

Abstract Number: 015-0653

**Abstract Title: MULTI-STAGE HYBRID RE-ENTRANT FLOW SHOP
PLANNING WITH APPLICATION TO ALUMINIUM ROLLED
PRODUCT**

Authors' Information: Debashish Jena & Rajiv K. Srivastava
Indian Institute of Management, Lucknow
Debashish.jena@iiml.ac.in
919453356522

POMS 21ST Annual Conference

Vancouver, Canada

May 7 to May 10, 2010

Introduction

In the face of competition and pricing pressure and dynamic demand Aluminium flat-rolled product industry players are looking for ways to cut costs and improve customer service. There is increased emphasis on customisation, operational efficiency and fast response. Aluminium rolled product is used in very wide ranging applications: automotives, aircrafts, housing, furniture, appliances, packaging etc. What makes Aluminium rolled product demand management more difficult and predominantly MTO based compared to Steel rolled products, is the fact that order specification widely varies across customers and product categories in terms of alloy grade, width, thickness, temper and weight depending on their final usage. Aluminium being a far (4 to 5 times) more expensive product than steel, the impact of scrap loss (despite possibility of recovery through *re-melt*) is much significant on productivity and profitability- which also justifies MTO policy to minimize scrap loss rather than fulfilling demand from over-width and over-grade MTS inventory.

In a real-life case under investigation, tasks of various types are to be processed on a complex hybrid flow shop with re-entry characteristics at critical stages. The case is taken from an Indian Aluminium Industry which manufactures primary metal as well as flat cold rolled products among other products. In such complex re-entrant flow processes, assessment of real plant capacity becomes very sensitive to the product mix, planning efficiency, other interruptions and transient process behaviours. Moreover, for re-entrant hybrid flow process, task of capacity planning, order commitment and subsequent production planning process becomes extremely difficult and more so with MTO policy in the face of unpredictable demand patterns. Besides, divergent product structures of ACI (Aluminium conversion industry) cause problems in requirements calculation and material balancing in conventional ERP and APS based applications (David et al, 2005, 2006). This along with batch processing machines (e.g. annealing) introduce variability in LT. As a consequence,

capacity and due date calculations are rendered highly inaccurate. To address such varied scenarios and unique problems of ACI industry, further research is required to develop more flexible and adaptable systems. .

The Production Process

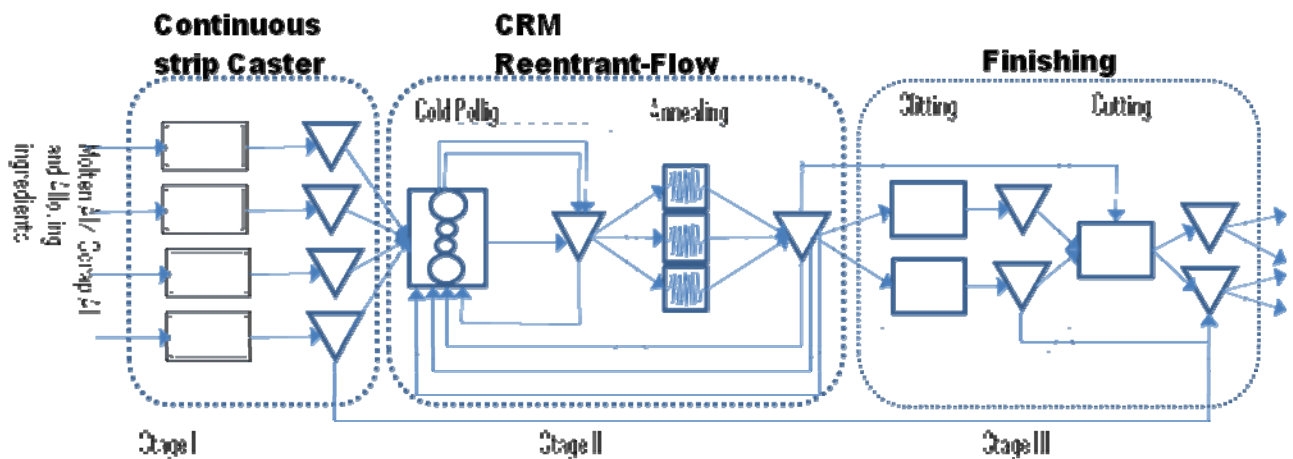


Figure 1 Complete Rolled Product Process Flow Diagram

Topologically this production process can be broadly characterized as a multi-item, multi-stage Hybrid Flowshop (HFS) (see Tang et al.,2006); accompanied by respective sets of technological constraints at each stage. The processing stages are: Continuous Strip casting, Cold rolling, Annealing, Slitting and Cutting (see Fig. 1). Continuous casting stage is a Parallel machine sequencing problem with sequence dependent setups. The second stage- Cold Rolling and Annealing can be jointly represented as a two-stage, Re-entrant; hybrid flow-line based manufacturing system (FBMS). Similarly bypass is possible between few other pairs of stages as delineated in the above schematic. Although the whole process can be characterised as a Hybrid flow shop, the more complex technical constraints(hard constraints) and scheduling criteria/rules/preferences(soft constraints), recirculation/bypass options render the system very difficult to plan optimally.

Cold Rolling & Annealing Re-entry Problem Description

Cold Rolling is a process of reducing thickness of material in flat form by passing it at pressure between two work rolls. Coil strip from strip caster after cool off period has to undergo multiple re-entry passes through 4HI Cold Rolling Mill (CRM), depending on the final thickness reduction and temper requirements (see Fig 1). During typical rough rolling (up to maximum of 5 passes) there is no need for coils to be sent for annealing but after two consecutive roughing passes it has to undergo natural cooling for a day before it can undergo further rough rolling passes. Between successive finish rolling passes (up to maximum of 3) the coils need to be sent for annealing, thereby causing re-entry between CRM and Annealing. Some coils may not at all need annealing and directly go to finishing line and will bypass annealing station. Variation in rolling speed is also significant: typically 150 m/min in 1st pass low gear to 400 m/min 5th pass high gear.

Annealing is a simultaneous batch process carried out in Annealing Furnace with Nitrogen Controlled atmosphere and has long cycle time of 18 hours followed by mandatory cooling off period of to complete. Some of the coils may not need all of roughing and finishing passes, depending on their final thickness requirement. Hence, processing requirement and re-entry requirement may vary depending on the grade, temper and thickness specifications. Depending on the production mix and batch process characteristic Annealing does become a bottleneck resource and does impact the quality of planning upstream.

Some of the relevant hard and soft constraints reported in literature from both Aluminium and steel literature followed by discussion with personnel from the industry are as follow:

- *Width transition: Coils should be processed in decreasing order of width to prevent damage to the coil/sheet .*
- *Hardness Transition: To the extent feasible softer alloys must be rolled before the their harder counterparts*
- *Gauge Transition: Rolling should be take place in non decreasing order of the gauge.*

Planning Issues and objectives

How should one go about planning such a complex system with emphasis on higher capacity realisation and improvement in planning efficiency? It is a common knowledge that measurement of realisable plant capacity is highly difficult and more so in such complex systems (see. Elmagharby, 1991). David et al.(2005, 2006) have raised several significant issues with planning in Aluminium conversion industry(ACI). They have questioned the very applicability of ERP & APS principles in the light of divergent product structure (BOM) and heterogeneous process characteristics; alternate BOMs causing uncertainty in LT which in turn impact capacity requirement calculations and inaccuracies in order commitment dates; non-standard order quantity giving rise to overestimation of capacity requirements and unwanted semi finished inventory generation and so on.

The objectives of our research are:

- *Develop mathematical models for capacity feasible under different priorities: max Profit , min Cost, min Make span and so on in a re-entrant production environment.*
- *Understand the impact of re-entrant workflow on planning efficiency, and develop insights and decision rules for planners and practitioners.*
- *Examine Capacity sensitivity issues in a re-entrant workflow environment and develop methodology to accurately process orders and freeze order-mix for planning horizon with a view to improving order commitment, response and delivery performance.*
- *Deriving insights about the extent and pattern of rated capacity degradation under various scenarios of product mix, corporate objectives and policies and possible tactical response to address the issue.*

Relevant Literature Review

Since this is an ongoing research which involves stage wise modelling of planning problems, we, in this paper, restrict ourselves to the second stage i.e. Cold Rolling Mill and Annealing planning. There is very little publication on the specific type of problem configuration that is under study. However, more of the publications are for Steel Industry and more so about Hot Rolling lines. Two rare publications for aluminium industry by

Ladurantaye et al. (2007) and Stauffer et al. (1997) demonstrate heuristic algorithms and rule based mathematical model respectively to schedule hot rolling mills in the aluminium industry. The heuristic by the former author consist of two phases. First, batches of ingots are constructed for the furnaces. These batches, called blocks, are then sequenced on the mill. A rare cold rolling production scheduling work by Zhao et al.(2008) describes models and algorithms for coil-merging optimisation followed by cold rolling batch planning using double travelling salesman problem (DTSP) for enforcing width, gauge, hardness transition. However, coil merging model is not relevant for Aluminium rolled products as continuous cast strips are produced in coiled state. They have also highlighted the importance planning well for the bottleneck annealing process. But, there is no re-entry phenomenon in the case. The only work that captures Annealing as a re-entrant process is by Moon et al.(1999). But, the re-entry context is in conjunction with crane scheduling.

Assaf et al.(1997) have demonstrated the efficacy of an enumeration based algorithm to generate optimal schedules for sequencing slabs through the reheat furnace and the Rolling Mill in which he has considered many relevant constraints. Like wise, VRP/TSP based models to schedule the Hot Rolling process have been proposed by many authors (see Chen et al. 1998, Chen et al.2008; Pan et al. 2009). In terms of solution methodology, metaheuristics have evolved as a popular tool among of publications discussed, apart from traditional MIP and heuristic algorithms. Cowling et al.(2003) have reported very detailed DSS for multi-objective model. Across all publications, '*coffin schedule*' generation is a common theme. Invariably all the authors have followed the seminal work by Kosiba(1992) for penalty structure generation which provides coefficient vector for objective function in guiding VRP/TSP based models. Besides, other objectives such as minimization of cost of tardiness, maximisation of profitability and productivity have also been reported.

Neither publication for Steel nor for Aluminium industry throws any light on detailed planning and scheduling aspect of Aluminium Cold Rolling interspersed with annealing batch process. Secondly, most of the hot rolling models are more of continuous flow process in a sense that hot slabs undergo all the successive stages of rolling in one go/pass successively at consecutive rolling mills. However, Tang et al. (2001, p.12, section 5.1) describe that in the conventional steel making and steel rolling production (cold charge process), the production plan for both stages are made independently based on the design units called *heat, cast and roll*. They describe that rolling plans are mainly constrained by strip width and thickness; width must vary from wide to narrow and thickness should change smoothly. Therefore lot planning problems for cold charge process are essentially single production stage problem. But, for the case under study and more so for aluminium rolled product manufacturing which has some fundamental difference in terms of manufacturing process and policy, there is this issue of re-entry characteristic between rolling and annealing with thinner gauge lots requiring higher number of re-entries than the thicker gauge counterparts. Hence not every lot follows exactly the same process flow which increases the inter-stage dependence and its impact overall capacity realisation if not planned efficiently. So it cannot be treated like a single stage planning which is a direct sequencing decision. While in steel industry VRP based order sequencing implicitly handles scheduling, in our case, because of joint planning with annealing and re-entry characteristic doesn't allow that liberty and there is need for explicit scheduling model.

As regards re-entrant workflow, we observe this phenomenon is more commonplace in semiconductor manufacturing literature. Excellent review papers by Uzsoy et al.(1992, 1994) provide insights into the development of planning and scheduling models in Semiconductor industry. Majority of literature in re-entry planning are from semiconductor manufacturing which is short cycle in nature. Predominance of transient behaviour doesn't lend itself to

good deterministic planning and scheduling. Hence most of the applications in re-entry process are based on queuing and simulation models aside from use of sequential algorithm (see Pearn et al.2004) for analysing system performance because of the intractability of analytical model.

Conceptual Models for Multi-stage planning

In order to be able to model this multi-stage production environment in an optimal way, ideally one would think of an integrated model so that there is no loss of optimality which might occur when stage wise optimisation and subsequent synchronisation strategy is deployed. It may be noted that joint rolling-annealing sub models are structurally inseparable and should always be maintained as a single bloc. But, continuous casting sub-model is separable but, is linked to rolling-annealing sub model using their natural stage precedence to establish the linkage. This model is expected to achieve complete optimality.

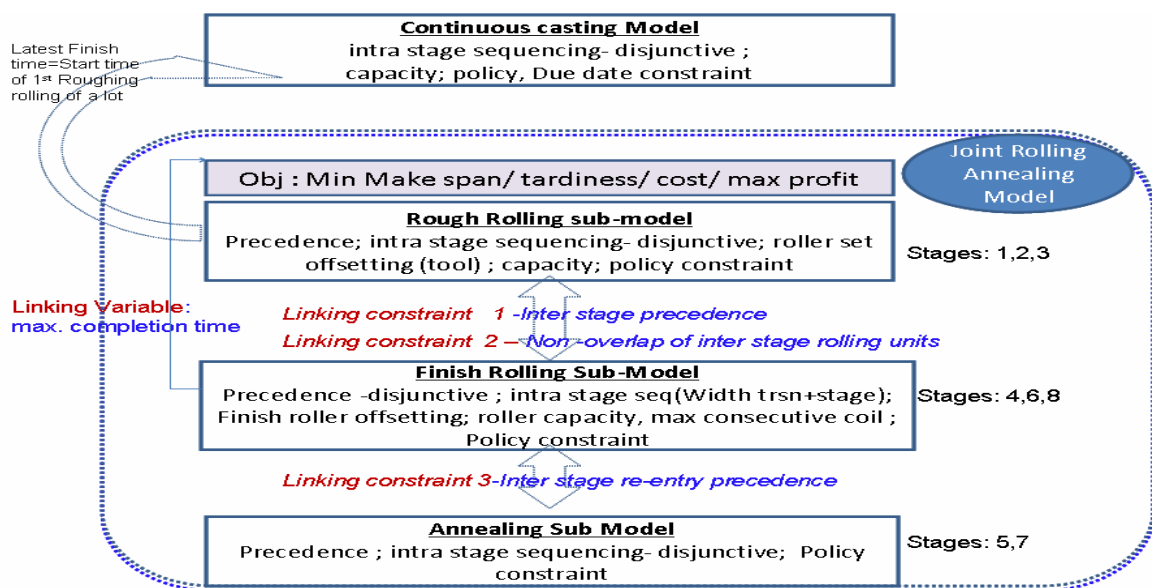


Figure 2: Multi-stage Synchronized Planning: Architecture –I

In order to improve tractability we have decoupled Continuous casting sub-model and the joint rolling-annealing model. The idea behind this follows from our understanding that our system develops multiple constraints depending on factors like product mix, degree of re-

entrant product flow, lot sizing and actual order release. Sometimes rolling stage becomes a bottleneck if higher percentages of finer gauge coils are in product mix. Similarly, if smaller lot size and diverse alloy groups are to be processed, continuous casting can also be a bottleneck. Finally annealing being a *simultaneous batch* process, it may as well turn out to be a bottleneck, if too many heterogeneous lots are there. In case of steel industry it has been reported as a major bottleneck. In case joint rolling-annealing stage becomes a bottleneck, Multi-stage framework –I will be the approach to follow.

Having first solved the rolling stage problem, dynamically transfer the values for starting times for *first* stage roughing rolling tasks of different lots as latest finish time or operation *due date* constraint for Continuous casting sub model. Subsequently, the Continuous casting sub model is solved, which is basically a parallel machine work centre with sequence dependent setups. The outputs from continuous casting sub model will determine the latest lot order release times for Continuous casting units. The objective functions could be similar between the two sub models or dissimilar depending on corporate objectives and priorities.

Problem Definition

There are N number of Lots to be processed through a series of processes such as: roughing rolling $R\{1,2,3,4,5\}$, finishing rolling $F\{1,2,3\}$ and annealing $A\{1,2,3\}$ operations. Annealing processes are interspersed between finishing operations (see Fig. 3 & 4). The planning horizon is typically a month. There may be due date associated with each lot or different levels of priority weight attached to it. It may be recalled that not every lot is required to go through all the stages. There are missing operations and bypasses depending on their actual routing.

Annealing is a batch process and has multiple parallel units (3 units) available. Evidently there is re-entry between annealing and finishing stages for most of the lots. Similarly there is circulation between consecutive roughing operations (tasks) on each lot. Some lots may not need all the operations (missing operations). In addition there are certain stage specific technological and policy based rules that need to be enforced. Decreasing width transition rule (“*Coffin sequence*”) must be applied to finishing rolling stage for each finishing unit. This width transition rule is not so much sacrosanct for roughing rolling stage as surface finish is not very much critical at this stage. Likewise, annealing process also doesn’t require any width transition rule for batching etc. However, preference should be for similar alloy grades at annealing stage. As far as precedence constraints are concerned, all intra-lot operation (task) precedence which may be intra-stage (e.g. rough rolling 1 to rough rolling 2) or inter-stage (e.g. finish rolling 1 to annealing 1) in nature, should be accounted for. The unknowns are allocation of tasks (individual operations on each lot) to different processing units, their sequence and their completion time C_{task} . We need to plan for the lots in a manner that fulfils different intended objectives such as: minimisation of makespan, weighted tardiness, cost function or maximisation of profit.

Problem Formulation

We have reviewed the generic MILP modelling approaches reported in process industry (see Mendez et al. 2006, 2001; Moon et al., 1999) and adapted the notion of general precedence to model our problem. The basic idea behind this approach is to create an indirect task level ‘*coffin schedule*’ based on width transition constraints with the overall objective of minimisation of Makespan. Broadly speaking we have three sub models: (1). continuous casting, (2). joint model for rouging rolling, finishes rolling and annealing 3. Finishing line(cutting and slitting). The 2nd model has the most complex problem structure with re-entrant flow and annealing being batch unit with parallel units. Consequently we

intend to solve second model first, which in turn will drive the 1st stage model i.e. continuous casting.

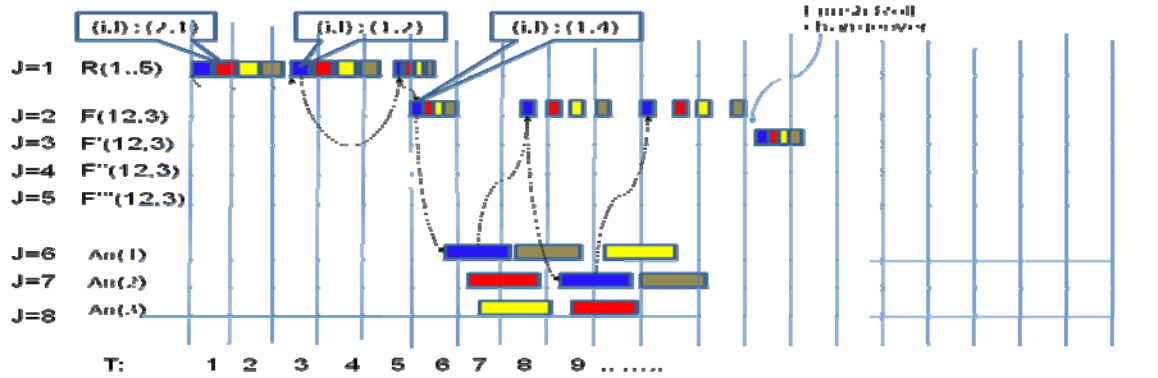


Fig 3: Illustration of the definitions and notations

The joint model for rolling and annealing are not directly amenable to typical process industry kind of formulation that we see in (Mendez et al. 2006, 2001; Moon et al., 1999) where each dedicated resource is represented on a different coordinate. In our case, the complication is on account of CRM, which is a single machine. CRM doubles up as a roughing rolling station and finishing rolling alternatively, which requires tool (roller sets) changeover every time there is a switch from roughing to finishing and vice versa. This issue needs to be resolved first. During a typical monthly campaign we may typically use *two* roughing roller sets and *four* finishing roller set. In order to have the benefit of modelling this work station as a dedicated processor, as if capable of carrying out each operation disjointedly, we treat each of the roller sets (4 finish roller set & 2 rough roller set) as different processors or units which are offset temporally so that a new roller unit is activated only when the previous one has been worn out. By this we have effectively treated one CRM like a multiple dedicated single processors whose availability can be temporally offset as illustrated in Fig.4. In Fig-3. $J \in \{1, 1'\}$ represents “roughRoller” units while $J \in \{2..5\}$ represent “finishRoller” units. The terms unit and machine are used synonymously. We will formulate appropriate constraints to ensure temporally they are offset and behave as unique processors. Similarly, $J \in \{6,7,8\}$ represent annealing units which are parallel processors and manifest batching process. A task

is tuple data entity represented as a pair of data namely Lot_id and stage or operation number of the task $\langle i,l \rangle$.

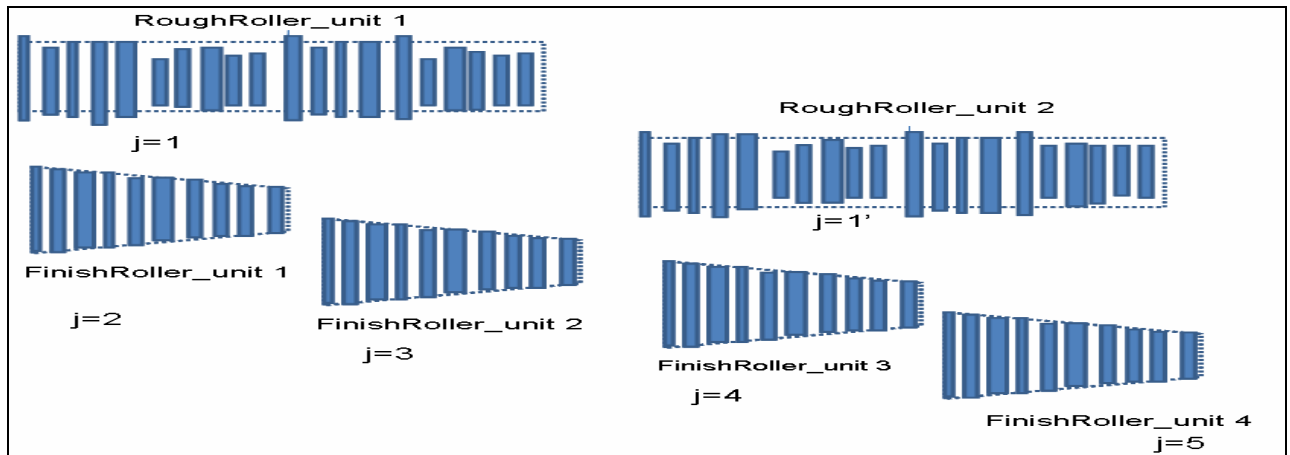


Fig. 4 : Graphic illustration of roller units with “Coffin Sequences” treated as independent processor units

Precise *set filtering* operations have been carried out to generate valid or relevant pre-specified pair wise general precedence sequencing. The idea underlying this exercise is to generate sets of “*relevant task pairing*” to be used in various sequencing variables and constraints that would be facilitate “*intra-stage*” sequencing of tasks on individual units (processing stations) as well as “*inter-stage*” sequencing of tasks on different units respectively. This exercise significantly reduces the number of variables and disjunctive constraints. Besides, it also results in more simplified and compact disjunctive constraints (see constraints 7, 8, 9, 10, 17, 18, 19, 20 etc.), which would be evident as we formulate the model subsequently. To illustrate the idea, let’s examine the “*relevant_fr_taskpair*”. Here we are generating valid *intra stage task pairs* for finishing rolling stages. *Set filtering* is done on the maximal task pairs sets so that only pairs conforming to width transition rules or stage precedence rule be selected as possible candidates for pair wise sequencing constraint (7) generation. Likewise there are quite a few of such and more complex set filtering based relevant task pair sets generated for our model in order to reduce feasible solution space and sparsity, thereby improving computational complexity.

Indices/ Abbreviations

i: OrderId /Lot_id/jobId
l : Process /operations stage
j, j' : Processing unit
rr: rough rolling
fr: finish rolling

Sets

roughRolling: {1,2,3} set of rough rolling task stages
finishRolling: {4,6,8} set of finish rolling task stages
annealing: {5,7} set of annealing task stages
stages : { rough_rolling } \cup { finish rolling } \cup { annealing } --- maximal set
tasks : { <Lot_id, stage> | Lot_id \in {Lots}, stage \in {stages} }
relevant_fr_taskpair: {Set of task pairs from different lots based on width transition} \cup {Set of task pairs from same lots based on stage precedence}
relevant_rr_taskpair = {<task1,task2> | task1, task2 \in {roughRolling}, ord(task1) < ord(task2) \wedge (task1 \neq task2) \wedge tsk1.Lot_id \neq tsk2.Lot_id } : from different lot & for non-duplicate pairing e.g <1,2> or <2,1>
relevant_rr_taskpair1 = { <task1,task2> | task1, task2 \in {roughRolling} , ord(task1) < ord(task2) , tsk1 \neq tsk2 } : from all possible lots & for non-duplicate pairing;
relevant_mixed_taskpair = {<task1,task2> | task1 \in {roughRolling}, task2 \in {finishRolling}, tsk1.Lot_id \neq tsk2.Lot_id } : from different lots
Wd: { set of all possible order widths }

Parameters

co[*]: change over
procs_time: processing time
max_fr_Cap: Upper bound on the maximum cumulative rolling hours on any finish roller set
max_rr_Cap: Upper bound on the maximum cumulative rolling hours on any rough roller set
max_b2b_frCap: Limit on number of consecutive tasks processed on any finish roller set.
W[i]: Width of order i

Continuous variable

C_{task} : Completion time of task

T_{max} : Makespan

Binary Variables

$X_{\text{task1, task2}}$: Define if task1 follows task2 (General precedence)

$Y_{\text{task,j}}$: Define if the task is allocated to unit j

Objective Function

Various objectives such as Cost, Profitability, Tardiness which can be incorporated, the case under consideration is facing pressing capacity realisation issues which is why improvement in Make-span performance has been chosen as a primary objective. However, other objective functions will also be incorporated in subsequent extensions to reflect various corporate & functional objectives and their impact on plan quality and performance. Various practical scenarios representing divergent objectives of different stages will be experimented with at a later stage while carrying out parametric and sensitivity analysis with a view to gaining managerial insights and developing decision rules.

Minimize T_{max}

Constraints for joint finishing-rolling -annealing model

Allocation Constraints

Every task must be assigned to a single processing unit j .

$$\sum_{j \in \{finishRoll_units\}} Y_{task,j} = 1 \quad \forall task \in \{finish\ rolling\}; \quad (1)$$

$$\sum_{j \in \{annealing_units\}} Y_{task,j} = 1 \quad \forall task \in \{annealing\}; \quad (2)$$

Precedence Constraints

Lower bound

$$C_{task} \geq \sum_{j \in \{finshRoll_units\}} Y_{task,j} * porcs_time[task] \quad \forall task \in \{finishRolling\}; \quad (3)$$

$$C_{task} \geq \sum_{j \in \{annealing_units\}} Y_{task,j} * porcs_time[task] \quad \forall task \in \{annealing\}; \quad (4)$$

Inter-stage precedence (*Linking constraint*)

$$\begin{aligned} C_{task2} &\geq co[fr_to_anl] + C_{task1} + porcs_time[task2] \\ \forall task2 \in \{annealing\}, task1 \in \{finishRolling\}, \\ \forall (task1.Lot_id = task2.Lot_id) \wedge (task2.stage = 1 + task1.stage); \end{aligned} \quad (5)$$

Inter-stage precedence (complimentary pair of previous inequality (5))

$$\begin{aligned}
 C_{task2} &\geq co[anl_to_fr] + C_{task1} + porcs_time[task2] \\
 \forall \quad task1 &\in \{annealing\}, task2 \in \{finishRolling\}, \\
 \forall \quad (task1.Lot_id = task2.Lot_id) &\wedge (task2.stage = 1 + task1.stage);
 \end{aligned} \tag{6}$$

Sequencing Constraints

Intra-stage sequencing

$$\begin{aligned}
 C_{task2} &\geq C_{task1} + co[taskpair] + porcs_time[task2] - M(2 - Y_{task1,j} - Y_{task2,j}) \\
 \forall \quad task1, task2 &\in \{relevant_fr_taskpair\}, j \in \{finishRoll_units\};
 \end{aligned} \tag{7}$$

$$\begin{aligned}
 C_{task2} &\geq co[anl_to_anl] + C_{task1} + porcs_time[task2] - M(2 - Y_{task1,j} - Y_{task2,j}) - M(1 - X_{task1,task2}) \\
 \forall \quad task1, task2 &\in \{relevant_annealing_taskpairs\}, j \in \{annealing_units\};
 \end{aligned} \tag{8}$$

$$\begin{aligned}
 C_{task1} &\geq co[anl_to_anl] + C_{task2} + porcs_time[task1] - M(2 - Y_{task1,j} - Y_{task2,j}) - M(X_{task1,task2}) \\
 \forall \quad task1, task2 &\in \{relevant_annealing_taskpairs\}, j \in \{annealing_units\};
 \end{aligned} \tag{9}$$

Tool (Roller set) Constraint

No overlap and roller (tool) changeover

$$\begin{aligned}
 C_{task2} &\geq C_{task1} + co[finishRoll_units] + porcs_time[task2] - M(2 - Y_{task1,j1} - Y_{task2,j2}) \\
 \forall \quad j1, j2 &\in \{finishRoll_units\}, task1, task2 \in \{finishRolling\}, (task1 \neq task2), (j2 < j1);
 \end{aligned} \tag{10}$$

Policy constraint

$$\sum_{task \in \{finishRolling\}} Y_{task,j1} * porcs_time[task] \geq \sum_{task \in \{finishRolling\}} Y_{task,j2} * porcs_time[task] \quad \forall \quad j1, j2 \in \{finishRoll_units\}, (j1 < j2); \tag{11}$$

Capacity Constraints

$$\sum_{task \in \{finishRolling\}} Y_{task,j} * porcs_time[task] \leq max_frCap \quad \forall \quad j \in \{finishRoll_units\}; \tag{12}$$

$$\sum_{\substack{task \in \{finishRolling\}, \\ wd[task.Lot_id]=w}} Y_{task,j1} \leq max_b2b_frCap \quad \forall \quad j \in \{finishRoll_units\}, w \in \{Wd\}; \tag{13}$$

Constraints for Rough rolling stage

Allocation Constraints

Every task must be assigned to a single processing unit j .

$$\sum_{j \in \{roughRoll_units\}} Y_{task,j} = 1 \quad \forall \quad task \in \{rough\ rolling\}; \tag{14}$$

Precedence Constraints

Lower bound

Completion time of each task must at least be greater than its processing time for each task. This is analogical to constraints (3) and (4) from other stages.

$$C_{task} \geq \sum_{j \in \{roughRoll_units\}} Y_{task,j} * porcs_time[task] \quad \forall task \in \{roughRolling\};$$

(14a)

Intra-stage precedence

$$C_{task2} \geq co[cooling] + C_{task1} + porcs_time[task2] \quad (15)$$

$$\forall task1, task2 \in \{roughRolling\}, (task1.Lot_id = task2.Lot_id) \wedge (task2.stage = 1 + task1.stage);$$

Inter-stage precedence (Linking constraint)

Evidently, this provides for the linkage between the roughing and finishing stage of a lot.

$$C_{task2} \geq co[rr_fr] + porcs_time[task2] + C_{task1} \quad (16)$$

$$\forall task1 \in \{roughRolling\}, task2 \in \{finishRolling\},$$

$$\forall (task1.Lot_id = task2.Lot_id) \wedge (task1.stage = last\ roughing\ stage) \wedge (task2.stage = first\ finishing\ stage);$$

Sequencing Constraint

Intra-stage sequencing

$$C_{task2} \geq C_{task1} + co[task1,task2] + porcs_time[task2] - M(2 - Y_{task1,j} - Y_{task2,j}) - M(1 - X_{task1,task2})$$

$$\forall task1, task2 \in \{relevant_rr_taskpair\}, j \in \{roughRoll_units\};$$

(17)

$$C_{task1} \geq C_{task2} + co[task2,task1] + porcs_time[task1] - M(2 - Y_{task1,j} - Y_{task2,j}) - M*(X_{task1,task2}) \quad (18)$$

$$\forall task1, task2 \in \{relevant_rr_taskpair\}, j \in \{roughRoll_units\};$$

Inter-stage sequencing (Linking constraint)

$$C_{task2} \geq C_{task1} + co[rr_fr] + porcs_time[task2] - M(1 - X_{task1,task2}) \quad (19)$$

$$\forall task1, task2 \in \{relevant_mixed_taskpair\};$$

$$C_{task1} \geq C_{task2} + co[fr_rr] + porcs_time[task1] - M*(X_{task1,task2}) \quad (20)$$

$$\forall task1, task2 \in \{relevant_mixed_taskpair\};$$

Tool (Roller set) Constraint

No overlap and roller (tool) changeover (new roller replacement)

$$C_{task2} \geq C_{task1} + co[NewRoller] + porcs_time[task2] - M(2 - Y_{task1,j1} - Y_{task2,j2}) \quad (21)$$

$$\forall j1, j2 \in \{roughRoll_units\}, task1, task2 \in \{relevant_rr_taskpair\}, (1 + j1) = j2;$$

Policy constraint

$$\sum_{task \in \{roughRolling\}} Y_{task, j1} * porcs_time[task] \geq \sum_{task \in \{roughRolling\}} Y_{task, j2} * porc_time[task] \quad (22)$$

$\forall j1, j2 \in \{roughRoll_units\}, (j1 < j2);$

Capacity Constraint

$$\sum_{task \in \{roughRolling\}} Y_{task, j} * porcs_time[task] \leq max_rrCap \quad \forall j \in \{roughRoll_units\}; \quad (23)$$

Linearization

$$C_{task} \leq T_{max} \quad \forall task \in \{tasks\}; \quad (24)$$

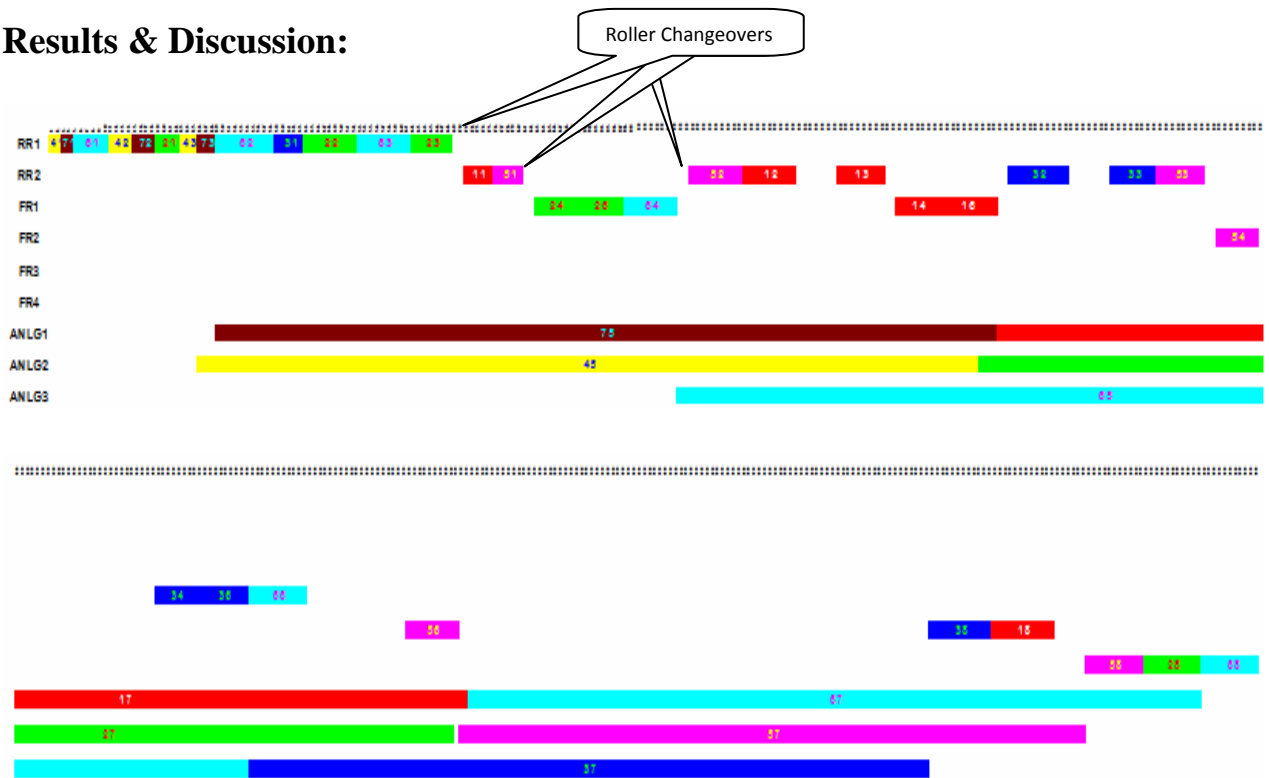
Uniqueness our formulation

- *We address the rolling batch scheduling problem at a task level granularity which is far more complex to model as against the traditional VRP based ‘coffin’ sequencing for pure flow shop which is the scenario in steel industry.*
- *We don’t follow the traditional VRP/TSP based models to formulate the problem, instead we have employed general precedence based continuous time model to formulate the problem because VRP based model has been found to be not so amenable for task level sequencing with variable re-entry flows, missing operations and so on .*
- *We have incorporated re-entry characteristics motivated by a real life Cold Rolling Plant in aluminium conversion industry (ACI).*
- *We have integrated planning of Annealing units with Cold rolling mill in a single model to examine schedule feasibility and capacity sensitivity.*
- *Data structure of our model allows for handling of hybrid re-entrant hybrid flow shop with missing operations.*
- *Our model tries to exploit the significant sparsity that is inherent in the problem on account of heterogeneous process structure through precise data structuring and slicing of parent data sets.*

Comparison with existing models from literature

Features	Our problem Aluminium FRP	Steel Rolling Problem from Literature
<i>Process Topology</i>	Multi stage , re-entrant hybrid flow based process with missing operations & by pass	Pure flow shop- <u>single m/c problem</u> with each job having same process seq.
<i>Decision</i>	Capacity feasible sequence & schedule	Roll wear minimization
<i>Schedule</i>	Non-permutation	Permutation
<i>Equipment</i>	Parallel m/c at some stages	All stages single m/c
<i>Processing</i>	Continuous(casting), Sequential(rolling) and batch process(annealing)	Only Sequential processing
<i>Equipment assignment</i>	Variable	None(dedicated one- to-one)
<i>Tool(Roller set)</i>	Frequent swapping between roughing & finishing	Dedicated work centres no tool(roller) changeover until wear out
<i>Granularity</i>	Task level	Lot/order level
<i>Changeovers</i>	Task , alloy , tool	Alloy dependent
<i>Resource constraint</i>	Dynamic – Annealing, CRM or Continuous casting depending on product mix, lot sizing and order release	None

Results & Discussion:



of non-permutation scheduling that could drive higher levels of optimisation in planning process and improve throughput. Most of the extant literature on “*Coffin sequencing*” is about *permutation* schedule on *Tandem rolling Mills* for hot rolling; no published work for metal industry models *annealing and rolling* jointly. In light of this, our formulation is an endeavour to bridge this significant gap in theory and practice. Analogous to width transition, hardness and gauge transition rules can also be incorporated when there is a need for them.

As for computational efficacy, there are tractability issues, when one tries to solve full scale commercial order book for a month. *General precedence* based formulation like ours does significantly reduce the complexity of traditional “*immediate precedence*” based formulations. Besides, use of accurate *set filtering* and *ordering* operation at pre-processing stage also helps to generate only strictly relevant pairs for computational experiments. We have been able to get very good integer solutions for up to 12 standard lots (350MT) in reasonable CPU time (under 30 mins) and work is underway to develop a suitable heuristic for solving much larger size problems(full month’s order-mix of about 3000MT). Further

interesting observation may be drawn from comparing the makespan vs number of lots or more precisely, cumulative/aggregate processing times of incremental lots from Fig.6. Experimentation is being carried out to assess the impact of degree of re-entry on capacity realisation and planning efficacy.

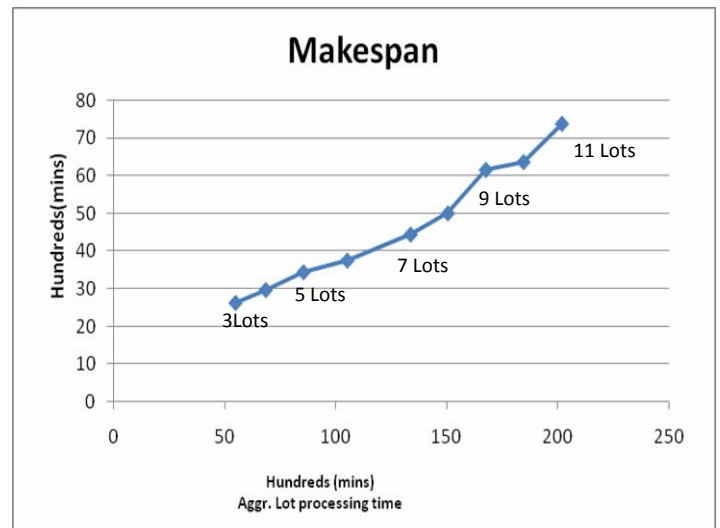


Fig-6 Makespan vs Lots

Work is also underway to develop dynamic pricing and discounting mechanism based on implication for capacity feasible planning in re-entrant flowshop. We are also in the process of quantifying the gains from such planning approach in comparison with permutation scheduling and cyclic scheduling that are being followed in industry.

The case under study is more amenable to deterministic analytical modelling as compared to popular dynamic capacity allocation modelling of typical repetitive semi-conductor manufacturing capacity planning. Besides, there is no significant publication for metal industry which addresses *re-entrant* product flow.

The current formulation doesn't provide for batching/ splitting decisions at annealing stages; there is a need for further research. There are formulation /computational difficulties in allowing for discrete batching decisions between Cold Rolling and Annealing which are serial and batch processes respectively.

References

1. Assaf et al.. Steel production schedule generation. *Int. J. Prod. Res.*, 1997, Vol. 35, No. 2, 467-477
2. Chen X., Wan W., Xu X. (1998) Modelling rolling batch planning as vehicle routing problem with time windows, *Computers and Operations Research*, 25 (12): 1127-1136.
3. Cowling P.(2003). A flexible decision support system for steel hot rolling mill scheduling. *Computers & Industrial Engineering* 45: 307–321
4. David et al. (2006) Advanced planning and scheduling systems in aluminium conversion industry, *International Journal of Computer Integrated Manufacturing*, Vol. 19, No. 7, October–Nov 2006, 705 – 715
5. David, F., Pierreval, H. and Caux, (2005) C, Enterprise resource planning systems in aluminium conversion industry. *Prod. Planning Control*, 2005, 16, 785–795.
6. Elmaghraby Salah E. (1991): Manufacturing capacity and its measurement: A critical evaluation. *Computers & OR* 18(7): 615-627
7. Kosiba, E. D., Wright, J. R., & Cobbs, AE. (1992). Discrete event sequencing as a travelling salesman problem. *Computers in Industry*, 19, 317–327.
8. Ladurantaye et al.. Scheduling a hot rolling mill. *Journal of the Operational Research Society* (2007) 58, 288–300
9. Moon et al.(1999) Scheduling of the batch annealing process — deterministic case, *Computers and Chemical Engineering* 23 (1999) 1193–1208
10. Pinto and Grossmann.(1998) Assignment and sequencing models for the scheduling of process systems. *Annals of Operations Research* 81: 433– 466
11. Pan et al. (2009) A method of solving a large-scale rolling batch scheduling problem in steel production using a variant of column generation, *Computers and Industrial Engineering* Volume 56 , Issue 1: 165-178
12. Simons & Simpson (1997), An exposition of multiple constraint scheduling as implemented in the goal system (FORMERLY DISASTERTM), *Production and Operations Management*, Volume 6, Issue 1 (p 3-22)
13. Stauffer L and Liebling TM(1997). Rolling horizon scheduling in a rolling-mill. *Ann Opns Res* 69: 323–349
14. Tang et al.. Lagrangian relaxation algorithms for real-time hybrid flowshop scheduling with finite intermediate buffers. *Journal of the Operational Research Society* (2006) 57, 316–324
15. Uzsoy, R., Lee, C.Y., Martin-Vega, L.A.(1992), "A Review of Production Planning and Scheduling Models in the Semiconductor Industry Part I: System Characteristics, Performance Evaluation and Production Planning", *IIE Transactions on Scheduling and Logistics*, 24, 47-61.

16. Uzsoy, R., Lee, C.Y., Martin-Vega, L.A.(1994), "A Review of Production Planning and Scheduling Models in the Semiconductor Industry Part II: Shop-Floor Control", *IIE Transactions on Scheduling and Logistics* 26, 44-55.
17. Zhang et al. (2008), Dynamic capacity modeling in semiconductor assembly manufacturing, *International Journal of Production Research* Vol. 46, No. 3, 1 February 2008, 739–752
18. Vollman et al.(2004) *Manufacturing Planning And Control Systems For Supply Chain Management*, The McGraw-Hill Companies