and interacts with several others in an integrated fashion to produce a finished product. Brown (1988) offered a rescheduling method to take care of disturbances and disruption produced during processing. Roy *et al.* (2004) and Schreiber *et al.* (1999) developed a knowledge based model for managing schedule disturbance in steel making process. A mathematical programming model for scheduling steel making-continuous casting production was provided by Tang *et al.* (2000). An example of off-line scheduling problem for steel production using dynamic mathematical programming was studied by Redwine and Wismer (1974). Petersen *et al.* (1992) have developed a mathematical programming model to optimally schedule the slabs through the reheating furnace and the rolling mill for a steel production scheduling problem. This model was solved heuristically. Tang *et al.* (2002) resolved the problem of steel making process using Lagrangian relaxation. Lally *et al.* (1987) constructed a simple model of a steel plant in which steel was started at an electric arc furnace, held in a ladle, and cast on a continuous caster and established a simple mixed-integer linear programming solution to the problem of caster scheduling. However, the model did not consider all the complexities of a real continuous caster. Tong *et al.* (1994) constructed a complex mixed-integer linear programming model and solved it using heuristic techniques for twin strand continuous slab caster scheduling problem at LTV and Geneva Steel Works. The model was intended to schedule caster production from customer order while optimizing several key objectives such as maximizing caster productivity.

Jimichi *et al.* (1990) presented an expert system to determine parameters and operational conditions to match slab production with customer orders. Another example of using expert system techniques for iron and steel production scheduling is provided by Sato *et al.* (1977). Numao and Morishita (1988), Numao and Morishita (1989), Morishita *et al.* (1990), and Numao and Morishita (1991) described an expert system application to perform co-operative scheduling in which the schedule was modified by the scheduler using a graphical user interface. They discussed about the difficulties to maintain the original short-term schedule due to dynamic nature of steel making process. The main justification for the use of expert systems came from reducing waiting time from charge to charge and minimizing energy consumption. Stohl and Spopek (1993) established a hybrid co-operative expert system modeling to solve SCC scheduling problems, but they were unable to construct an optimized mathematical model. Epp *et al.* (1989) described an interactive scheduling system developed using AI method for an SCC facility at Inland Steel Corporation. The multi-agent based shop floor manufacturing schedulers, agent based architecture to support distributed manufacturing systems are some of the logical research output found worth recent years (Ryu and Jung, 2003, Khoo *et al.* 2001, McDonnell *et al.* 1999 etc.). Hamada *et al.* (1995) presented a framework for solving complex steel making scheduling problems and then combined rule-based expert system and genetic algorithm to produce efficient schedules.

In this paper, an attempt has been made to adopt a heuristic procedure that is effective in minimizing large search space, discontinuity and noise to obtain near optimal solutions. The combinatorial auction based approach earlier has not been studied for complex scheduling problem discussed in this paper which exists in steel making processes. Previously this approach has been successfully implemented in e-business, e-manufacturing, tackling job shop scheduling, supply chain coordination, band width changer, electronic procurement etc. Present paper shows a combinatorial auction based heuristic that determines the optimal set from the pool of all possible solutions.

3. SCHEDULING PROBLEM IN STEEL MAKING PROCESSES

In this section, we describe about the scheduling problem in steel making processes. An Iron-carbon diagram used to determine the melting temperature of steel and cast irons is shown in figure 1. Major processing steps, steel making, refining and continuous casting are the main three stages. Each stage further contains parallel machines, as shown in figure 2 (a) and 2 (b).

<<Include Figure 1 about here>>

<<Include Figure 2(a) about here>>

<<Include Figure 2(b) about here>>

The various stages pertaining to steel making process are described in the subsections below.

3.1 Iron-making

The first link in the chain is the production of molten iron in the blast furnace by the reduction of iron ore. Iron ore is processed into pallets, or sinter, having more consistency and reducibility than the raw ore. Coal, another raw material for iron making, is baked in ovens to produce coke, a derivative product with higher combustion efficiency. Each separate oven chamber holds a charge of up to 30 tones of coal. The coal is heated, or carbonized, in the ovens until it becomes coke. It is then removed from the oven, cooled and graded before use in the blast furnace. Coke, ore and sinter pellets are charged into the top of the blast furnace, together with limestone. A hot air blast is injected through tuyeres in the base of the furnace creating a temperature gradient in the furnace, from about 1400^{o}C at the bottom to about 250^{0}C at the top. As these ingredients fall through the furnace, several actions take place. The ore is smelted and reduced through combination with carbon from the coke. The molten limestone serves as a flux; i.e. it forms a liquid slag that carries coke ash and other impurities away from the molten metal. At the base of the furnace, slag is drawn out for disposal, and hot molten iron is tapped out into ladles for steel making. Meanwhile, the raw material continues to be charged into the top of the furnace, and heated air blasted in at the bottom. This process is continuous and goes on throughout the life of the furnace, which can be 10 years or more. A blast furnace operates constantly, with the materials being fed continuously and the product tapped periodically. This is a necessary condition, since shutdown of the furnace could necessitate a rebuild (rehabilitating the furnace and replacing its refectory lining, a procedure that may cost 70 to 100 million dollars and require as long as a year). For this reason, hot iron produced by the blast furnace is viewed as a continuous supply, and the consumption of this continuous supply is an important constraint on the planning and scheduling of the next stage:

3.2 Primary steel-making

Primary steel-making accepts the supply of hot molten iron from the blast furnace and transforms it into semi-finished products (slabs, coils, billets, blooms, etc.) in a variety of grades (specific metallurgical compositions of steel) and dimensions. The principal processes for primary steel-making are basic oxygen furnace or electric arc furnace, ladle treatment facility, continuous casters, and hot strip mill.

3.2.1 Basic Oxygen Furnace or Electric Arc Furnace

Hot molten iron arrives from the blast furnace in insulated vessels, often via rail, and it is poured into refining furnaces along with scrap steel. Further heat is then applied to melt the combined charge into a homogeneous liquid state, remove impurities, and reduce the carbon content to a desired level. During this refining process, alloying additives can be added to achieve required metallurgical specifications for the particular grade produced. Basic oxygen furnace and electric-arc furnace are two types of refining furnaces predominant in the steel industry: In high production operations, the basic oxygen furnace is more common. A typical production facility, or basic oxygen furnace shop, might consist of two vessels and produce about 35 heats per day, with each heat consisting of 200 to 300 tons of molten steel. On the input side, refining furnaces are constrained by the requirement that they collectively must consume all hot iron arriving from the blast furnaces, a continuous supply with little available variation. On the output side, each heat of steel produced by a refining furnace is of a single specific grade, and furnaces normally are run for complete heats only. Therefore, one challenge in scheduling primary production is to make efficient use of material produced by the refining furnaces in full and grade specific heat lots. Refining furnaces are also subject to certain constraints concerning the sequence in which different grades are made, and the number of consecutive heats of certain grades they can produce, since some grades may damage the refractory lining of the furnaces if too many heats are scheduled.

3.2.2 Ladle Metallurgical Facility

From the refining furnaces, molten steel is transferred via ladles containing one heat of steel that is transported by a crane to a ladle metallurgical facility. At a ladle metallurgical facility, a heat might undergo any of several refining processes, which aim to produce molten steel of the correct grade or chemistry by subjecting the steel to processes that reduce the carbon content, and adding alloying additives such as nickel and manganese. Sometimes, degassing is also done to remove the gases, which may trap during various processes.

3.2.3 Continuous Caster

Molten steel from the ladle metallurgical facility next moves to the casting step, where liquid steel is transformed into different semi-finished shapes, dimensions, weights, and grades. Common cast shapes include slabs, blooms, and billets used to make flat-coiled products and plates etc. Each slab has several important characteristics: width, thickness, grade, weight, and length. The slabs are typically 150-320 mm thick, 500-3000 mm wide, and 10-20 meters long. Blooms and billets have smaller width and thickness dimensions, and are used to make long products such as pipes. Liquid steel is produced in heats generally of a fixed size for a given plant (e.g. 300 tones), and each heat produces a number of slabs (a 300 tones heat can produce about 16 slabs) in the continuous caster, and all of the slabs cast will essentially have the same grade. In this paper, we consider only the production of slabs. At a continuous caster, the ladles of molten steel or heats are drained into a tundish at the top of the machine. The ladle is lifted by a crane into a rotating turret, which contains a second empty ladle opposing it at 180 degrees. The full ladle is rotated into place over the caster as the previous empty ladle is rotated out for return to the steel-making shop. A ceramic nozzle and slide gate is attached to the bottom of the ladle; the ladle is opened and molten steel flows into the tundish.

Owing to above facts, it is very difficult to assess optimal solution for scheduling various charges on different machines. It is imperative that every stage of steel making processes at high temperature. So, in order to achieve the minimum the waiting time and maximum the throughput, an efficient algorithm should be needed. In this paper, a combinatorial auction based heuristics has been applied to get optimal or near optimal solution of the scheduling problem taken in consideration.

Few special terms have been used in this paper; their definitions are defined in *Appendix I,* appended in last.

Figure 3 shows a diagrammatic representation of a few of the terms mentioned in the *Appendix I.* The vertical line is for time, and each line stands for machine. One charge path includes units and handling times, which are represented by lines connecting the units. The waiting time are shown by dotted lines before the units.

<Include Figure 3 about here>

4. COMBINATORIAL AUCTION: AN OVERVIEW

An auction provides a mechanism to allocate a set of goods to a set of bidders on the basis of bids and requirement. When there are uncertainties in demand and supply, unresponsive suppliers, and demand uniqueness then auctions are frequently used for allocation of multiple resources (Banks et al 1989). In a sequential auction, the items are auctioned one at time and auctioneer always want to allocate that item to the highest bidder among the group of bidders. But if the bidders are interested in a combination of items then it is very difficult for the bidders to submit bids because they don't know what items they will receive in later auction. In parallel auction, items are auctioned in parallel. Here bidders face same difficulties as that in sequential auction. In combinatorial auctions (CAs), multiple goods are auctioned simultaneously i.e. each bid may claim any combination of goods. This characteristic helps in overcoming the inefficiencies in allocations due to related uncertainties because in combinatorial auction, the value of an item that bidder wins greatly depends on the winning of other items. The concepts of complementarity and substitutability are very important in CAs.

- Complementarity: The property that shows the willingness of bidder to pay more for the whole than the sum of what he is willing to pay for the parts is termed as Complementarity. Complementary goods have a super additive utility function

$$V(\{a, b\}) > V(\{a\}) + V(\{b\}) \ldots (1)$$

Where, $V(\{a, b\})$ = Utility function for combination of item a and b.
$V(\{a\})$ = Utility function for item a.
$V(\{b\})$ = Utility function for item b.

- Substitutability: A bidder may be ready to pay for the whole only less than the sum of what he is willing to pay for the parts. This is termed as Substitutability. Substitutable goods have a subadditive utility function:

$$V(\{a, b\}) < V(\{a\}) + V(\{b\}) \ldots (2)$$

Numerous industrial applications have been reported by different researchers for combinatorial auctions. Spectrum auctions, collaborative planning, resource scheduling, train scheduling, airport slot allocation, supply chain management, and e-procurement are few of them. In this paper, combinatorial auction has been used for steel scheduling problem to get coherent schedules for the wide variety of production steps in a dynamic environment.

In a manufacturing plant, a set of jobs is to be scheduled across a set of machines to minimize metrics like tardiness or total delay, maximize throughput etc. In auction-based manufacturing, various entities in manufacturing system bid themselves, accept bids and select a bid based on some heuristic procedure from the available bids (Shaw 1987).

In combinatorial auction, bidding languages and allocation of bids to bidders are two important issues. Section 4.1 discusses the various bidding languages.

4.1 Bidding languages

Bidding language can be used for expressing valuations. Bidding languages should have following characteristics

- Must be expressive enough to represent every possible valuation.
- Representation should not be too long
- Simplicity
- Easy for humans to understand
- Easy for auctioneer algorithms to handle

Various types of bidding languages are discussed below.

1. Atomic Bids: In Atomic Bids, a bidder has to put forward a bid (B_d) which contains two elements (I, P), where, I is the subset of items and P is the price that a bidder has to pay for I. Conditions to be satisfied for subset A:

   $I \subseteq A$, C (A) = P otherwise, C (A) = 0, this means the bidder has to pay price P if A items are to be taken from a set I.

2. OR bids: In OR bids, there is no restriction over the number of atomic bids to the bidder. The bidder is willing to obtain any number of atomic bids and the price of these atomic bids will be equivalent to aggregate of there individual prices.
3. XOR bids: In XOR bids, the bidder can submit any number of atomic bids but he has to procure at most one of these atomic bids.

4. OR of XOR bids: In these bids, the choice of number of XOR bids depend on the bidder and any number of these bids can be obtained by the bidder by paying the price of these bids that is equal to sum of their individual prices.
5. XOR of OR bids: In these bids, the bidder cab submit any number of OR Bids but only one bid can be obtained by him.
6. OR^* bids: Let there are Z set of items for sale, and each bidder b has Z_b set of phantom items, on which only it can bid. Each bidder b can submit an arbitrary number of pairs (I_b, P_b); where, $I_b \subseteq Z \cup Z_b$, and P_b is the maximum price that the bidder is willing to pay for that subset. The bidder is willing to obtain any number of disjoint bids for their respective prices.

4.2 Optimal subset determination

All bids are accepted in combinatorial auction unlike any other auctioning process because a bid may form a combination with other bids that may emerge a better combination for auctioneer. Optimal subset is determined by optimizing some target value, generally the auctioneer revenue or the total economic efficiency. This problem is modeled as an integer linear programming model and formulation is an instance of weight set-packing problem. Karp (1972) proved that the weighted set-packing problem is an NP-complete problem. Therefore, many heuristics have been used to solve this problem (Rothkopf *et al.* (1998), Fujishima *et al.* (1999)).

Any fractional allocation is not allowed in the combinatorial auction problem but in some cases, the auction setting itself may allow fractions to bids to be won as opposed to only complete bids. Possible examples of such auctions are for raw materials like oil or for electricity (Market Design Inc., http://www.marketdesign.com)

4.3 Motivation to use combinatorial auction theory

Steel making plant is a cluster of several interacting subsystems such as machines, raw materials, storage, order processing, etc. These systems work cooperatively with respect to the allocation of raw materials. Recently, a great deal of research has been directed towards new tools and techniques to obtain real time solutions for planning and scheduling problems. One such approach is mathematical programming model. Tang *et al.* (2000) have developed a mathematical programming model for scheduling steel making-continuous casting production, Redwine and Wismer (1974) presented an example of off-line scheduling for steel production using dynamic mathematical programming. Petersen *et al.* (1992) have developed a mathematical programming model to solve scheduling problem in steel-making. The main goal of these mathematical programming models is to ensure the fulfillment of objectives; minimum price paid and maximize the charged price to satisfy the charge's requirement. The above bidding procedure has been organized using combinatorial auction theory and model is developed for intelligent real time operational control of steel making plant.

5. AUCTION BASED MODEL FOR SCHEDULING PROBLEM IN STEEL MAKING PROCESS

5.1. The problem characteristics

After the composition of charges and the size of casts are defined, the task of charges scheduler is to determine when and where (on which device) each charge should be processed at each production stage. The following general assumptions have been made in steel making process.

(a) All charges follow the same process route: steel-making, refining, and then continuous casting. At each stage, a charge can be processed on any one of the machines at that stage, and the parallel machines at that stage are identical.

(b) A machine can process at most one job at a time.

(c) A job can be processed on at most one machine at any time.

(d) Job processing is non-preventive.

5.2. Integer programming formulation

The scheduling problem in steel making has been formulated as a linear integer program to find out the optimal charge sequence to assign various charges on different machines. In this auction model, the bids presented by each charge determine the order in which the different charges are to be processed on different machines. To evaluate each bid, a heuristic based approach is used next.

The integer programming formulation for determining the optimal charge sequence from the charge pool is described below.

***Notations*:**

k: 1, 2, 3……, m Machine

CON: Converter

REF: Refining equipment

CC: continuous caster

W_i: Waiting time for i^{th} charge

RT_k: Resting time for k^{th} machine

UT_{im}: Unit processing time of i^{th} charge on machine m

$b_j(s)$: Bidder j's value for bid for subset s of the sequence

Y(s,j): 1, if charge sequence subset s is selected and allocated to bidder ,
: 0 otherwise

TH: Throughput

NS: number of steel slab

Evaluation criteria:

The following criteria related to the quality of the charge scheduling have been used to solve the scheduling problem in steel making process.

1. Minimization of waiting time

   The process of steel making should be finished while the iron is still molten state. Otherwise, molten iron starts solidifying and goes into mushy state, which would be very difficult to cast it through continuous casting machine. The initial temperature of iron is assessed by the total waiting times on each machine during each charge processing. Therefore, the process waiting time should be minimized in order to reduce the heating cost. For evaluating the sequence with the objective of minimization of waiting time by satisfying the problem constraints, the objective can be expressed as:

$$\text{Min } f_1 = \sum_{k=1}^{m} W_{ik} \quad \dots (3)$$

Where, W_{ij} is the waiting time of ith charge on machine k.

2. Maximization of output:

   Output is defined as the number of steel slab of different cross section produced from the steel making plant without violating the problem constraints in one day. When the objective is to maximize output, charges are arranged in a sequence so as to *ensure* maximization of number of steel slab produced by satisfying the system constraints.

$$\text{Max } f_2 = \sum_{k=1}^{m} NS_k \quad \dots (4)$$

Where, NS_k is the number of steel slab produced from continuous caster machine k and m is the number of continuous casting machines.

Constraints:

Aforementioned evaluation criteria are subjected to the following constraints which are typical in steel making process.

1. limitation of waiting time:

   The process should be finished while the iron is in molten state. Thus, the sum of waiting times of each charge on different machines is limited to less than 30 minutes.

   $$\sum_{i=1}^{n} \sum_{k=1}^{m} W_{ik} \leqslant 30 \qquad \ldots (5)$$

   Where n is the number of charges and m is the number of machines.

2. Use of some machines continuously:

   Continuous caster machine is known for its continuous operation. In steel making process, all charges end with continuous casters, which should be perform regularly i.e. no resting time in between operations, in order to maximize the throughput. Keeping in view, this characteristic of continuous caster machine the process of refining a charge must be completed before the previous casting process ends.

3. Requirements of resting time for some machines:

   In steel making process, temperature of steel is handled with the aid of various machines and that varies from 1200^0C to 1400^0C depending on the percentage of carbon equivalent present in that steel. Due to this, some of the machines need regular repair. For example, damaged refractory tiles inside the converters need to replaced by new one after a few continuous processing cycle. Scheduling of different charges should take this kind of resting time into account.

5.3. Heuristic procedure

To determine the winning condition for each bid, stepwise heuristic method is described below.

Step1. Construct a detailed table consists of charge number, machines on which charge will processed, and the time required on that machine for various operation. Here, each bid stands for one possible charge routing.

Step2. In order to determine charge sequence, all possible combinations of two charges are made and for each combination the value of objective functions are determined without violating system constraints.

Step3. The combination which gives better value of objective functions that is minimum waiting time and maximum throughput is set as one group. If is there a tie for any bid of the charge in the sequence, then the bid with earlier charges is accepted as a group.

Step4. The selected group is again combined with rest of the charges and again the value of objective functions are determined without violating system constraints for each combination. The combination which gives better value of objective functions is set as one group again.

Step5. Step 3 and Step 4 are repeated until all charges would not be combined.

Step6. For the determined charge sequence, the overall waiting time and the through put are computed.

6. CASE STUDY

A combinatorial auction-based heuristic approach has been developed and applied to solve scheduling problem of a steel making process that consists four converters, four refiners, and four continuous casters. Table 1 shows the detailed problem description that includes unit processing time of each charge and corresponding machine. The scheduling problem has been reorganized to suit the requirements of proposed auction-based approach and shown in Table 2. For simplifying the coding problem related to machine, “C” is assigned for converter, “R” is assigned for refiner, and “CC” is assigned for continuous caster. This has been shown in table 2.

<Include Table 1 about here>

<Include Table 2 about here>

The planning horizon for this case study is 10h. First 15 bids can be generated from 15 bidders that are individual charges. The problem is then formulated for the XOR bidding language and heuristic procedure described in section 5.2 is applied to the problem given in table 1 and is described in stepwise below.

Step 1. First, a detailed table consisting of charge numbers, time required on different machines for various charges for each bid is constructed (as listed in Table 1 and Table 2)

Step 2. All possible combination of two charges are made and for each combination the corresponding waiting time has been calculated.

Step 3. Since, there are four converter machines, therefore four charges can be scheduled at a time. From those combination, 6-9, 3-5, and 12-11 offer better objective function value i.e. minimum waiting time and maximum output.

Step 4. Now selected combinations are set as one group separately and combined with rest of the charges.

Step 5. Step 3 and Step 4 are repeated until all charges would not be combined.

Step 6. Finally a sequence has been determined in detailed and described in Figure 4, which gives minimum waiting time (35minutes) and also maximize output (15 charges per shift).

The results of combinatorial auction-based heuristic approach have been shown in figure 4. To show the efficacy of the proposed algorithm, the results have been compared with that of standard scheduling rules such as SPT, LPT, FCFS, SPT/TOT, SPT.TOT, LPT/TOT, and LPT.TOT (Table 3). The waiting time and output for the corresponding sequences of the charges are shown in Table 4. The comparative study of the results, obtained by various scheduling rules as shown in figure 5 and figure 6, clearly depicts the superiority of the proposed algorithm i.e. minimum waiting time and maximum output. The comparative percentage improvement in the results of the proposed auction-based approach with the other scheduling rules is shown in table 5. The percentage improvement has been calculated according to the expression defined below:

$$(O_T - A_C)/\, O_T \qquad \ldots (6)$$

Where, O_T = Performance measure of the other scheduling rules

A_C = Performance measure of Auction-based approach

<<Include Figure 5 about here>>

<<Include Figure 6 about here>>

<<Include Table 3 about here>>

<<Include Table 4 about here>>

<<Include Table 5 about here>>

7. CONCLUSION

In this paper, scheduling of charges in steel making process has been carried out. To determine the optimal charge sequence, integer programming model has been formulated, that takes care of waiting time of different charges along with number of steel slabs produced in the system. The scheduling problem has been addressed using a Combinatorial-auction based approach. The main objective of the scheduling problem is to minimize the waiting time and maximize the number of steel slabs. In combinatorial auction based approach, combinations of two charges have been made; combinations are evaluated as per the specified evaluation criteria, based on the performance value. Best combination is treated as a single group. Now, selected combinations are considered as one separate group and combined with rest of the charges and process is iterated till all charges are combined. Finally a sequence has been generated which gives better value of objective functions. The results obtained by the auction based heuristics have been compared with the other existing approaches and this has been authenticated by the percentage improvement in the results.

Even the numbers of scheduling methods are available to determine the optimum schedules; there is a need of development of an expert system, based on some rules that can efficiently handle scheduling problems in steel making processes. In this article auction based algorithm is proposed considering the future scope, in which different agents considered in steel making shop floor situation can mediate/ interact with each other and this can best be mapped using auction based mechanism. Major breakthrough attained in implementing effective protocol and network architecture will enable the shop floor manager to witness the generation of effective schedules for complex and dynamic shop floor situations in real time basis. The proposed approach also needs to be tested in dynamic environment where multiple objectives and multiple constraints are present.

ACKNOWLEDGEMENT:

The authors would like to acknowledge the Research Promotion Cell (**RPC**) at the National Institute of Foundry and Forge Technology (**NIFFT**), India, for funding and supporting this research.

APPENDIX I

Charge: A unit of production that consists of a sequence of operations on a heat

Charge set: a set of charge that produces the same dimension product

Billet: A steel piece with square cross section, smaller than a bloom

Bloom: A steel piece with square cross section, larger than a billet

Machine: A production device which performs one operation at a time. The machines for performing identical operations are called alternative machines. Different machine perform different operation like a converter converts pig iron into steel, refining machine do refining and alloying addition, and continuous caster make steel slab.

EAF: Electric Arc Furnace

BF: Blast Furnace

BOF: Basic Oxygen Furnace

LMF: Ladle Metallurgical Facility

Tundish: A receptacle at top of caster

LF: Ladle Furnace

Grade: Steel with a specified metallurgical composition

Heat: Furnace-load of steel

Slab: A steel piece with elongated rectangular cross section

Strand: Stream of steel from a caster

Unit: an operation that specifies the machine, the starting time, and completion time.

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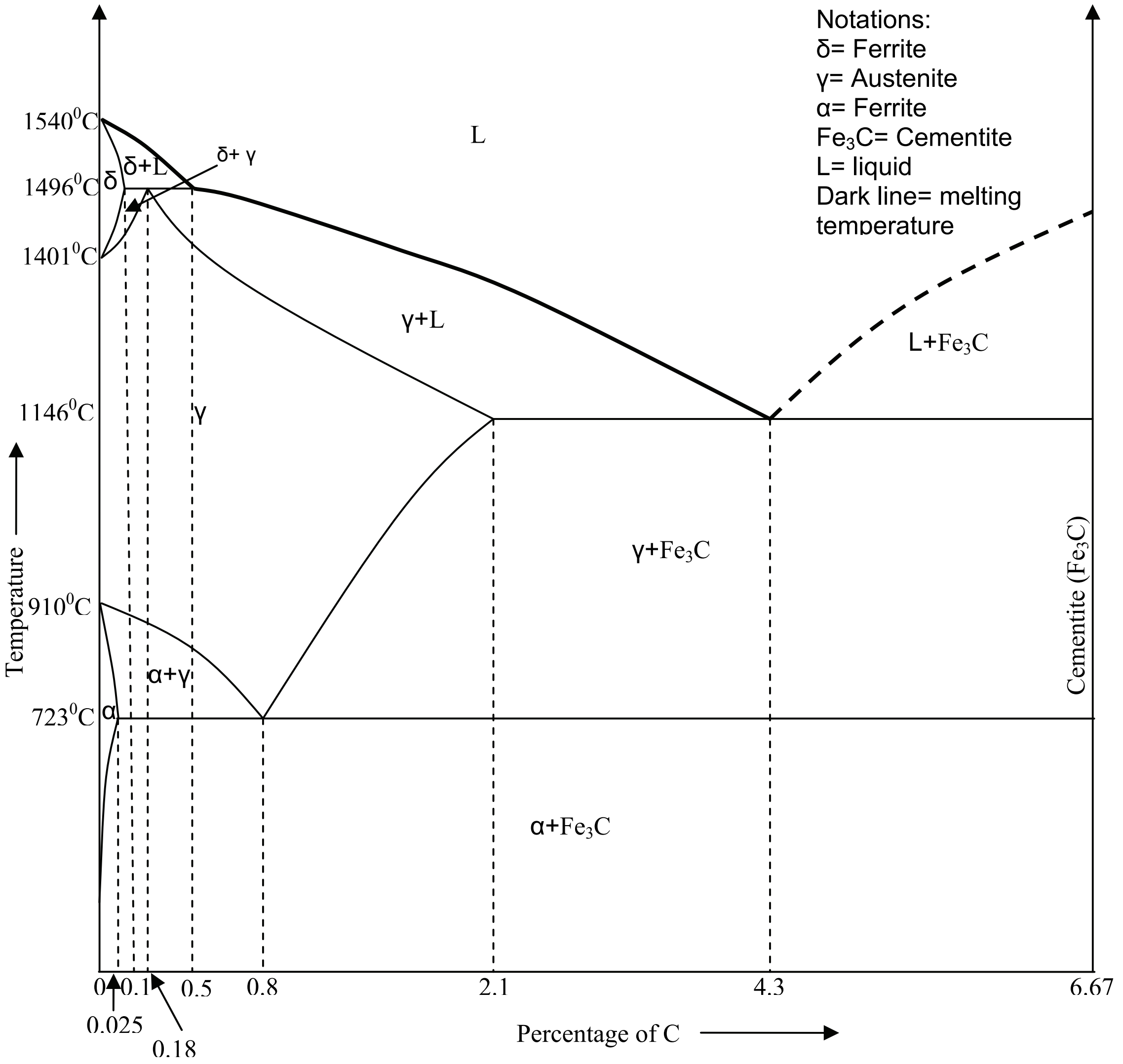


Figure1. Iron-carbon diagram for determining the melting temperature of different steel and cast irons.

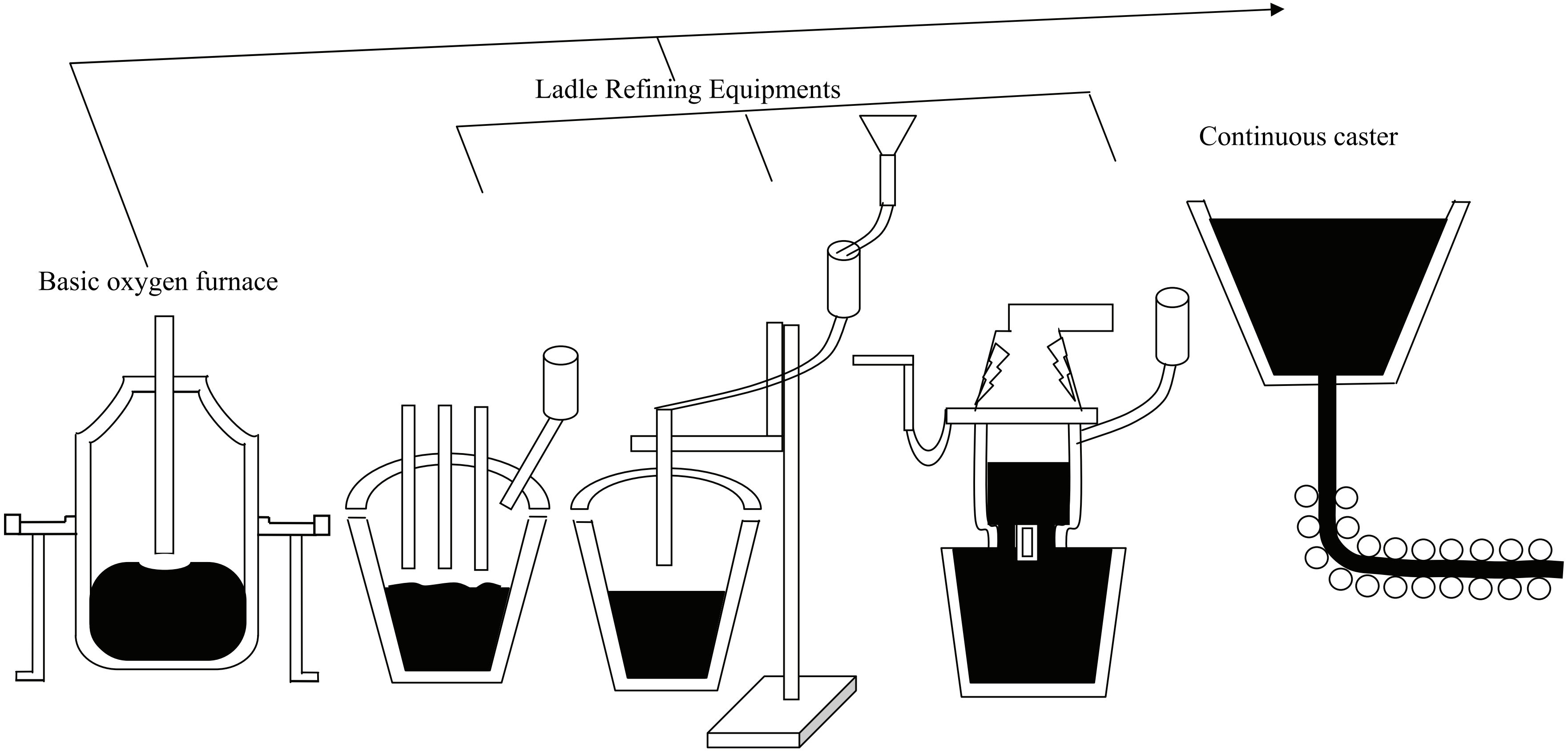


Figure2 (a): Steel making process

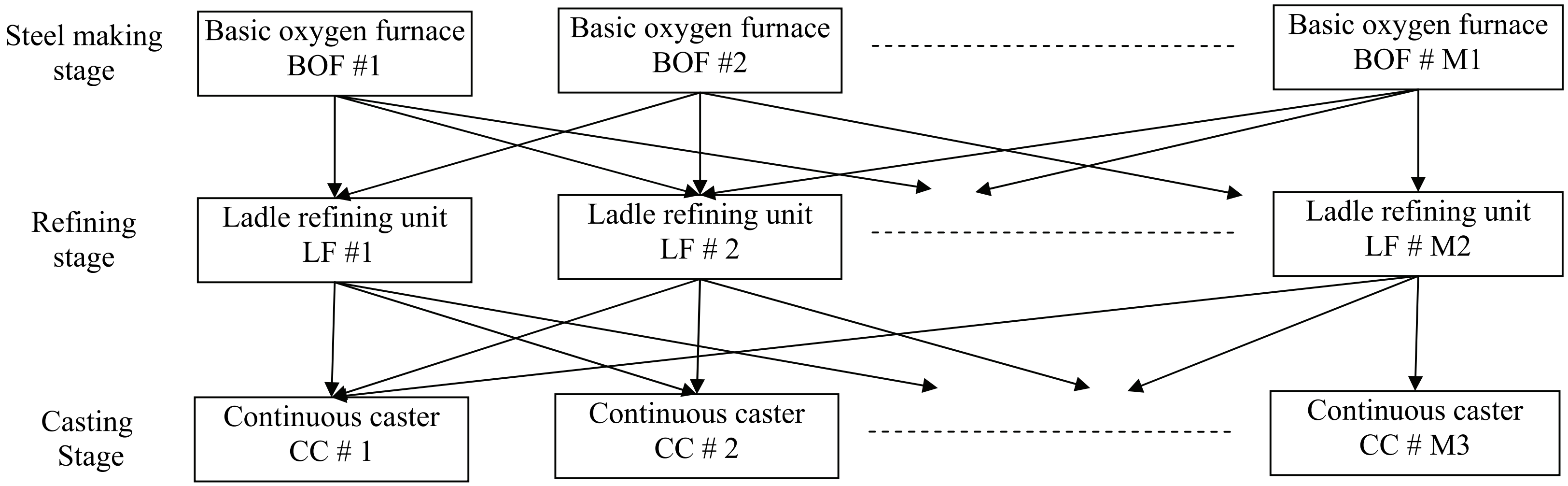


Figure2 (b) Steel Making process

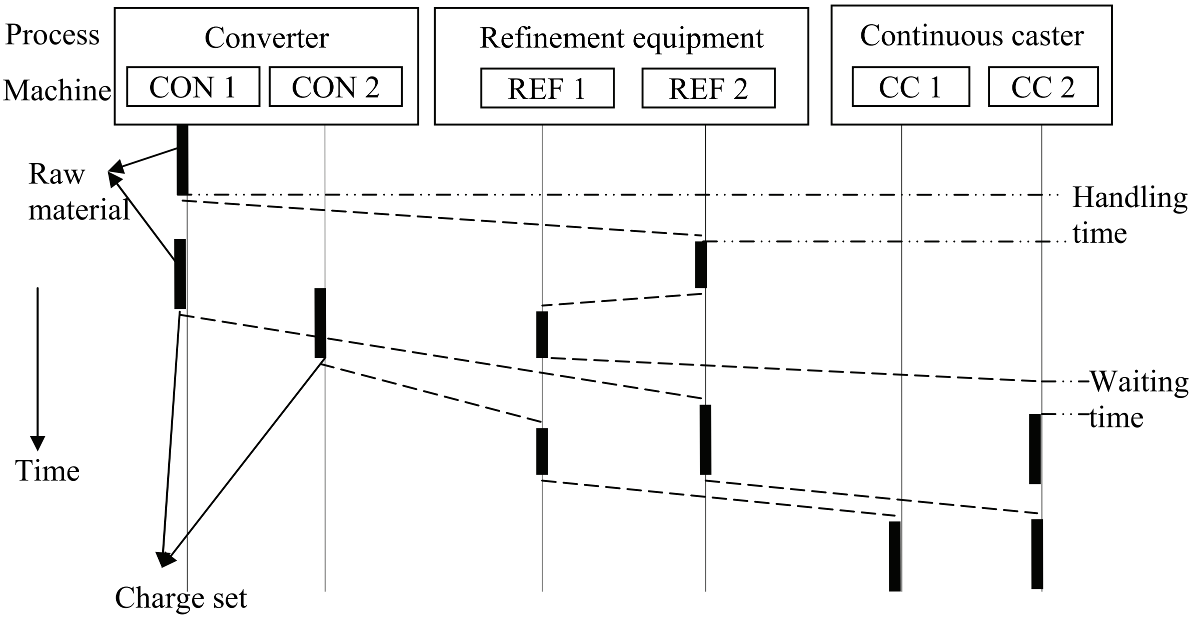
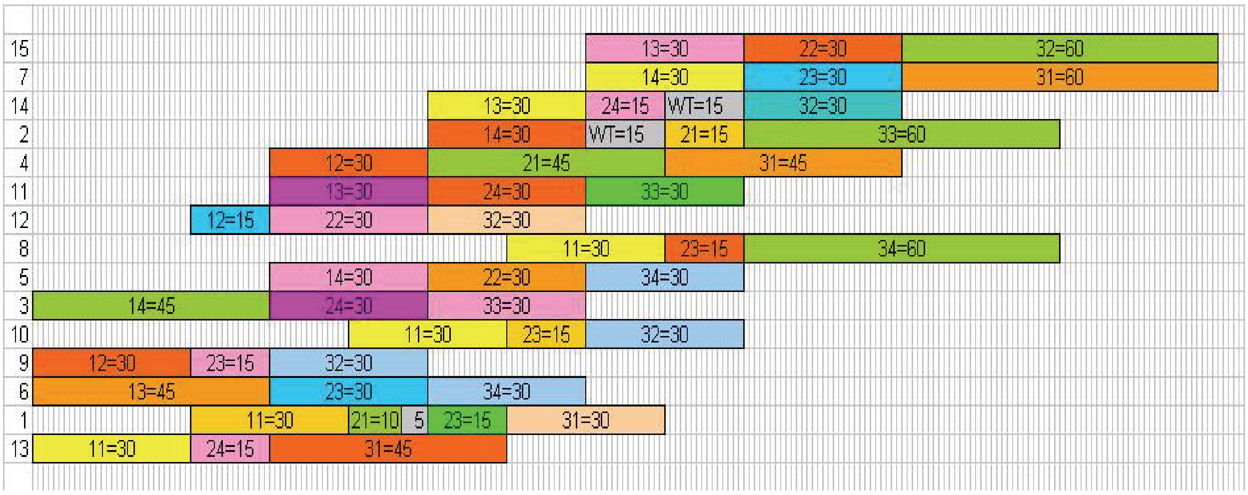


Figure3. Representation of scheduling terminology



Time in minutes

Minimum waiting time = 35 minutes, Throughput =15 charges per shift

Figure4. Final Charges sequence obtained by applying auction based approach

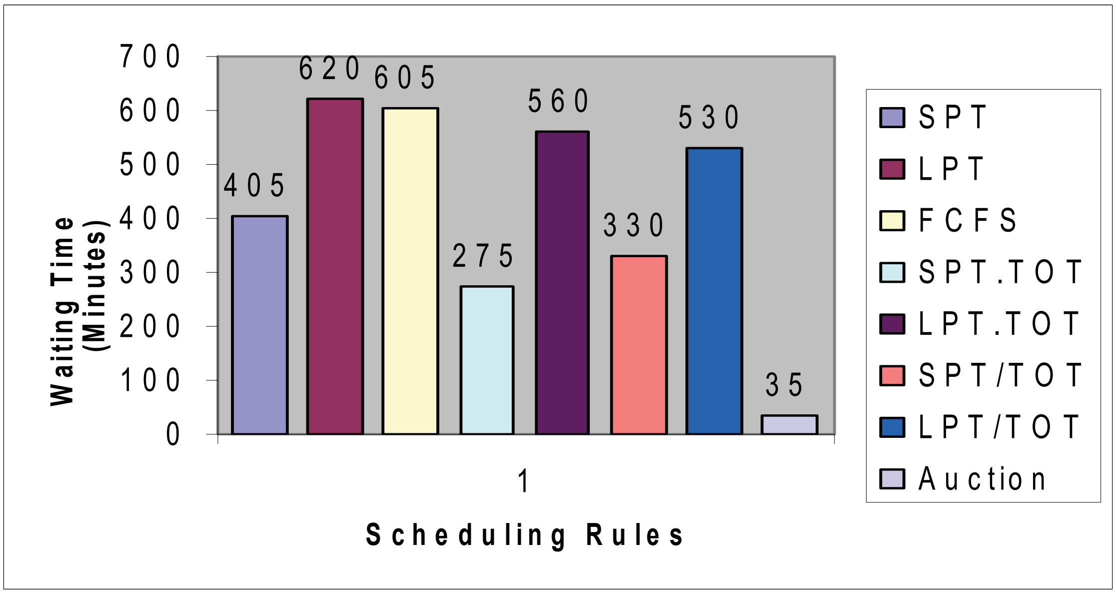


Figure5. Waiting time for various scheduling rules

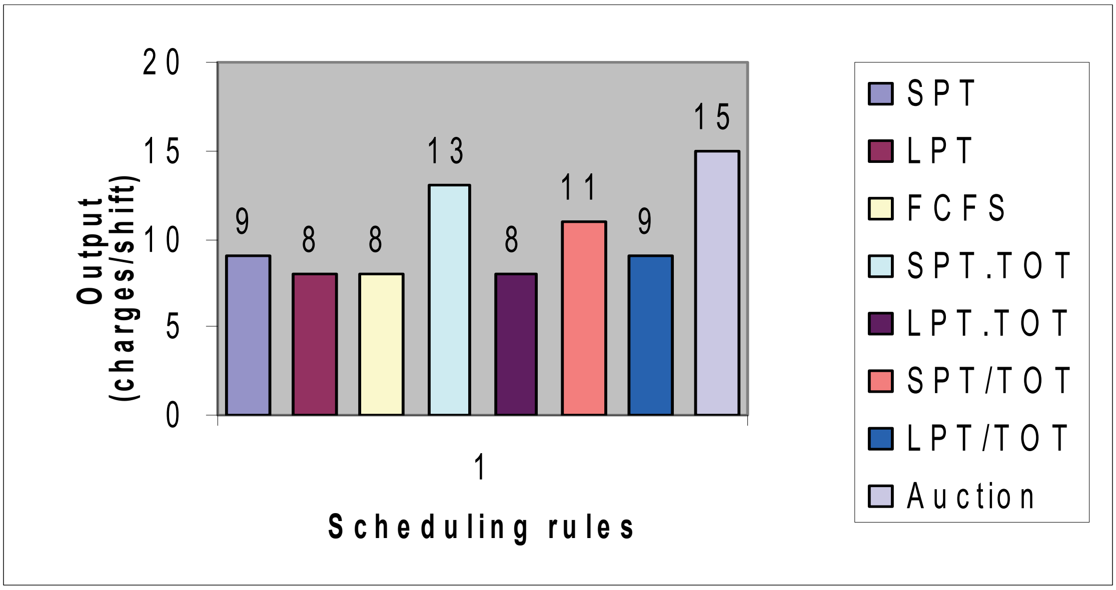


Figure6. Output for various scheduling rules

Table1. Processing time on various machines for different charges.

Charge	Unit processing time (in Minute)	Machine
1.	30	CON1
	10	REF1
	15	REF3
	30	CC1
2.	30	CON4
	15	REF1
	60	CC3
3.	45	CON4
	30	REF4
	30	CC3
4.	30	CON2
	45	REF1
	45	CC1
5.	30	CON4
	30	REF2
	30	CC4
6.	45	CON3
	30	REF3
	30	CC4
7.	30	CON4
	30	REF3
	60	CC1
8.	30	CON1
	15	REF3
	60	CC4
9.	30	CON2
	15	REF3
	30	CC2
10.	30	CON1
	15	REF3
	30	CC2

Charge	Unit processing time (in Minute)	Machine
11.	30	CON3
	30	REF4
	30	CC3
12.	15	CON2
	30	REF2
	30	CC2
13.	30	CON1
	15	REF4
	45	CC1
14.	30	CON3
	15	REF4
	30	CC2
15.	30	CON3
	30	REF2
	60	CC2

Where, CON1 = Converter 1, CON2 = Converter 2, CON3 = Converter 3, CON4 = Converter 4; REF 1= Refiner1, REF 2= Refiner2, REF 3= Refiner3, REF 4= Refiner4; CC 1= Continuous Caster1, CC 2= Continuous Caster2, CC 3= Continuous Caster3, CC 4= Continuous Caster4.

Table2. Detailed table for various charges.

Charge Number (Bidder $b_j(s)$)	Unit Processing Time (UT_{im})											
	C1	C2	C3	C4	R1	R2	R3	R4	CC1	CC2	CC3	CC4
1	30	0	0	0	10	0	15	0	30	0	0	0
2	0	0	0	30	15	0	0	0	0	0	60	0
3	0	0	0	45	0	0	0	30	0	0	30	0
4	0	30	0	0	45	0	0	0	45		0	0
5	0	0	0	30	0	30	0	0	0	0	0	30
6	0	0	45	0	0	0	30	0	0	0	0	30
7	0	0	0	30	0	0	30	0	60	0	0	0
8	30	0	0	0	0	0	15	0	0	0	0	60
9	0	30	0	0	0	0	15	0	0	30	0	0
10	30	0	0	0	0	0	15	0	0	30	0	0
11	0	0	30	0	0	0	0	30	0	0	30	0
12	0	15	0	0	0	30	0	0	0	30	0	0
13	30	0	0	0	0	0	0	15	45	0	0	0
14	0	0	30	0	0	0	0	15	0	30	0	0
15	0	0	30	0	0	30	0	0	0	60	0	0

Where, C1= Converter 1, C2= Converter 2, C3= Converter 3, C4 = Converter 4;
R1= Refiner1, R2= Refiner2, R3= Refiner3, R4 = Refiner 4;
CC1=Continuous Caster 1, CC2=Continuous Caster 2, CC3=Continuous Caster 3,
CC4 = Continuous Caster 4.

Table3. Machine scheduling rules

Machine scheduling rules (symbol)	**Description**
SPT	Shortest processing time
LPT	Largest processing time
FCFS	First come first served
SPT/TOT	Smallest value of operation time divided by total operation time
SPT.TOT	Smallest value of operation time multiplied by total processing time
LPT/TOT	Largest value of operation time divided by total operation time
LPT.TOT	Largest value of operation time multiplied by total processing time

Table4. Waiting time and output for various scheduling mechanisms

Scheduling Rules	Charge sequences															WT (minutes)	TH (charges/ shift)
SPT	14	12	10	9	1	5	11	13	2	3	6	8	15	4	7	405	9
LPT	4	7	15	2	3	6	8	11	13	5	1	9	10	12	14	620	8
FCFS	1	13	4	12	9	6	15	7	11	8	10	3	5	14	2	605	8
SPT/TOT	1	2	8	13	9	10	12	14	15	7	4	3	6	5	11	330	11
LPT/TOT	2	8	13	15	7	3	6	9	12	10	14	4	1	5	11	530	9
SPT.TOT	1	9	10	14	12	13	2	8	5	11	3	6	4	15	7	275	13
LPT.TOT	7	15	2	8	4	3	6	13	5	11	1	9	10	12	14	560	8
Auction Based	**13**	**1**	**6**	**9**	**10**	**3**	**5**	**8**	**12**	**11**	**4**	**2**	**14**	**7**	**15**	**35**	**15**

Where, WT = Waiting Time, and TH = Throughput

Table5. Comparative study of Auction-based approach with other scheduling rules

Scheduling rules	% Improvement
S P T	91.36
L P T	94.35
F C F S	94.21
S P T/ T O T	89.39
L P T/ T O T	93.39
S P T. T O T	87.27
L P T. T O T	93.75