A COST MODEL FOR THE EFFECT OF SETUP TIME REDUCTION IN STAINLESS STEEL STRIP PRODUCTION

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Abstract: Setup time reductions facilitate the flexibility needed for just-in-time production. An integrated steel mill with meltshop, continuous caster and hot rolling mill is often operated as decoupled processes. Setup time reduction provides the flexibility needed to reduce buffering, shorten lead times and create an integrated process flow. The interdependency of setup times, process flexibility and integration were analysed through system dynamics simulation. The results showed significant reductions of energy consumption and tied capital. It was concluded that setup time reduction in the hot strip mill can aid process integration and hence improve production economy while reducing environmental impact.

Keywords: Steel production, hot rolling, continuous casting, manufacturing flexibility, production economy, setup time reduction, lean production, system dynamics

1. INTRODUCTION

Steel production is a highly capital and energy intensive industry subject to intense global competition. It is vital for any steel producer to work continuously to reduce costs while at the same time responding to customers' expectations on lower prices, shorter lead times and better quality.

This research explores the opportunities for improved production economy that result from setup time reductions in steel production. The study is based on experiences from Outokumpu Stainless' plant in Avesta, located in mid-Sweden, where stainless steel strip is produced in an integrated mill with meltshop, continuous casting and hot rolling.

The Avesta plant has a traditional functional organization, with each production step managed as a separate unit. This has resulted in a decoupled operation of meltshop and continuous casting (CC) on one hand, and hot rolling mill (HRM) on the other. Production is characterised by long lead times and extensive buffering of workpieces that wait to be processed to coils of strip in the rolling mill.

A high level of buffering inevitably means that the average lead times for workpieces (known as *slabs*) to enter the rolling mill are longer than in a process

with less buffering. While slabs wait for rolling, they cool gradually and the heat from the melting process is lost. Decoupled operation of meltshop/CC and rolling mill is therefore 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*.

It is desirable that the lead-time of slabs from casting to hot rolling is short enough for a non-negligible fraction of the thermal energy to remain as they enter the rolling mill. Since slab temperature must be in the region of 1250°C at the beginning of the rolling operation, maintaining a closely integrated production with short lead-times is a highly efficient way to save energy since some of the need for the costly reheat process is eliminated.

The amount of buffering in any manufacturing process is intrinsically related to cycle-time, a relation known as Little's law (Hopp and Spearman 2000). Buffer level and lead-time from casting to rolling is related to the level of process integration, which in turn is related to some commonly known operating-modes as illustrated in Fig. 1 (Storck and Lindberg 2007). As lead-time and buffering is reduced, the average temperature of slabs increases. At the same time fuel consumption (energy) in the reheat furnaces of the rolling mill decreases. Another

aspect is that the amount of tied capital is reduced, which is particularly desirable for stainless steel production since the prices of alloying elements such as Ni and Mo has increased dramatically recently.
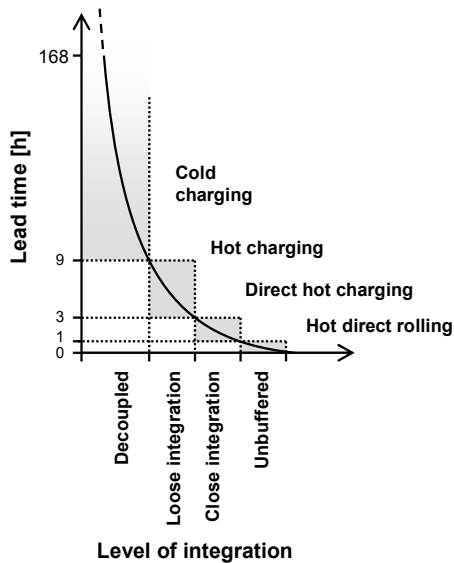

Fig. 1. Relation between lead time, level of process integration and corresponding operating mode. Flexible production means a shift towards lower lead times and better integration of meltshop and rolling mill.

In previous work by Storck and Lindberg (2007), it was concluded that a strategy based on lean production should be an efficient way to implement hot charge operation since a 'lean' value stream implies a 'hot' process flow due to shorter cooling times for workpieces. A 'lean' production system is characterised by minimum waste due to unneeded operations, inefficient operations or excessive buffering (Narasimhan et al. 2006). Hence, a mill that exhibits a high degree of 'leanness' should be characterized by efficient operations in each unit, but also by minimum buffering between process steps.

A lean transformation of the value stream is based on elimination of wastes such as waiting, buffering, defects, unnecessary transports etc. as defined by Ohno (1988). Supplying process steps must be flexible and responsive enough to have the capacity to deliver products just-in-time with respect to downstream processes. 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. (1984, cited in De Toni and Tonchia, 2005), 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 translated 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 process a slab of a particular steel grade, width and thickness into the desired target thickness.

Setup time reduction, i.e. continuous efforts to reduce the time needed to change tools, dies or rolls in any machine, is essential to generate this flexibility. When Toyota started their first attempts at just-in-time production, they soon found that their machines lacked the capacity to deliver small quantities while maintaining productivity (Ohno 1988). After that, Toyota worked systematically on setup time from 1945 and forward, and according to Ohno (1988), setups in some large presses that had taken two to three hours in 1955 were down to fifteen minutes in 1962 and as little as three minutes in 1971. Today, systematic setup time reduction has become a standard method to achieve flexibility in assembly, sheet metal stamping, machining etc.

However, it appears that the steel industry has been lagging. Setup time reductions have not got the same attention in comparison to what has become state of the art in the automotive and manufacturing industries. This may be due to lack of understanding of the fundamental role of setup time reductions to create manufacturing flexibility. Therefore, the aim of this research has been to assess the economic potential in increased process integration made possible by quick and frequent roll changes in the hot rolling mill. A cost model was developed and evaluated by *system dynamics* simulation (Sterman 2000) in order to analyse the effect on overall mill economy as margin costs for reheat energy, tied capital and work roll consumption vary in response to changed setup times.

In the sections that follow, we will briefly cover production planning requirements for the continuous casting and hot rolling processes. The relations between mill scheduling, process flexibility, lead-times and work in process (WIP) will be covered in Section 2. A cost model along with the relevant assumptions and mathematical relations is described in Section 3, and the method used to simulate production costs and determine optimal setup times is subsequently covered in Section 4.

The model has been used to generate a response surface for different combinations of energy and material prices. This analysis is presented in Section 5 and indicates that there is an optimal setup time with a corresponding minimal margin cost for the circumstances at hand. The conclusions in Section 6 include that setup time reduction in a hot strip mill may help to improve overall mill economy.

2. PRODUCTION SCHEDULING, PROCESS FLEXIBILITY AND INTEGRATION

There are many examples of research with a focus on creating optimal schedules based on the assumption that setup times are fixed. However, we have found no examples of published work that assess the effects of either improved process flexibility or setup time reductions on production with the perspective that these parameters could be changed. The following section represents an attempt to fill this gap and examine how production scheduling requirements affects the level of manufacturing flexibility and process integration.

The organisation of production and planning processes is shown in Fig. 2. Meltshop and rolling mill are scheduled individually based on a common central order book and current availability of slabs in the slab yard.
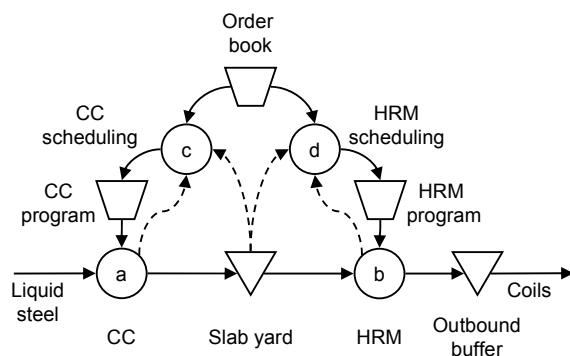

Fig. 2. Production in meltshop and continuous caster (a) is decoupled from production in the hot rolling mill (b). Separate scheduling departments (c, d) produce schedules that are optimised for their respective processes.

Jobs are grouped into programs designed to give the best (suboptimal) trade-off between mill economy and customer satisfaction for each production step. The scheduling procedure is carried out with the aid of database tools that help mill planners to create feasible schedules and select the best sequence of jobs, but is still largely a manual process where individuals have to deal with complex rules designed e.g. to ensure optimal utilization of work rolls and consistent quality of the produced strip.

According to Outokumpu's guidelines for scheduling of the rolling mill, in addition to comply with order due-dates, schedulers should take into account the following overall objectives:

a. Distribution of strip width over the span of a program to contain the requirements for strip profile in the roughing mill.

b. Sequencing steel grades and slab geometry to obtain maximum productivity in the reheat furnaces.

c. Minimisation of variations in strip thickness between consecutive coils in the finishing mill to ensure high reliability.

d. Optimisation of scrap handling to minimise the need to change scrap containers.

A requirement that was not explicitly stated, but present as an underlying assumption, is the design of schedules to ensure maximum utilisation of work rolls. Every time the work rolls are changed, they are conditioned in a roll grinding machine to remove surface defects that emerge during the rolling process. A pair of rolls typically last 30 to 60 grindings before they have to be scrapped, depending on the type of rolls. Since work rolls cost in the order of 0.5-1 MSEK per pair depending on type, they represent a substantial cost that can be expected to increase if rolls are changed more frequently.

Maximisation of work roll utilisation appears to be central in existing research on production scheduling. Cowling and Rezig (2000) mention work roll consumption and downtime due to roll changes as the primary concern for hot strip mill scheduling and impose requirements for minimum and maximum rolled length to ensure optimal work roll utilisation. The rationale behind the lower limit is not mentioned but appears to be based on the assumption that maximum roll utilisation is generally beneficial.

Hot strip rolling is normally scheduled in programs with workpieces arranged in order from wide to narrow during the course of a program. For the rolling mill, the program duration is given by the time between setups due to work roll changes in the roughing mill, which is done approximately twice per week. This frequency is chosen to comply with requirement (a) above, while ensuring reasonable downtime and utilisation of work rolls. A similar set of rules apply to production in meltshop and continuous casting. The result is a general width distribution over time similar to Fig. 3, where T_{RM} and T_{CC} represent the durations of rolling mill and caster programs respectively.
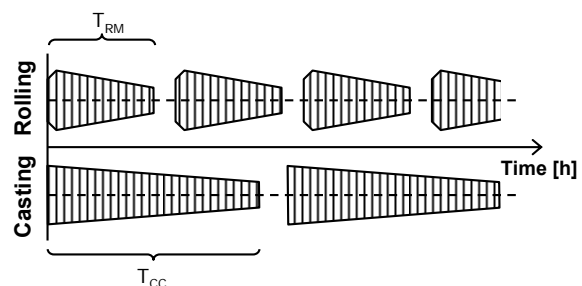

Fig. 3. Schematic representation of production schedules for hot rolling and continuous casting with slab and strip going from wide to narrow over the course of a program.

The period between work roll changes constitute a natural time span for programs in the rolling mill, but

there is no such natural limitation for the caster. Therefore, caster scheduling is governed by the requirement that products are delivered on time while a general width distribution from wide to narrow is maintained during the course of a program. Since the central order book in Avesta prescribes a production week for all orders, the natural time span for a program is roughly equivalent to one week.

Hence, meltshop planning generates programs spanning one week, while rolling mill programs span approximately three days. The result, seen in Fig. 4, shows how production in the meltshop matches production in the rolling mill. If more slabs are produced of a particular width than needed to create a rolling program, the remaining slabs are assigned to coming programs. Thereby, slabs originally cast in sequence are distributed over several programs with varying lead times as result.
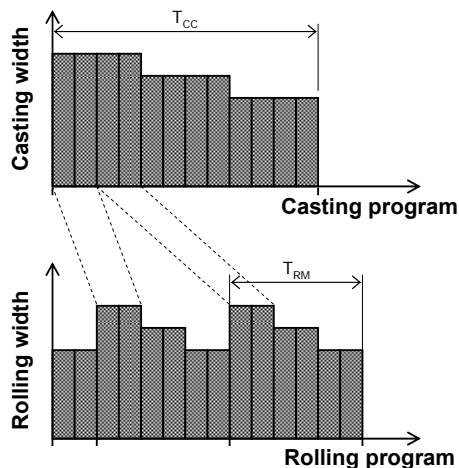

Fig. 4. Slabs that were originally cast in one sequence are often distributed over several rolling programs due to different scheduling constraints.

Slabs are generally not scheduled for rolling until they exist physically in the slab yard. When a program has been filled, all completed slabs are placed in queue. This, in combination with the distribution of slabs over several rolling programs, appears to result in an average lead time equal to or longer than the time span of a rolling program.

Complex rules for program design assume the existence of a slab buffer from which fitting slabs can be chosen. This opposes process flexibility, which requires short lead-times and low intermediate buffering. Hence, existing scheduling requirements inhibit production flexibility since they pose restrictions on what slabs can be rolled at a particular time. However, if fewer slabs are rolled on each pair of work rolls the readiness of the mill to process any type of product on short notice is improved.

Based on these observations, it seems reasonable to state that scheduling requirements designed to maximise work roll utilisation contribute to poor process integration since they impose rigidity on production. Similarly, measures to improve process flexibility effectively counteract the opportunity for traditional production scheduling. It can therefore be concluded that the required degree of flexibility has to be weighed against the need to limit work roll consumption by scheduling jobs to maximise roll utilisation, i.e. improved process flexibility require less focus on work roll utilisation.

3. COST MODEL

The following section describes the cost model developed to assess the contributions of WIP, reheat energy and replacement work rolls to total production cost in the hot strip mill. The problem, visualised in Fig. 5, is thus a matter of calculating the margin cost of these cost components based on a number of factors, such as energy and material prices, setup times, work roll consumption and lead times.
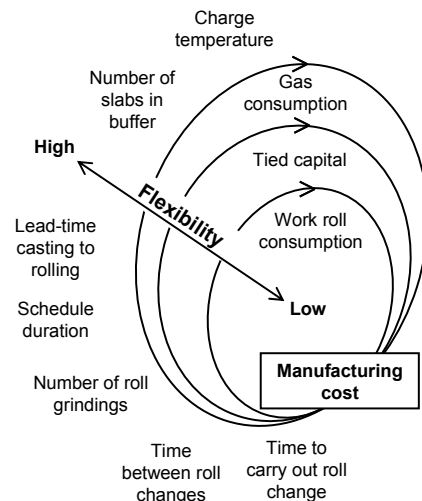

Fig. 5. Structure of the cost model. The level of process flexibility balance costs for work roll consumption against buffering and reheat energy.

The schematic model of Fig. 5 was further developed into a causal loop diagram (CLD) according to Fig. 6, where the causal relations between parameters have been included. The CLD was then formulated as a system dynamics (SD) model, where each variable is described as a function of those other variables with which it is directly connected with inward arrows. Fig. 5 was thus elaborated and cast into a system of differential equations that could be solved numerically directly in the simulation environment. The equations behind Fig. 6 are given in Appendix 1.
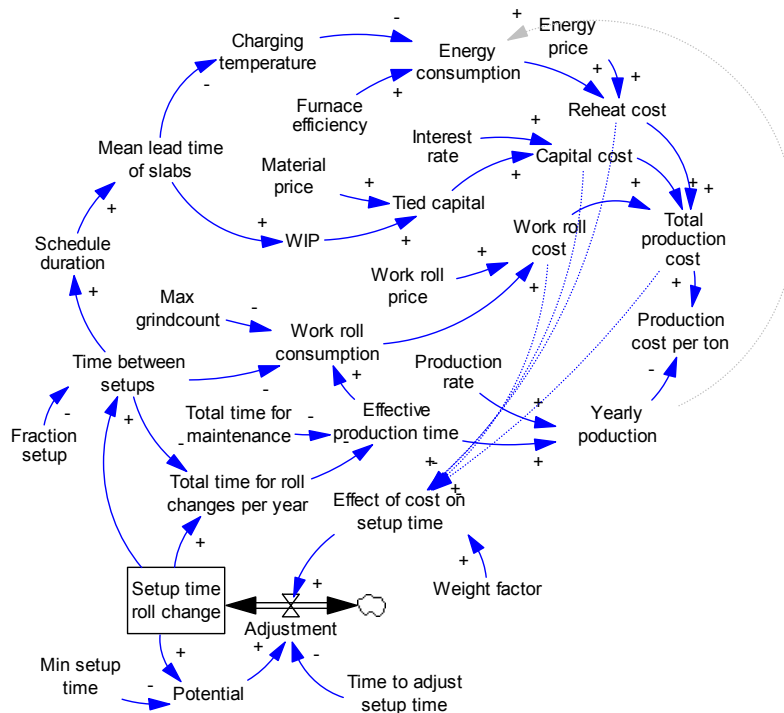
Fig. 6. Causal loop diagram (CLD) for the cost model. The preferred time to carry out a roll change is influenced by the current cost structure through the variable "effect of cost on setup time".

A fundamental assumption was that the sum of setup times remains constant when the duration of a single setup is varied. Shorter setup times give more setups, while longer setup times give fewer. The work roll cost is reduced if the setup time is increased, while it increases if setup time is reduced. The work roll cost is based on the work-life of rolls counted in number of grindings, which was set to 60 times per roll pair and a price per pair of 500 kSEK.

A simple relation between lead time and work roll temperature was applied, based on simulation of cooling for three stacked slabs using the commercial finite difference code STEELTEMP (Leden, 1986). The cost of reheat energy then follows from gas price and consumption, based on heat content, charging temperature and a furnace efficiency of 0.45.

The cost of tied capital was calculated for 10% interest rate based on production volume, lead time and material price. The material price was calculated from the prices of raw materials and is at present approximately 30 kSEK/ton for an 18% Cr, 8% Ni stainless steel.

4. SIMULATION ANALYSIS

The model calculates the production cost and adjusts setup time by a negative feedback loop so that the different cost components are balanced by the setup time. The weight factor ξ determines the relative focus on lead time versus work roll consumption. If ξ is set to zero, the cost contribution of work rolls is neglected. In the same way $\xi=1$ means that the cost of energy and tied capital are ignored.

An example output from one run is seen in Fig. 7. It shows how the model converges for a particular set of input parameters. In this case the total cost converges against 116 SEK per ton.
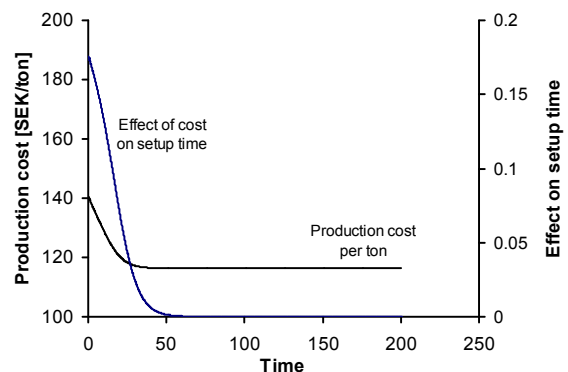

Fig. 7. Convergence against equilibrium during one simulation run for c_m=21 kSEK/ton, c_e=0.5 SEK/kWh and ξ=0.7. The "effect of cost on setup time" shows how setup time stabilises.

The effect of cost on setup time, e, was given by

$$e = \frac{(1-\xi)(c_e + c_m) - \xi c_r}{c_{tot}} \qquad (1)$$

where c_e, c_m and c_r are the contributions from reheating, capital and work rolls respectively. Setup time was then adjusted in each time step with the rate

$$r = e / \tau \qquad (2)$$

where τ is "time to adjust setup time" in Fig. 6.

The "effect of cost on setup time" indicated in Fig. 7 shows the change in setup time given by Eq. (2) based on the relative sizes of the cost components, i.e. the result of Eq. (1).

The equilibrium cost attained for the same input as in Fig. 7 with the exception of the weight, which was varied in the interval from zero to one, has been assembled in Fig. 8. As seen in the figure, the contribution of the different cost components vary depending on the weight on flexibility as previously discussed. It can be seen that there is a minimum margin cost located near $\xi = 0.7$.
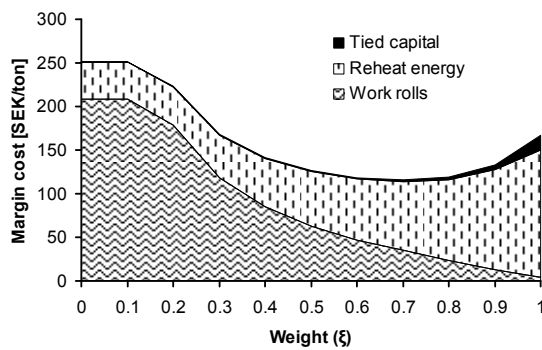

Fig. 8. Simulated margin cost distributed on cost components as a function of the weight factor ξ for a material price of 21 kSEK/ton and an energy price of 0.5 SEK/kWh.

Fig. 8 shows how the relative contributions of the factors change when the weight factor ξ is varied so that the total cost can be minimised. The result can be seen as a transformation where the total cost is a function of the prices of energy, c_e, raw materials, c_m, and the flexibility of the manufacturing system, ξ:

$$c_{tot} = f(\xi, c_e, c_m) \qquad (3)$$

The type of data represented by the curves in Fig. 8 has been collected for all combinations of weight, energy and material price as these variables were varied over the intervals:

Weight $\xi \in [0, 0.1, \ldots, 1]$

Energy $c_e \in [0, 0.1, \ldots, 1]$ SEK/kWh

Materials $c_m \in [0, 3, \ldots, 30]$ kSEK/ton

This resulted in a total $11^3 = 1331$ simulation runs, from which the output, corresponding to the result of Eq. (3), was processed to produce a response surface (Law and Kelton 2000) seen in Fig. 9.
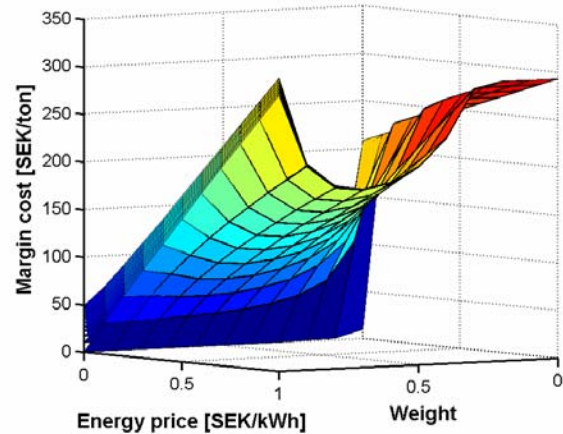

Fig. 9. Response surfaces for margin cost as function of energy price and the weight factor ξ. The figure shows eleven stacked surfaces that each represents a material price from zero (bottom) to 30 kSEK/ton (top).

In the next step the value of ξ that gave the lowest cost for each combination of c_e, c_m was chosen and the corresponding setup time was plotted. A search function was used to extract the optimal value of ξ for each combination. The result of this procedure is seen in Fig. 10.
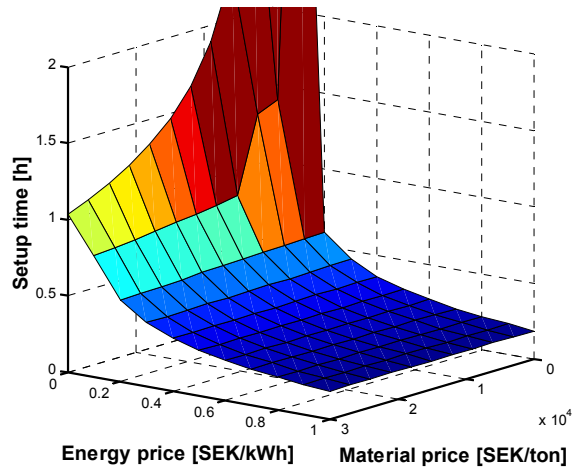

Fig. 10. Optimal setup time as function of energy and material prices based.

The results of Fig. 10 were used to plot the optimal setup time with respect to lowest margin cost for energy, tied capital and work roll consumption as function of actual material and energy prices over the period from 2000 to 2007 (Fig. 10). In the same plot was included for comparison the optimal setup time for maximum work roll utilisation. This result in fewer roll changes and setup times in the order of three hours become acceptable. Contrary, setup times for best overall production economy require setup times in the order of 20 minutes.
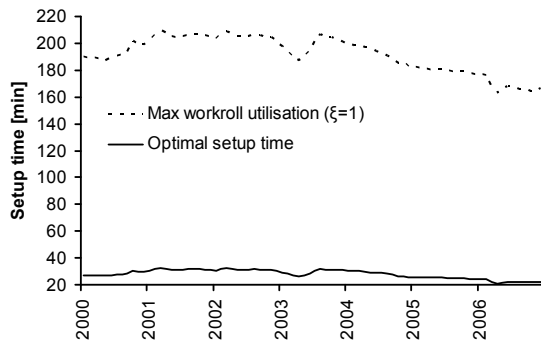
Fig. 11. Optimal setup time for lowest cost (solid) and max work roll utilisation (dashed) as function of actual gas and raw material prices during the period from 2000 to 2007.

A plot of the total cost contribution per ton corresponding to the data in Fig. 11 is shown in Fig. 12. As seen in the figure, production cost has increased dramatically over the last years, which is in response to raised gas and material prices. The dashed arrow shows how a development against shorter setup times correspond to moving from the current high cost curve to the lower cost curve made possible by shorter setup times.
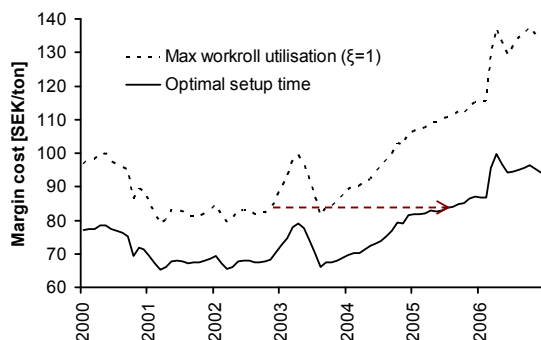

Fig. 12. Optimal accumulated margin cost as function of actual gas and raw material prices during the period from 2000 to 2007.

From Fig. 12 it can be seen that shorter setup times can reduce overall production cost by approximately 40 SEK per ton.

5. DISCUSSION

The development against higher prices for material and energy means that the incentives to improve flexibility by reducing setup times are growing stronger. It seems clear that shorter lead times and less buffering yield lower overall cost if the focus on work roll utilisation is reduced to promote better flexibility. Looking at present energy and material prices, the sum of the estimated cost components may be lowered by as much as 40 SEK/ton (Fig. 12). This represents a total 40 MSEK on a yearly production of 1 million tons, a cost reduction that can be directly accounted for as increased profit.

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

- setup times are fixed and unalterable,

- the cost of energy and tied capital is small in comparison to the cost of work rolls.

However, once the full picture is examined, it becomes clear that energy and tied capital represent substantial costs, and that mere minimisation of work roll consumption does not necessarily give the best overall production economy. Setup time reductions generate flexibility that can be used to improve process integration at the expense of more frequent roll changes. Better integration can be expected to shrink the costs for buffering and reheating, thereby balancing the increased work roll costs.

An explanation for the strong focus on work roll utilisation may be due to clear cost ownership. Work roll consumption is the responsibility of the rolling mill manager, who can control this cost component through the design of scheduling practice aimed at maximisation of roll utilisation. Contrary, it is less clear who is responsible for heat losses and capital tied up in buffering. These are system costs generated by poor integration of meltshop and hot strip mill. If improved integration is not rewarded by the economic control system, managers tend to target costs that are within their field of responsibility. The result is sub-optimisation that results in excessive buffering, overproduction, wasted energy, long lead times and slow follow up on product defects.

It should be noted that the model has some limitations that may be addressed. First, it was assumed that average lead time for slabs is equal to program duration in the rolling mill. There is a clear correlation between schedule design parameters and lead time, but the precise relationship needs to be further researched. Second, the work rolls' resistance to wear was not included in the model. A more realistic model could account for the differences in durability of work tolls depending on type and price. These factors may then be evaluated in order to better assess the economic potential of setup times to generate flexibility and process integration.

6. CONCLUSIONS

A system dynamics model for estimation of the effect of setup time on manufacturing cost in continuous casting and hot rolling of steel was formulated and evaluated. The main findings were:

- Maximisation of work roll utilisation does not necessarily generate the best overall production economy, as seen in Fig. 12.

- Fig. 8 shows that the cost function has a distinct minimum that represents an optimal setup time. The location of the minimum depend on the prices of raw materials and gas for reheating, and are particularly sensitive to changes in energy cost.

- Higher energy prices are a strong incentive for improved manufacturing flexibility and shorter setup times.

- Long setup times and lead times appear rational if energy consumption and tied capital are disregarded. Resulting optimal setup times and lead times are representative of actual, present values.

In order to further improve the model, there is a need for better knowledge regarding the relations between schedule design, WIP, lead time and process integration. Also, it may be interesting to investigate the effect of using different types of work rolls.

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APPENDIX 1

Vensim equations for the cost model.

```
Effect_of_cost_on_setup_time=((1-
   Weight_factor)*(Reheat_cost+
   Capital_cost)-Weight_factor*
   Work_roll_cost)/Total_production_cost

Weight_factor=0.75

Furnace_efficiency=0.55

Energy_consumption=(1250-
   Charging_temperature)*477*1000*
   Yearly_production/Furnace_efficiency

Energy_price=1 [SEK/kWh]

Production_cost_per_ton=Total_
   production_cost/Yearly_production
   [SEK/ton]

Adjustment=min(Potential, Effect_of_
   cost_on_setup_time)/Time_to_adjust_
   setup_time

Time_to_adjust_setup_time=5 [h]

Min_setup_time=0.05 [h]

Potential=Setup_time_roll_change-
   Min_setup_time

Fraction_setup=0.05

Yearly_production=Production_rate*
   Effective_production_time [tons]

Tied_capital=WIP*Material_price [SEK]

Interest_rate=0.1

Work_roll_cost=Work_roll_price*
   Work_roll_consumption [SEK/year]

Schedule_duration=Time_between_setups [h]

Max_grindcount=40

Material_price=30000 [SEK/ton]

Mean_lead_time_of_slabs=
   Schedule_duration [h]

Work_roll_price=500000 [SEK/pair]

Production_rate=60 [tons/h]

Capital_cost=Tied_capital*Interest_rate
   [SEK/year]

WIP=Mean_lead_time_of_slabs*
   Production_rate [tons]

Setup_time_roll_change=
   INTEG(-Adjustment,1) [h]

Charging_temperature=1000*exp(-0.1086*
   Mean_lead_time_of_slabs^0.872) [C]

Effective_production_time=8640-
   Total_time_for_maintenance-
   Total_time_for_roll_changes_per_year
   [h/year]

Time_between_setups=
   Setup_time_roll_change/Fraction_setup [h]

Total_production_cost=Work_roll_cost+
   Capital_cost+Reheat_cost [SEK/year]

Total_time_for_maintenance=2000 [h/year]

Total_time_for_roll_changes_per_year=
   (8640/Time_between_setups)*
   Setup_time_roll_change [h/year]

Work_roll_consumption=
   Effective_production_time/
   (Time_between_setups*Max_grindcount)
   [pairs/year]

Reheat_cost= Energy_price*
   (Energy_consumption/3.6e+006) [SEK]
```