Steel Production Methods Improvement Study

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Abstract

We present a three-phase, interdisciplinary study undertaken to improve methods of steel production within timing and capital investment constraints. The defined objective of this study was to increase the throughput of the hydrogen annealing process via assessment of various operating policies and resource levels. The three phases of the study successively involved work measurement project management, and discrete process simulation.

Keywords

Steel production, process improvement, work measurement, project management, discrete simulation.

Introduction

Economic and competitive pressures force industrial and process engineers to seek continuous improvement in industrial production processes [19]. In this paper, we describe the analytical methods used and the results achieved in a three-phase study undertaken to improve the hydrogen annealing process in the context of steel production.

The three phases of this study were sequential yet synergistic. The first phase used traditional methods of work measurement drawn from industrial engineering practice, such as process definition, development of flow charts, and data collection via time-and-motion studies [8, 14], to obtain a complete, quantitative understanding of current system operational procedures, work flow patterns, and location of productivity constraints. The second phase, a methods improvement study, built upon the understanding gained during the first phase. In the second phase, industrial and production engineers identified opportunities to improve throughput, with particular attention to those opportunities requiring relatively low capital investment. The principal analytical tools used for this phase were the operations research techniques of project management [6] and heuristic scheduling [13], to identify both critical paths within work flow and utilization imbalances among system resources. The third phase, a discrete process simulation study, assessed the relative merits of all promising improvement opportunities. In this phase, analysts applied methods of simulation modeling and inferential statistics to the output of a "replica" of the system as constructed using a software modeling tool. These methods assess proposed improvements relative to sources and magnitudes of stochastic variability within the system [20]. Therefore, the analyses of simulation results helped the analysts provide highly robust recommendations relative to plausible future changes, irrespective of whether those changes are internal (e.g., availability of new manufacturing equipment and technology), or external (e.g., changes in demands upon the system caused by shifts in the market).

In this paper, we first describe the original hydrogen annealing process and the metrics used to judge proposed improvements to it. We then present the three phases of this improvement study, with particular attention to their synergistic interrelationships and flows of data from one phase to the succeeding phase. Next, we describe the recommendations provided by the study and the observed results of implementing those recommendations. The conclusion draws lessons from this study and indicates promising directions for future work.

The Hydrogen Annealing Process and Desired Improvements

Hydrogen annealing, the final finishing step for steel coils prior to shipment governs mechanical properties such as yield strength and hardness via control of grain growth within the steel. Specifically, hydrogen dissolved in molten steel may cause internal cracks ("flakes") to form as the steel cools from the hot-working operation. Annealing at 600-650° Celsius for several days, followed by slow cooling, eliminates this danger by_reducing hydrogen content [21]. This process of heating and cooling under precisely controlled environmental conditions requires heavy capital investments in bases, furnaces, cooling hoods, and material handling equipment.

In the heating process, twenty-ton coils arrive on automatic guided vehicles (AGVs) from the rolling mills. The annealing recorder specifies groups of (typically) three or four coils using criteria of steel on hand, cycle compatibility relative to steel chemistry and end-product destiny of the coil, and delivery-date requirements. An overhead crane stacks these coils on a base, picks up a furnace from floor storage or a currently vacant base, and lowers the furnace over the stack of coils. After attachment of natural gas and control lines, the furnace heats the coils for twenty-five to forty hours. Then, after detachment of the lines, the crane lifts the furnace away from the coils stacked on the base. Next, in the cooling process, the overhead crane places the cooling hood over the stack. After a cooling cycle of approximately twenty hours, the crane removes the cooling hood, and the coils are unloaded to a truck or the floor for subsequent shipment.

Managers identified the hydrogen annealing step as the bottleneck within the steel production process because of inadequate throughput, the large number (120 or more) of coils awaiting annealing, and high average waiting time of those coils. System improvement metrics were increasing throughput and reducing both the number of waiting coils and their wait time. Specifically, since the coils inevitably rust while waiting, four days was specified as the maximum acceptable waiting time.

Phase One: Work and Process Measurement

The data collection and process assessment of phase one were undertaken by traditional direct observation, activity categorization, and work-measurement methods [5]. Engineers stationed in the plant on a seven-day week, twenty-four-hour day basis developed process Gantt charts and calculated resource utilizations. A comparison of throughput achieved during the week of intensive observation with throughput logged during each of the previous seven weeks confirmed lack of the Hawthorne effect [10]: the act of observation neither raised nor lowered throughput. The bases spent 57% of time heating, 28% of time cooling, 11% awaiting furnace, and 4% (un)loading, (dis)connecting fuel lines, or awaiting a load (hence 85% productive time). The furnaces achieved even higher utilization, 98%, and the cooling hoods, 84%. In sharp contrast, the crane/hooker utilization per base was only 2%, with 98% idle time.

During this work and process measurement, observers noted that outgoing shift personnel typically do not begin any tasks (e.g., preparation of base, (un)loading, or placement of a furnace or cooling hood on a base) that cannot be completed before the personal “wash-up" time granted in the closing minutes of a shift. Such tasks are deferred to the beginning of the subsequent shift.

Significant randomness of system behavior, much of it attributable to high variability of product mix, was also observed; for example, during the week of intensive observation, there were times that one base awaited a furnace, times that two bases each awaited a furnace, and times that one base awaited a cooling hood. When the system runs many short-cycle coils, two bases may each be awaiting a cooling hood at times. This randomness alerted the engineers that process simulation, in addition to "closed-form" analytical techniques, would be a required tool during the third phase of the study [4]. These observations were consistent with the observation that heating and cooling times are measured in hours or days, whereas material-handling times are measured in minutes. Therefore, the engineers concluded that no change in the load/unload process could yield much improvement in throughput. On the other hand, the significant proportion of time bases spent waiting for furnaces provided the first hint of a promising improvement opportunity.

Phase Two: Methods Improvement Study

Next, techniques of project management and workflow analysis were used to identify recommended alternatives for evaluation using the data collected in the first phase. The analysts compared the current furnace/cooling hood/base ratios to those that would be ideal for a given product mix. If the product mix yielded a higher percentage of 40-hour heating cycles, then a higher furnace-to-base ratio would be required. Conversely, a product mix yielding a higher percentage of 25-hour heating cycles would require a higher cooling hood to base ratio. The analysts assumed that due to the randomness inherent in the system and given a steady-state system, an individual base heating/cooling cycle was essentially independent as long as sufficient heating and cooling hoods were provided. This assumption was validated by statistical analysis of actual system performance. Under this assumption, if the heating and cooling cycle intervals are equal, then the number of furnaces and cooling hoods should also be equal. This indicated that the percentage of time a furnace is required for a single base is proportional to the furnace/base ratio. The ideal furnace/cooling hood/base ratios were then calculated for a range of heating cycles. The analysis of these results, coupled with the observations of very high furnace utilizations and significant durations of "base -waiting for furnace" times, indicated that the alternative most deserving of detailed evaluation was adjustment of furnace/cooler/base resource levels and further, that this evaluation should be based upon a long-range forecast of product demand mix.

Given a fixed number of bases, determination of a heuristic for loading and scheduling strategies depended on two main factors: the forecasted product demand and the primary resource constraints. If furnaces and cooling hoods are constrained, then the focus of the heuristic should be achievement of an average cycle time coinciding with the furnace/cooling hood/base ratio, to achieve a schedule yielding, maximum utilization of these resources (sequencing problem [1]). On the other hand, if furnaces and cooling hoods are unconstrained relative to any conceivable product mix, then the focus of the heuristic should be selection of coils constituting loads (selection or load problem [18]). Therefore, the analysts reemphasized the importance of long-range forecasts of consumer demand to management and subordinated the choices of scheduling heuristics to be evaluated to the investigation of primary resource levels (previous paragraph).

Last and least, the impact of current shift change practices on total system throughput appeared minor, rarely causing even brief delay due to the long heating- and cooling-cycle times. A comparison of system performances under current practice (if the work cannot be completed before wash-up, it is deferred to the next shift) and the alternative (turnover is on-the-job, even if mid-move) was relegated to the contingency that a subsequently chosen upgrade of furnace, cooling hood, and base levels might cause a marked rise in personnel utilization levels.

Phase Three: Discrete Process Simulation

In the third phase, the SIMAN™ simulation language [15, 17] was used to construct a model of the system based on fourteen months of historical data on product mix, heating cycle times, cooling cycle times, load sizes, and arrival patterns. The elements of this simulation model, all within the boundaries of the hydrogen annealing system, were the work in process (coils of steel), the bases, furnaces, and coolers (value-adding resources); and the crane, hooker, and AGVs (material-handling equipment). This model was verified by use of structured walkthroughs and detailed examination of model execution traces [23].

To validate this model [2], it was run with parameters of the current system for comparison with observed performance. Additionally, the model was later rerun with "extreme" loading strategies to check that output performance measures changed in the expected direction. For example, batches would never be ordered by shortest processing time (SPT) in practice because large batches would rust while waiting behind newly arrived smaller batches. Nevertheless, such experimental runs provided additional validation, plus indications of any system sensitivity to choice of loading policy. After validation, the model was modified to hypothesize implementation of the most promising improvements identified in the second phase of the study.

Observational data obtained from the first phase of the study was then fitted to appropriate probability distributions (triangular and normal for batch sizes; gamma, lognormal, and Weibull for heating and cooling cycle times). The intuitive appeals of the triangular and normal for batch sizes were high due to their tight lower and upper bounds and their resemblance to histograms of observed data. Likewise, the intuitive appeals of the gamma, lognormal, and Weibull for cycle times were high due to their lack of symmetry, "minimum < mode < mean" relationship, and their slender but long upper tails. Use of the Kolmogorov-Smirnov and Anderson-Darling goodness-of-fit tests available within the UniFit™ (now ExpertFit™ [24]) software tool corroborated intuition.

Since the system was inherently a steady-state, not a terminating system, experimental runs were made with a one-week warm-up time, chosen due to (a) client comments that any unusual events within the actual system dissipated within a week, and (b) examination of graphs of performance metrics versus time, which reached steady-state within a week. After the lapse of the warm-up time and clearing of statistics, the model steady-state runs simulated one year of actual time. To achieve sufficiently narrow confidence intervals for prediction at the $\alpha = 5\%$ level chosen by client management, six independent replications of each scenario were run. Predicted means from the replications of the base scenario (current process operation) agreed with observed means well; all relative errors were less than 2 ½% and all observed process metrics lay inside the confidence intervals. This agreement of the model with the current real-world system achieved model credibility with client engineers and managers.

Study Recommendations and Results

After validation of the simulation model and experimental runs of the validated model, the study produced the following quantitative results:

Table 1 -. Throughput Increases Available

Scenario	Furnaces	Bases	Cooling Hoods	Throughput Increase (%)
Base	8	14	6	n/a
1	9	14	6	11%
2	10	17	7	35%
3	11	17	7	40%

Hence, from management's point of view, the quickest and easiest significant increment of throughput was achievable via the addition of one furnace. Also, managers had been planning to add three bases anyway, and valued the predictions of throughput increase achievable by adding those bases plus different numbers of furnaces and cooling hoods.

Additional results important to ongoing planning and process improvement efforts were:

- throughput is independent of the queuing discipline used for incoming batches; therefore FIFO, which typically provides a minimax of waiting time [7, 16], is best used to reduce rusting of coils; intuitively, FIFO is "fair" to each coil, and additionally is easy to implement [11]

- as long as product mix tends to longer heating cycles, always consider an additional furnace before new bases
- given current and typical variations in product mix, it is reasonable that the number of furnaces plus the number of cooling hoods exceed the number of bases (this possibility had never been considered prior to the study)
- projected increases in demand with_no system expansion would result in out-of-control queue lengths, primarily due to the constraint imposed by the current number of bases
- no changes in material handling warrant consideration unless and until more than a 50% increase in base capacity is considered.

Lessons Learned and Directions for Future Work

Since utilizations of bases, furnaces, and coolers were currently high, and remained so in the promising upgrade alternatives listed in Table 1, there is as yet little opportunity to improve throughput by load sequencing as examined during the second phase of the study. However, the "load selection" problem is as yet quantitatively uninvestigated and provides opportunity to increase throughput by maximizing the weight of individual loads placed upon the bases for heating and cooling cycles. Approaches for improving individual load weight will be investigated relative to their abilities to (a) meet customer specifications for coil widths and delivery dates, and (b) enhance control or predictability of coil availability from the upstream mill. Since empirical estimates indicate that a 10% increase in average load weight would increase throughput by 18,860 tons annually, the load selection problem represents a promising opportunity for further productivity increases. Load selection analysis can be integrated with the scheduling analyses already undertaken, using the integrated-model approach described in [9].

Currently, the scheduling (phase two) and simulation (phase three) studies of this system use separate but interfacing software tools. Advancing software technology buoyed by the object-oriented paradigm, however, is making, integration of production-floor scheduling and simulation analyses within an integrated suite of software tools rapidly more attractive [3].

As learned during the second phase of the study, a qualitative examination of labor allocation is not yet warranted. Should that examination become necessary by virtue of markedly increased personnel utilization levels, an integer programming model presented in [22] is available to begin it.

Management is eager to "aggregate" this study, i.e. extend it beyond the boundaries of one plant to include upstream suppliers of raw materials and downstream consumers of plant production (the steel coils). Such aggregation, using the same analytical tools already used here in one plant, helps broad-scale optimization of both materials availability and capacity planning decisions to increase bottom-line benefits [12].

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Appendix

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