A Dynamic Cost Model for the Effect of Improved Process Flexibility in Steel Plants

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Abstract

Reduced setup times in the rolling mill generate flexibility which allows shorter leadtimes through continuous casting and hot rolling. Traditionally known as schedule-free rolling, this flexibility allows the rolling mill to handle variations without the need for buffering. Cost models based on system dynamics methodology are used to assess the economic potential. Effects on inventory, energy and work roll consumptions are analysed. The simulation results show that investments in flexible processes can be evaluated with dynamic cost models. There is an opportunity for significant cost reduction, but also lowered environmental impact due to reduced energy consumption.

Keywords:

Hot rolling; Setup time reduction; Cost estimation

1 INTRODUCTION

This paper presents a model for the influence of setup time reductions in the hot rolling mill (HRM) on manufacturing costs in steel production. The model concerns an integrated steel mill with continuous casting (CC) and hot rolling of slabs for production of stainless steel strip. Setup time reduction is a generally recognised method to gain the flexibility needed for one-piece just-in-time (JIT) flow [1,2,3]. However, as noted by Nye et al. [4], most authors follow the advice of Shingo [5] and recommend that changeover times are reduced to less than 10 minutes. The actual relation between setup times and production performance has not been much discussed and it is not clear how large investments in setup time reduction that can be economically justified.

Steel production is a very capital and energy intensive business, and producers must take every opportunity to reduce manufacturing cost. If the meltshop/CC processes are isolated from the rolling mill through buffering, this will cause the average leadtime for workpieces (**slabs**) to be longer than in a process with less buffering [6]. Slabs cool more the longer they are stored, and the heat from the melting process is lost. Decoupled operation of meltshop/CC and HRM is thus known as **cold charging**, since slabs are cool when they enter the rolling mill. The opposite, i.e. integrated production with short lead times, is known as **hot charging**.

The economic potential in setup time reduction is mainly due to energy savings when transfer times are short between meltshop, CC and HRM. It was previously reported [7] that setup time reduction may facilitate savings in the order of 4 EUR/ton even when no measures are taken to reduce work roll consumption due to the increased amount of roll conditioning. This represents a total a cost reduction of 4 MEUR on a yearly production of one million tons, translating directly into increased profit. If work rolls are utilised more efficiently the potential is even bigger, an issue that will be discussed in the present paper.

1.1 The role of flexibility

When many different products are made in the same production line, the need for quick changeovers arises to allow production to rapidly shift to the product currently in demand. Browne et al. (cited in [8]), termed this **process flexibility**, i.e. 'the ability to produce a given set of part types'. Process flexibility in the context of steel production can be interpreted as the ability, at any given time,

- of the meltshop to produce a particular steel grade,
- of the continuous caster to cast a particular steel grade and slab geometry,
- of the hot strip mill to roll a slab of a particular grade, width and thickness into the desired target thickness.

Setup times in a modern hot strip mill as seen in Figure 1 are typically in the order of 15 minutes, but it is not unusual that setups in older mills are in the order of one hour or more. If a

Figure 1: Hot strip mill with replacement roll pair ready.

modern finishing mill is paired with an older roughing mill, overall production planning will be controlled by the flexibility of the older (less flexible) mill. It becomes the job of production planning to ensure efficient resource utilisation on expense of increased buffering and leadtimes.

Extensive research has been done on production scheduling in steelmaking. Lee et al. [9] reviewed scheduling research until 1995. Dorn and Shams [10] implemented an expert system at Böhler Uddeholm in Austria. More recently Tang et al. presented optimisation models for meltshop/CC [11] and hot rolling [12], while Cowling and Rezig [13] presented an optimisation model for integrated scheduling of meltshop/CC and HRM. Singh et al. [14] presented an optimisation model for minimising material handling in the slab yard.

Production scheduling aims to produce schedules that e.g. maximise equipment utilisation and charging temperature while minimising buffering and work roll consumption. The above cited examples of scheduling research show that there is a potential for improvement which can be realised through advanced production scheduling algorithms. However, the quality of an optimal schedule deteriorates as the number of grades and geometries increases, i.e. in plants that produce a large number of low volume high-grade products.

Instead, the constraints on job order can be relieved if each process step can be made more flexible, with the ability to adapt to the current situation. Buffer levels and leadtimes may then be reduced [6]. We argue that inflexible processes is a major source of waste in steel production, and that setup time reduction and similar investments in improved flexibility should have the highest priority for steel producers.

1.2 Problem structure

The conceptual problem, shown schematically in Figure 2, is to relate operating conditions in the plant to manufacturing costs. Figure 2 does answer how this should be done; it only shows some of the considered process parameters, and the division of costs into three components: gas for reheat furnaces (energy), tied capital (inventory/WIP) and work rolls.

In the following sections we present two models based on the **system dynamics** methodology [15,16]. System dynamics (SD) is a generic method for describing complex causal relations with stocks and flows [16], which are visualised as **causal loop diagrams** (CLD). The method is based on continuous simulation [17], with an emphasis on feedback structures. The models presented in this paper are implemented and run in the Vensim® simulation environment.

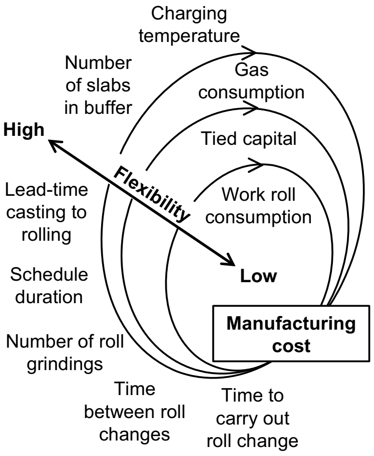

Figure 2: Structure of the cost model. The level of process flexibility balance costs for work roll consumption against buffering and reheat energy.

The first model, which is described in [7], is called the **basic model**, and estimates the cost of WIP, reheat energy and work rolls without respect to the dynamics of manufacturing over time. As shown schematically in Figure 2, this model accounts for the costs of;

(a) **Energy**: If leadtime and buffering is reduced, some heat from the melting and casting is preserved, and the mean temperature of slabs entering the rolling mill increase. Since slabs must hold about 1250°C during hot rolling, and reduced leadtime allow fuel consumption in the reheat furnaces to be lowered.

(b) **Material**: The amount of WIP and hence tied capital is reduced, which is of particular interest to producers of stainless steel due to high raw material prices.

(c) **Tools**: Increasing the number of roll changes also require more frequent conditioning of the work roll surface. This may result in raised overall roll consumption, hence causing the tool costs to increase.

The second, more elaborate model, is called the **dynamic model**, and is discussed in detail in [18]. It is in effect a manufacturing simulation model designed to predict resource consumption during production, and to produce hourly cost rates during a simulation run. As with the basic model, the dynamic model is used to predict costs that arise from WIP, reheating and work roll consumption. The principles behind this are presented in the following section. Details specific to the basic and dynamic models will be discussed in Section 3 and 4 respectively, while the simulation results are presented and analysed in Section 5.

2 WIP, ENERGY AND WORK ROLLS

According to Little’s law [2], the amount of WIP is the product of throughput (tons/h) and the average cycle time. If all workpieces that are scheduled for rolling within the next HRM program are temporarily stored in the slab yard while the preceding program is processed, the average transfer time becomes equal to the duration of the HRM program, i.e. the time between roll changes (setups).

The cost of tied capital is defined as the internal interest rate of return on WIP. If the amount of WIP and the material price is known, this can be readily calculated. The material price depend on raw material prices and is at present around 3000 EUR/ton for an 18% Cr, 8% Ni stainless steel. For a throughput of 100 tons/h, and 10 h between roll changes, average WIP becomes 1000 tons. This yields 3 MEUR in yearly interest on tied capital for a 10% internal rate of return.

Energy costs cover only fuel consumption in the reheating furnace of the HRM. The energy required to reheat a workpiece to rolling temperature can be estimated if the initial and final temperatures are known along with the geometry and boundary conditions. A relation between lead time and workpiece temperature was found [18] through simulated cooling in STEELTEMP® [19]. If transfer time from casting to rolling is 6 h, workpieces hold about 500°C on arrival to the rolling mill. The actual fuel consumption will then depend on e.g. furnace efficiency and the reheat cost follows from gas

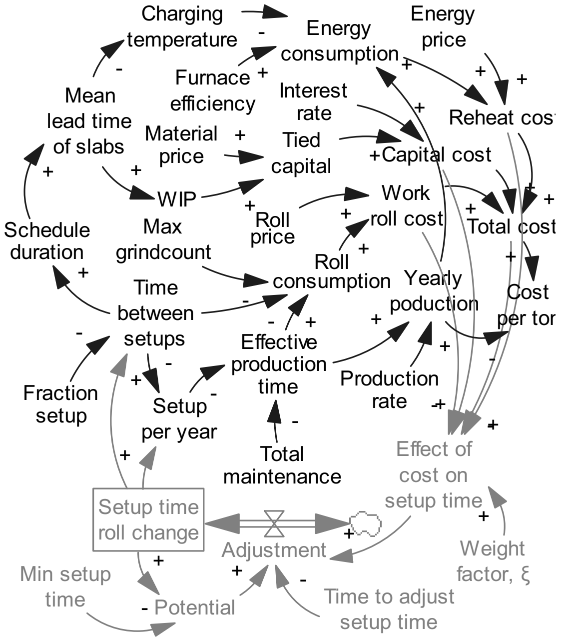

Figure 3: Causal loop diagram for the basic cost model.

price and consumption based on heat content, charging temperature and furnace efficiency.

The work roll cost is a consequence of roll wear due to frictional and thermal forces during rolling [20,21]. The rolls are therefore conditioned in a roll grinding machine after each roll change. Work rolls normally have a cast iron core covered by a steel surface. When the surface layer has been worn down the roll pair is scrapped and replaced. Provided that throughput is 100 tons/h and that a 0.5 h changeover is initiated every 10 h, production during one program is 950 tons. If a roll pair lasts 40 grindings and costs 0.1 MEUR, the approximate work roll cost becomes 2.6 EUR/ton.

The actual relation between roll wear and operating conditions is complex, and Munther and Lenard [20] concluded that the wear depends on process parameters such as temperature, velocity, load and geometry, but also that the material properties of the rolls and the rolled metal are of equal importance. Still, experiments by Pellizzari et al. [21] indicated that after a transitory running in period, wear was in effect proportional to the rolled distance. It therefore seems reasonable to make the assumption that wear is proportional to the production volume (tons).

A fundamental assumption in both models is that the total amount of setup is constant even though the duration of a single setup can change. Hence, if the setup time can be decreased through investment in setup time reduction, more frequent roll changes can be carried out while the total fraction of setup is unchanged. This results in less buffering and shorter lead times since the average time that slabs wait for the previous program to be completed is shortened.

Rolling mill schedules are designed by selecting workpieces that can be processed in sequence during a single setup of the mill [9]. A schedule lasts from one roll change to the next, and it is assumed that all workpieces which are to be rolled within the next schedule must be produced in advance and buffered while the current program is completed. Hence, the average amount of WIP depends on the setup time, and the dynamics of the entire model can be controlled by altering the setup time in the rolling mill.

3 THE BASIC MODEL

The basic model implements the cost equations in an SD model, the CLD of which is seen in Figure 3. This model can be compared to the conceptual model in Figure 2. When executed, it runs through a transient period as it converges against equilibrium due to a negative feedback loop where the setup time is adjusted based on the cost distribution.

The relative size of cost components is controlled by the parameter ‘effect of cost on setup time’, seen in the lower part of Figure 3. The balance between capital costs and reheat energy on one hand and work roll consumption on the other is adjusted through the weight factor, ξ. Changing ξ corresponds to altering the flexibility; an increase reduces buffering and lead times, i.e. capital and reheat costs, while a decrease reduces work roll consumption (cf. Figure 2).

The basic model assumes that a roll pair lasts for a given number of changes and that the grinding depth during conditioning is unchanged when the frequency of roll changes increase. The rolls may therefore have to be scrapped unnecessarily often, causing the work roll cost to increase sharply for quick setups with frequent roll changes.

4 THE DYNAMIC MODEL

The dynamic model can be used to simulate production over extended periods, e.g. several months. The output includes hourly estimates of the power and energy consumption in the reheat furnace, throughput in the rolling mill and build-up and depletion of WIP in the slab yard. The model is described in detail in [18], but some of its main features are discussed in the following paragraphs.

The dynamic model targets some of the limitations in the basic model mentioned in [7], namely:

- Leadtimes and WIP depend on the current state of the model and vary over time in response to events such as roll changes and maintenance stops.
- It accounts for actual roll wear and adjusts the amount of conditioning depending on produced volume on the current roll pair.

The excess conditioning of the work rolls that occur in the basic model with increased setup frequency (cf. Section 3) is handled by lowering the grinding depth to compensate for the reduced wear. The extent to which this is done is controlled by the **grinding efficiency**, which is introduced in the model as seen in Figure 4. The parameter ‘rolling rate’ in this figure

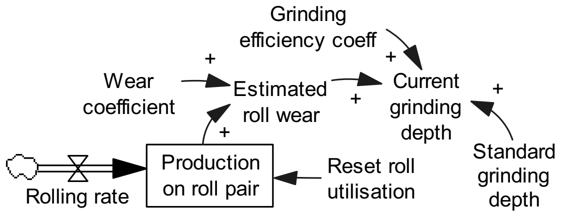

Figure 4: Estimation of roll wear and grinding depth in the dynamic model.

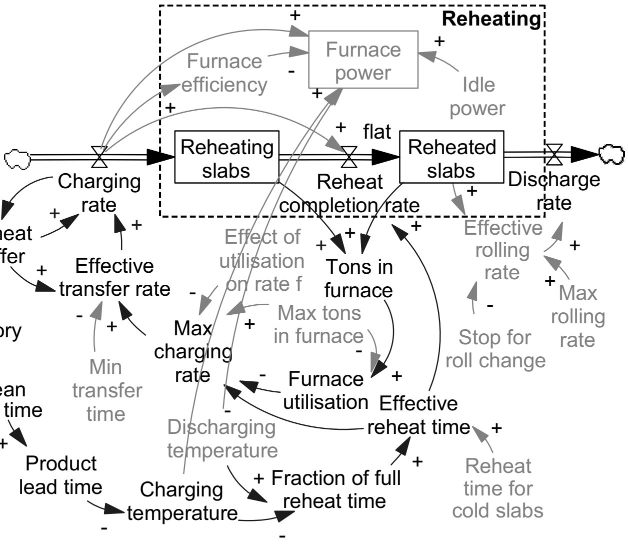

Figure 5: Causal loop diagram of the reheating process in the dynamic cost model.

is equal to the ‘discharge rate’ of Figure 5. The ‘current grinding depth’ is a fraction of a standard grinding depth which follows from the maximum number of grindings that a roll pair is estimated to last, i.e. ‘max grindcount’ of Figure 3.

The part of the CLD representing the rolling mill reheat furnace is shown in Figure 5. Reheating is modelled as a two stage process, where cold slabs are turned into hot slabs with a rate that depends on the time needed to reach rolling temperature. This ‘effective reheat time’ (Figure 5) is a function of the charging and discharging temperatures. The discharging temperature is set to the rolling temperature (1250°C), while the charging temperature depends on the cooling time, i.e. the leadtime from casting to rolling.

Energy consumption is calculated from the furnace power which, as seen in Figure 5, depends on the charging rate (tons/h), as well as on the initial and final temperatures. The charging rate in turn depends on current furnace utilisation and effective reheat time.

5 RESULTS AND DISCUSSION

The dynamic model was used to simulate 20 weeks of production with a time step of 0.0625 h (3.75 min) for 126 different combinations of setup time and grinding efficiency. The experiment covered 21 different setup times in the range from 0.05 to 1.5 h, while six different values of the grinding efficiency coefficient, ranging from 0 to 1, were used. Material price was set to 3000 EUR/ton (cf. Section 2), and the energy price was 50 EUR/MWh. Each run resulted in one value per cost component. The results from all these runs were aggregated to produce the plots of Figures 6, 7 and 8.

Two extremes were considered; that the grinding depth is the same regardless of rolled volume, or that it is proportional to the rolled volume. Figure 6 shows the costs of work rolls, reheating and tied capital for the case of constant grinding depth. As seen in the figure, the contribution of work roll costs increase dramatically for low changeover times (i.e. frequent changeovers). This corresponds to the results of the basic model reported in [7].

If proportional wear and grinding is assumed, this results in constant work roll cost irrespective of the changeover frequency. In the ideal case, conditioning removes only the wear that actually occurred since last setup, essentially only a touch up of the surface finish when the rolls are changed very often. Figure 7 shows the cost components as function of setup time under these conditions.

In reality, it is unlikely that the ideal of Figure 6 can be achieved. The actual amount of conditioning can be expected to fall between the cases in Figures 6 and 7. Figure 8 shows

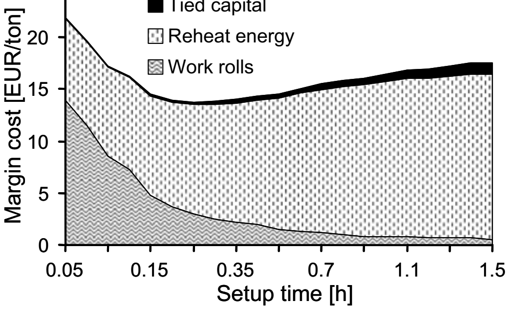

Figure 6: Cost as function of setup time in the dynamic model with constant roll grinding (q=0).

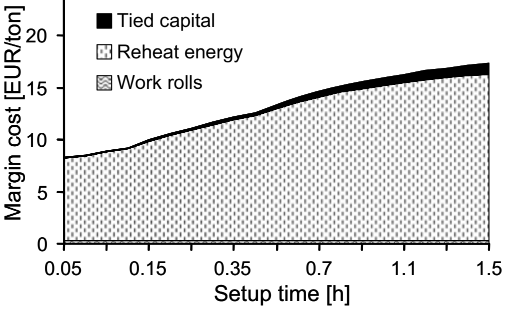

Figure 7: Cost as function of setup time in the dynamic model with ideal proportional roll grinding (q=1).

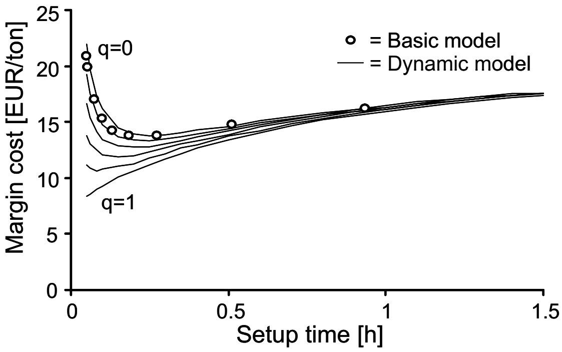

Figure 8: Total cost for the two models. q indicate grinding efficiency (constant=0, ideal=1) in the dynamic model.

the sum of the cost components based on the results of the dynamic model for constant grinding as well as for the ideal and intermediate proportional grinding cases. Figure 8 also includes the results from the basic model, which can be seen to correspond well with the case of constant grinding depth in the dynamic model. The real outcome of an investment in improved process flexibility can be expected to be represented by an intermediate curve, depending on to what extent unnecessary conditioning can be avoided.

As shown in Figure 6, and in accordance with [7], setup time reduction for the case of fixed grinding depth (Figure 8, q=0) give a maximum 21% cost reduction of 3.7 EUR/ton at 0.25 h setup compared to a margin cost of 17.5 EUR/ton at 1.5 h setup; in itself a considerable improvement. If proportional grinding is employed, i.e. any of the curves representing q>0 in Figure 8, further cost reductions are possible. The case of ideal proportional grinding (Figure 7 and Figure 8, q=1), allows a total 47% cost reduction, or 8.2 EUR/ton at 0.1 h setup. The savings potential at 0.25 h setup is 6.4 EUR/ton, i.e. 37% of the cost at 1.5 h setup time. Hence, a mill with one million tons yearly production may increase its revenue by 8 MEUR per year.

Throughout this paper it was assumed that improved flexibility is achieved through setup time reduction. However, the same problem is traditionally targeted in **schedule free rolling**, which can be accomplished in several ways. One is to use inline roll grinding [6], constantly refreshing the work roll surface. Another option is to use very durable work rolls, and change these before any pronounced wear contour develop. The investment in quick setups is thereby replaced by investment in more expensive work rolls. In practice, a combination of both may be of interest.

Results from a run with 1.5 h setup time and 30 h mean schedule duration are shown in Figure 9. The upper plot

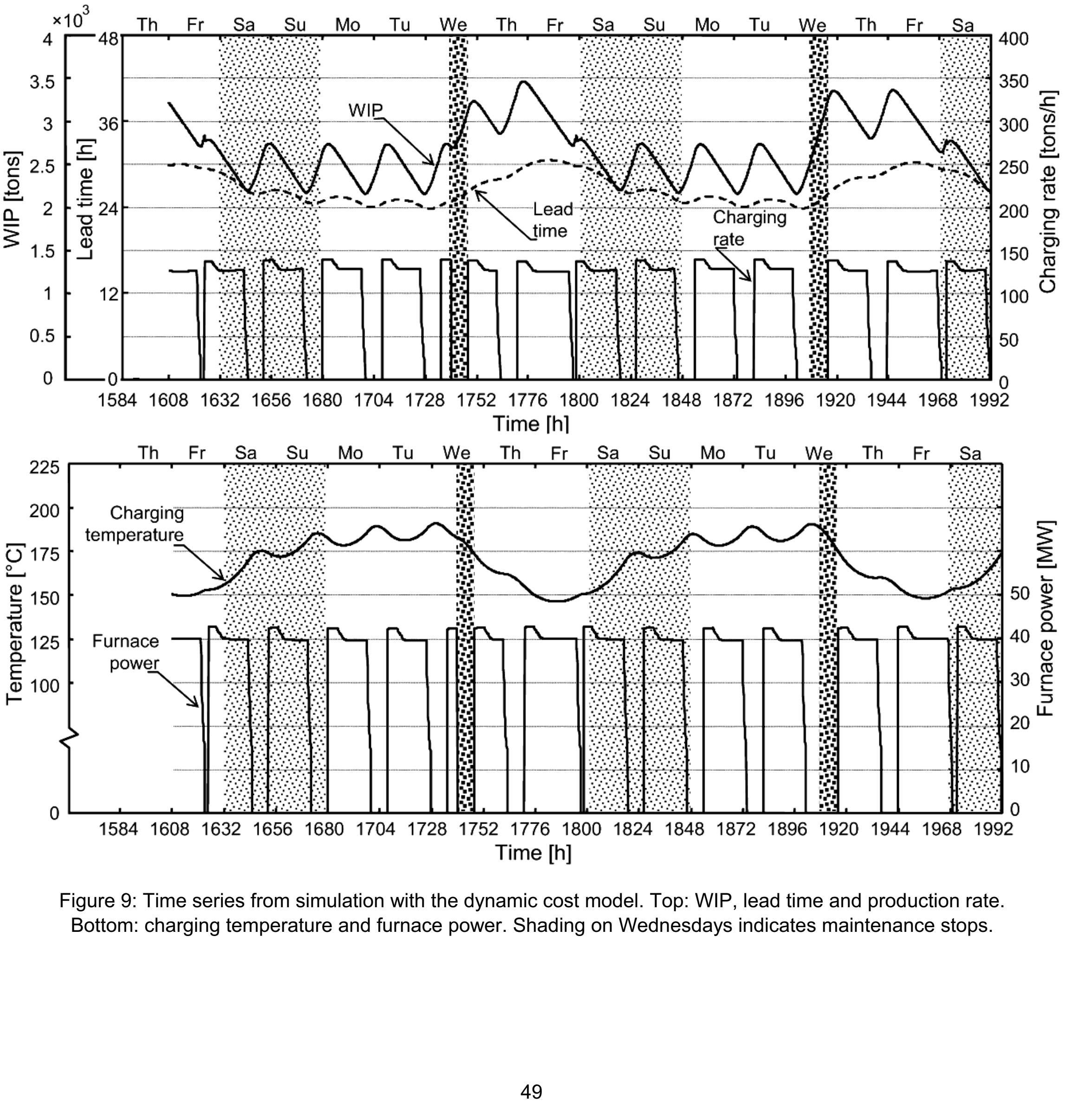

Figure 9: Time series from simulation with the dynamic cost model. Top: WIP, lead time and production rate. Bottom: charging temperature and furnace power. Shading on Wednesdays indicates maintenance stops.

shows WIP, cooling time and throughput over two weeks starting about 10 weeks into the simulation, while the lower plot shows charging temperature and furnace power for the same period. Roll changes are carried out in the periods when charging rate is zero. These periods also correspond to completion of the previous and initiation of a new rolling mill schedule. The amount of WIP varies from 2200 tons to 2500 tons, a variation that is mainly caused by the scheduling mechanism. The magnitude of this variation grows when the time between scheduling events increase, i.e. with longer setup times. Since variation is buffered by some combination of inventory, capacity or time [2], reducing setup times has an overall beneficial effect. This is shown by the results presented in this paper.

6 CONCLUSIONS

Scheduling requirements for the hot strip mill were conceived to ensure maximum utilisation of the work rolls and minimise the number of roll changes in order to maximise utilisation of the mill. They are the result of a strong focus on roll economy, and reflect the assumption that

- setup times are fixed and unalterable, and
- the cost of energy and tied capital is small in comparison to the cost of work rolls.

Two models for estimation of the effect of setup time on manufacturing cost in continuous casting and hot rolling of steel were presented. The main findings were:

- Setup time reduction and more frequent roll changes can reduce manufacturing costs significantly.
- Quick setups allow more frequent changes and shorter rolling mill programs, which stabilises WIP on a lower level with less variation.

The savings potential is mainly due to reduced energy consumption. As previously stated [7], increasing energy prices are a strong incentive for improved manufacturing flexibility and shorter setup times.

Based on the results of the models presented in this paper, the claim that inflexible processes is a major source of waste in steel production seems to be justified. Setup time reduction and similar investments in improved flexibility should therefore gain higher priority for steel producers in their future attempts to improve competitiveness.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] Ohno, T., 1988, Toyota Production System: Beyond large-scale production, Productivity Press, New York.

[2] Hopp, W.J., Spearman, L., 2000, Factory Physics: Foundations of manufacturing management, 2nd ed., Irwin/McGraw-Hill, New York.

[3] Liker, J.K., , 2004, The Toyota way: 14 Management principles from the world's greatest Manufacturer, McGraw-Hill, New York.

[4] Nye, T.J., Jewkes, E.M., Dilts, D.M., 2001, Optimal investment in setup reduction in manufacturing systems with WIP inventories, Eur. J. Oper. Res., 135:128-141.

[5] Shingo, S., 1985, A revolution in manufacturing: The SMED system, Productivity Press, Cambridge, MA.

[6] Storck, J., Lindberg, B., 2007, A lean production strategy for hot charge operation of a steel mill, Proc. of the 2007 IET Int. Conf. on Agile Manufacturing (ICAM'07), 158-167, 9-11 July 2007, Collingwood College, Durham University, Durham, U.K.

[7] Storck, J., Lindberg, B., 2007, A cost model for the effect of setup time reduction in stainless steel strip production, Proc. of the 1:st Swedish Production Symposium, Stahre, J. (Ed.), Chalmers University of Technology, Göteborg.

[8] De Toni, A., Tonchia, S., 2005, Definitions and linkages between operational and strategic flexibilities, Omega, 33:525-540.

[9] Lee, H.S., Murthy, S.S., Haider, S.W., Morse, D.V., 1996, Primary production scheduling at steelmaking industries, IBM J. Res. Dev., 40/2:231-252.

[10] Dorn J., Shams, R., 1996, Scheduling high-grade steelmaking, IEEE Expert, 11/1:28-35.

[11] Tang, L., Liu, J., Rong, A., Yang, Z., 2000, A mathematical programming model for scheduling steelmaking-continuous casting production, Eur. J. Oper. Res., 120:423-435.

[12] Tang, L., Liu, J., Rong, A., Yang, Z., 2000, A multiple traveling salesman problem model for hot rolling scheduling in Shanghai Baoshan iron & steel complex, Eur. J. Oper. Res., 124:267-282.

[13] Cowling, P., Rezig, W., 2000, Integration of continuous caster and hot strip mill planning for steel production, Journal of Scheduling, 3:185-208.

[14] Singh, A.K., Srinivas and Tiwari, M.K., 2004, Modelling the slab stack shuffling problem in developing steel rolling schedule and its solution using improved parallel genetic algorithm, Int. J. Prod. Econ., 91:135-147.

[15] Forrester, J.W., 1961, Industrial Dynamics, MIT-press, Cambridge, MA.

[16] Sterman, J.D., 2000, Business Dynamics: Systems thinking and modeling for a complex world, Irwin/McGraw-Hill, New York.

[17] Law, A.M., Kelton, W.D., 2000, Simulation modelling and analysis, 3rd ed. MacGraw-Hill Int.

[18] Storck, J., Lindberg, B., 2007, Dynamic cost modelling in steel production, submitted to Int. J. Prod. Econ., December 2007.

[19] Leden, B., 1986, STEELTEMP – A program for temperature analysis in steel plants, Scand. J. Metall., 15:215-223.

[20] Munther, P., Lenard, J.G., 1995, Tribology during hot, flat rolling of steels, CIRP Annals, 44/1:213-216.

[21] Pellizzari, M., Molinari, A., Straffelini, G., 2005, Tribological behaviour of hot rolling rolls, Wear 259:1281-1289.