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DISTRIBUTED CO-ORDINATION OF STEEL-MAKING OPERATIONS FOR REDUCED PRODUCTION STOPPAGES

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Abstract: This paper reports on the development of algorithms for factory decision-making and scheduling systems. The particular decision-making and schedule co-ordination problem studied relates to the synchronisation of a series of events in the context of a production changeover in electric arc steel-making. The paper explores two distributed approaches to this co-ordination problem. The first is a simple manual algorithm that helps co-ordinate the behaviour of steel-plant production via (i) the exchange of relevant inter-unit process information and by (ii) recommending operators take appropriate local actions. The second approach provides a framework for a more general class of problems, and supports either a partially or fully automated co-ordination approach. It is based on an approach from the field of distributed artificial intelligence, referred to as Partial Global Planning (Durfee 1988).

Keywords: Co-ordination, Real-time decision making, Distributed Artificial Intelligence

1. INTRODUCTION

This paper is concerned with improving dynamic production performance (responsiveness) via innovations in shop-floor level decision-making and execution control strategies[1]. An underlying theme of these investigations was to transform concepts from the field of distributed artificial intelligence into the real-time scheduling domain (Baker, 1998).

The particular distributed co-ordination problem studied here was in the context of an electric arc furnace steel-making operation (See Section 2). In the selected process, achievement of the desired production throughput was of critical importance in minimising conversion costs per tonne of steel produced. Achievement of higher production throughput was found to be limited due to tight inter-process physical and operational coupling constraints and significant cycle time variabilities in production operations. In addition to this, throughput control was also complicated by implementation constraints on shop-floor decision-making strategies. In particular, the shop-floor control (SFC) environment was distinguished by characteristics such as: (a) the localisation of control decisions associated with individual production operations, (b) the absence of persistent centralised/global information, (c) the requirement of aligning localised decisions with the global goal of achieving higher production throughput, and (d) the need for human based control decisions.

The particular problem studied here is concerned with minimisation of stoppage times of the caster unit. We examine the co-ordination needs that arise between the caster and the previous stage, the Ladle Furnace (LF). Such issues, which relate to (distributed) decision-making at the scheduling/execution control interface in a process-manufacturing environment (like a steel-plant), are not highly prevalent in the existing literature. However, a number of studies have developed significant insights into similar problems. For example, Baker (1998), Duffie and

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[1] The authors gratefully acknowledge the support of industrial collaborators Allied Steel and Wire and of the U.K. Engineering and Physical Sciences Research Council.

Prabhu (1994), Lin and Solberg (1994), Bongaerts et.al. (1997) discussed the integration of online scheduling and execution control in discrete component manufacturing applications. Distributed approaches proposed therein use autonomous decision-making strategies integrated within a co-operative framework to facilitate better management of the influence of disturbances on production performance. Mori et.al. (1988), Numao (1994) and Agre et.al. (1994) proposed co-operative methods for information sharing and/or decision making in steel plant operations (not necessarily in a distributed manner). Cott and Macchietto (1989) considered the problem of reactive scheduling in batch processes. We demonstrate in this paper that the problem of achieving minimal stoppages at the caster in steel-making can be addressed as a distributed, co-ordinated scheduling problem (section 3). A co-ordination strategy which addresses this problem is presented and evaluated (Section 4) and it is demonstrated that the use of such strategies can reduce the throughput loss due to caster hold-up by a value of 5-25 minutes on average compared to current operating practice. In order to generalize this strategy to a wider class of problems, in Section 5 we propose a co-ordination framework which uses the concept of Partial Global Planning (Durfee, 1988).

2. PROCESS DESCRIPTION

The steel-making operation under investigation starts with an electric arc furnace (EAF) as the primary melting converter. The steel scrap is melted here into batches or *heats* of approximately 120 tons. The molten steel (melt) is then tapped into ladles, which are then transferred to the next stage, the Ladle Furnace (LF). Here temperature and metallurgical corrections are made to the melt using electric power and alloys. The treated ladles are then delivered to the caster using cranes, where the melt is cast into billets of the desired length and shape.

It is important that ladles be delivered to the caster within a time-window, which is governed by current production conditions. Late delivery of a ladle may cause a premature loss of continuity in the planned sequence of heats, resulting in a significant loss to production throughput. Similar throughput losses occur due to late delivery after caster changeovers (as described in section 3). Early delivery of a ladle is also problematic. Having treated the melt in a ladle, its temperature tends to drop. To ensure the adequate temperature of the melt during casting, the treated ladle must be transported to the caster and opened within approximately a half-hour of completion of ladle treatment (this allowable waiting duration for the ladle is termed $\boldsymbol{d_{MAXWAIT}}$). If a ladle has been waiting for a period exceeding this limit, then it needs to be retreated before it is cast. This may also result in ladles, which have already been delivered to the caster needing to be moved back to the LF. Such retreatment situations incur additional production costs (e.g. extra power consumption, lost ladle furnace and crane availability). To avoid such repercussions of early or late ladle delivery, it is always essential to achieve co-ordination between ladle treatment and the operating cycles of the EAF and the caster. We next illustrate a particular scenario called caster *Turnaround*, where the co-ordination of ladle treatment with caster operation is essential in improving the caster throughput.

3. TURNAROUND CO-ORDINATION PROBLEM

During continuous steel-making operation, a number of planned/unplanned scenarios arise that require the shutdown of the continuous casting process. In these situations, the maintenance process that is carried out to set-up the caster again is termed the caster *Turnaround*. Aggregate loss of production time due to non-availability of the caster during turnaround has a major influence on throughput. The total stoppage time of a caster during turnaround comprises a period of carrying out the actual maintenance jobs (not examined further) and a period thereafter, during which the caster awaits the delivery of a treated ladle. The paper investigates co-ordination mechanisms to reduce this lateness in delivery of a treaded ladle, so that the overall caster *stoppage time* can be lessened.

Ideally, late delivery of a ladle can be avoided if the ladle treatment and the ladle delivery (to the caster) have been scheduled accordingly in advance of turnaround (See Fig.1), albeit such that the wait limit ($\boldsymbol{d_{MAXWAIT}}$) is not exceeded before the ladle is opened.

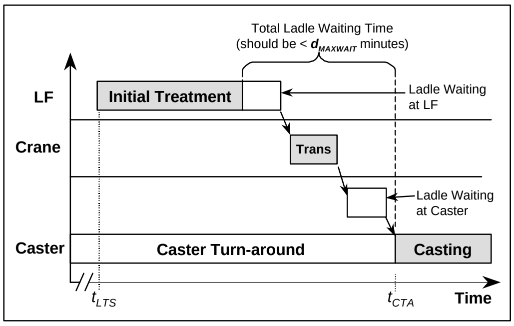

Fig. 1. Gantt chart of Ladle Treatment and Caster Turnaround

In this situation, the decision to be made by the LF operator is to choose a suitable value of the ladle treatment start time ($\boldsymbol{t_{LTS}}$) as per following equation.

$$t_{LTS} = t_{CTA} - d_{TRANS} - d_{LF} - d_{WAIT} \qquad (1)$$

Where, $\boldsymbol{t_{CTA}}$ is the turnaround completion time, $\boldsymbol{d_{LF}}$ is the ladle treatment duration, $\boldsymbol{d_{TRANS}}$ is the ladle transfer duration, and $\boldsymbol{d_{WAIT}}$ is any choice for the ladle wait duration such that $\boldsymbol{d_{WAIT}} + \boldsymbol{d_{TRANS}} < \boldsymbol{d_{MAXWAIT}}$. Thus, if the LF operator gets an estimate for $\boldsymbol{t_{CTA}}$ and

d_{TRANS} from respective unit operators and estimates the value of d_{LF}, he can easily calculate a candidate value of t_{LTS} using equation (1). Provided the estimates involved are sufficiently accurate, this value of t_{LTS} will result in zero caster hold-up and will avoid the need for retreatment.

In practice, however, there may be significant errors in the t_{CTA} and d_{LF} estimates due to uncertainties in process dynamics and the limited duration estimation capabilities of human operators. These estimation errors may lead to early or late delivery of the ladle with consequences as described in section 2, namely lost production throughput, increased power consumption, lost LF availability. What current plant practice is to exercise a *safe* option in terms of completely avoiding retreatment, that is to start ladle treatment only after the turnaround has been finished. However, this rather conservative, non-coordinated approach results in a caster hold-up of at least 25 to 30 minutes, a major loss to production throughput in the long term.

Also, the estimated values of t_{CTA} and d_{LF} (and thus the value of t_{LTS}) may change over time as new information concerning process execution becomes available. In fact, actual throughput performance depends not only on the estimation accuracy of processing durations and the rescheduling of t_{LTS} using equation (1), but also on the timing of these activities and the nature of time-variation in estimation error (so-called estimation error profile).

This paper proposes co-ordination approaches which can cope with time-varying duration estimates, and which result in a reduced caster hold-up delay compared to current practice, albeit with an increased (but normally small) chance of retreatment.

4. CO-ORDINATION ALGORITHMS FOR ITERATIVE RESCHEDULING OF LADLE TREATMENT

In the case of turnaround co-ordination, it would be advantageous if the turnaround completion time (t_{CTA}) estimates could be revised while turnaround execution is in progress (in general, these estimates become more accurate over time). Using these revised estimates, the ladle treatment start time (t_{LTS}) can also be amended accordingly. Under these circumstances, a decision is required as to precisely when and how often this re-estimation (referred here as *sampling*) and the ladle treatment rescheduling procedure should be performed. These timings must be chosen such that sufficient information related to turnaround is acquired, as well as ensuring that the workload on operators due to the overhead of the estimation and co-ordination activities is not unduly high. A manually[2] operable numerical algorithm is required, which (i) uses the most recent revised duration estimates to calculate the subsequent re-estimation time (referred to here as the *sample time*) t_S, (ii) provides a value of t_{LTS}, which eliminates or reduces the caster hold-up resulting from late delivery of a treated ladle, and (iii) avoids the retreatment. Also, this algorithm should remain valid over a wide range of turnaround estimation error profiles and should give consistent reduction in caster hold-ups. A general procedure, as described next, was first sought which interleaves these tasks of duration estimation, communication and decision-making.

4.1. General Procedure for Co-ordinating the Ladle Treatment

The general procedure operates as follows: (i) At the start of and during the turnaround, the LF operator obtains estimates of t_{CTA} from the caster operator. These estimates can be in the form of the most likely value or upper/lower bounds. (ii) Each time the LF operator must decide to either wait for a period and obtain further estimates or to wait for a period and start the ladle treatment. A constant d_S, the so-called nominal sampling interval, (which influences but does not uniquely determine the actual average sampling interval) is introduced here to calculate the next t_S value. A suitable choice of d_S needs to be made in order to achieve a trade-off between estimation accuracy which results from a higher average sampling rate and the overhead of rescheduling.

Four different ladle treatment co-ordination algorithms were devised using this general procedure as a common framework. These algorithms employ different methods of calculating the next value of t_S, namely: forwards sampling, backwards sampling and anticipative (predictive) sampling. We next describe the backwards sampling based algorithm as an illustration. (Refer to Matson (1999) for further details).

4.2. The Backwards Sampling Based Algorithm

In the backwards sampling based co-ordination algorithm (Fig. 2), the current estimate of t^{+}_{CTA} is used to obtain a new time variable $t^{+}_{MAXWAIT}$[3] and hence the value of the next sample time t_S. (t^{+}_{CTA} denotes the upper bound on the estimate of t_{CTA}. This conservative estimate is used to try and avoid any chance of early delivery of the ladle). The time between the two consecutive samples in this algorithm should not be less than the minimum

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[2] *Manual* operability of the algorithm was a critical requirement in respect to the industrial collaborator involved in this work.

[3] $t_{MAXWAIT}$ is the earliest time before which if ladle treatment is started, the ladle would require retreatment. ($t^{+}_{MAXWAIT}$ represents an estimated upper bound on its value based on t^{+}_{CTA}, the estimated upper bound on turnaround completion time). Mathematically,

$$t_{MAXWAIT} = t_{CTA} - d_{LF} - d_{MAXWAIT} \qquad (2)$$

sampling period d_S^{min}- the minimum time required to obtain an estimate.

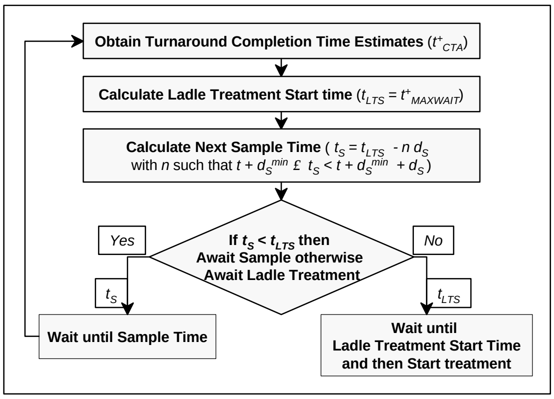

Fig. 2. The Backwards Sampling Based Algorithm

4.3. *Evaluation of Co-ordination Algorithms*

In order to analyze the throughput performance of the ladle treatment co-ordination using the proposed algorithms, we simulated these algorithms in Matlab® software. Four different turnaround duration error profiles were adopted as means of capturing the dynamics in the turnaround process and the errors in human duration estimation. The profiles describe upper and lower estimates on turnaround duration estimation errors and are characterized as follows: (a) linearly decreasing error with varying slopes, (b) linearly decreasing error with varying slopes and additive random noise, (c) error profiles extrapolated from the data collected during plant trials, and (d) step drop in errors. Illustrations of these profiles for a turnaround of 90 minutes are shown in Fig.3. In addition to the profiles, the actual turnaround duration and d_S values were also varied in order to determine the general algorithmic performance.

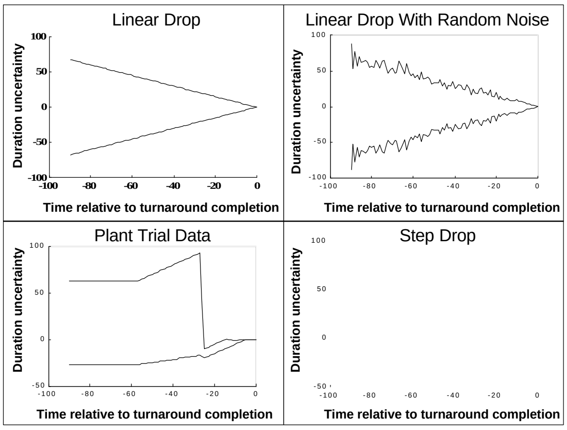

Fig. 3.Turnaround Duration Estimation Error Profiles

The error profiles shown in Fig. 3 were used with the forward and anticipative[4] algorithms for a range of turnaround durations (20 to 90 minutes). Fig. 4 depicts the resulting caster hold-up delay values (averaged over the whole range of turnaround durations) vs. the average sampling period. (Note that values on both axes depend on d_S, the algorithm and the estimation error profile).

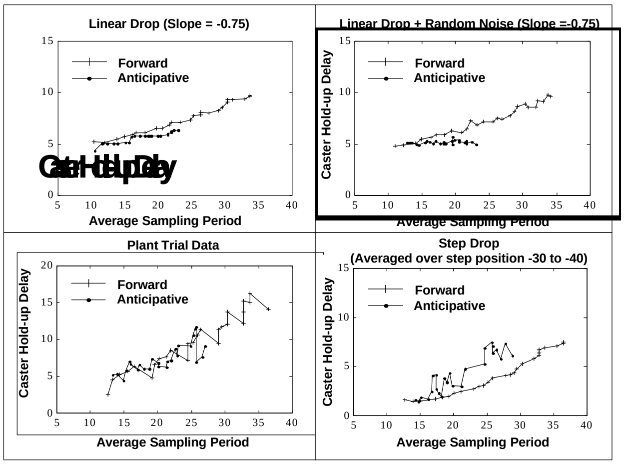

Fig. 4. Caster Hold-up vs. Average Sampling Period Curves

In general, it was inferred from the simulations that the use of the suggested co-ordination algorithms should reduce the caster hold-up delay due to late ladle delivery by a value of 5-25 minutes compared to the current *safe* option (Matson 1999). Further analysing the performance of two algorithms in Fig. 4, indicates that the anticipative algorithm results in lower value of hold-up delays for the linear drop as well as the linear drop with random noise type of estimation error profiles, while the performance remains relatively the same for the plant trial profiles. We note, however that the performance of these two algorithms in the case of step-drop type estimation errors is not well understood yet and requires further investigation. In order to examine the consistency of this algorithmic performance, the curves in Fig. 4 were appended (not shown here) with the standard deviation values of the hold-up delay (averaged over the range of turnaround durations). It was observed that the anticipative algorithm performs more consistently with less variance compare to forwards algorithm for the linear and the linear with random noise type errors.

Observations made during plant visits suggested that co-ordinating ladle treatment with turnaround in isolation - without considering the operation of adjoining production units such as the EAF - could significantly limit the achievable gain in production throughput. Introducing such additional constraints requires the extension of the co-ordination algorithms described in this section to include production parameters of adjoining units. Further, in order (i) that a similar predictive approach can be more

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[4] The anticipative algorithm operates very similar to the backwards algorithm except it includes the prior anticipation of estimation errors in rescheduling calculations as a means of improving the performance.

generally applied to other rescheduling problems within this and other production environments, and (ii) that the suggested co-ordinated strategies be automated partially or fully, a more generalised framework for managing distributed co-ordination was sought.

5. SCHEDULE CO-ORDINATION USING PARTIAL GLOBAL PLANNING

In this section, we introduce a general co-ordination framework that can support the (distributed) co-ordination algorithm introduced in the last section while readily enabling extensions and generalisations of this approach. A number of applications within the Distributed Artificial Intelligence (DAI) field have discussed co-ordination issues in a distributed framework (See e.g. Smith (1980); Cammarata et.al. (1983); Lin and Solberg (1994), Durfee (1988)), and we will apply such methods to the process manufacturing co-ordination problem discussed in this paper. In particular, Durfee (1988) proposed a unified co-ordination framework of *Partial Global Planning*, using intelligent, autonomous computing elements or *nodes* which co-operate with other nodes to solve distributed problems in a co-ordinated manner. The use of *self-modelling* as a means of managing the interaction between nodes and the achievement of the global co-ordination behaviour by aggregation of partial group-based co-ordination are the two key attributes of a Partial Global Planning co-ordination framework (Durfee,1988). In the case under investigation, these two attributes were explored in the turnaround co-ordination problem.

5.1. Partial Global Planning Based Scheduling Framework

We briefly describe here the attributes of a Partial Global Planning kind of scheduling framework. (See Durfee (1988) for further details.)

- *Identification of scheduling nodes and node-groups:* The initial phase in developing a Partial Global Planning based scheduling framework involves identifying the so called *scheduling nodes* and how they are organised within the framework. In our case, we designated each production unit as a single scheduling node. These nodes are then clustered to form several *node-groups*. The clustering is done by identifying operational couplings that exist between production units involved in different parts of the overall process. In this situation, a single scheduling node (or referred hereafter as a node) can form a part of several node-groups.
- *Forming Local Plan (LP) and Node Plan (NP):* Once organized in node-groups, each node in a node-group identifies its operational requirements and accordingly schedules its local activities to be performed in the near-term future. This schedule model, detailing the local activities is referred as the *Local-plan* (LP) of the respective node. A LP contains necessary execution-time details such as predicted process outcomes of individual activities, their start/end times, operational costs, equipment operating modes etc. Each node then summarises the details of its local schedule (LP) into an abstract higher-level schedule model referred as the *Node-plan* (NP). A NP contains an aggregated but sufficient level of information about its associated LP, such as start/end times of major local activities, coupling variables between the local process and the adjacent unit processes etc. As NPs are much less detailed than LPs, nodes can exchange their NPs (as their self-models) with other nodes in the node-group to provide them with a view of their ongoing local processes. By doing this, nodes enable themselves to establish a global view of overall group activities and hence to identify how their local activities fit into this more global view.
- *Partial Global Planning:* In order to harmonise the achieved partially global view of group activities, each node in the node-group then interleaves the NPs of other participating nodes with its own NP and forms a group-level schedule model called as the *Partial Global Plan* (PGP). Forming a PGP also allows a node to identify what possible conflicts can arise in the future between node processes and/or what opportunities exist to improve the overall group performance. All nodes form and maintain their own set of PGPs according to their participation in different node-groups. Each node then (i) strives to resolve the identified conflicts (if there are any) using its scheduling knowledge (ii) selectively reschedules its own as well as other nodes' activities in its set of PGPs, and (iii) forms a modified set of PGPs which is better in respect of achieving the process requirements. Nodes then propose these modified PGPs to other participating nodes in the node-group to initiate negotiation on the proposed changes. This process of PGP formation/modification and proposals/ counterproposals iterates between nodes till they converge on a satisfactory (not necessarily optimal (Durfee, 1988)) solution. At this instance, each node translates changes proposed in its set of PGPs to its local schedule (LP), so that the actual process execution matches with the agreed changes. The overall scheduling activity and the actual process execution remains interleaved in real-time.

5.2. Modelling the Turnaround Co-ordination inPartial Global Planning Framework

In the turnaround co-ordination problem, all production units (i.e. EAF, LF, Crane and the caster) were represented by separate scheduling nodes. These nodes were then clustered into two node-groups: (i) a node-group (comprising LF, Crane and the caster) to co-ordinate turnaround related activities, and (ii) a node-group (comprising EAF, LF and the crane) to synchronise the ladle treatment and empty ladle replacement activities with the EAF cycle. Fig 5 depicts a view of LPs and NPs formed during turnaround and the subsequent casting period (sample durations are also shown in brackets).

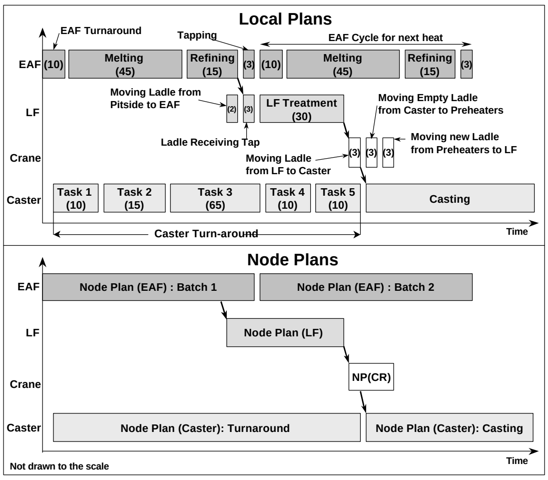

Fig. 5. Gantt Chart For Local Plans and Node Plans

Fig.6 represents the schedule models present at the LF node. The PGPs denoted: PGP_LF:1 and PGP_LF:2 signify the participation of LF node in both node-groups.

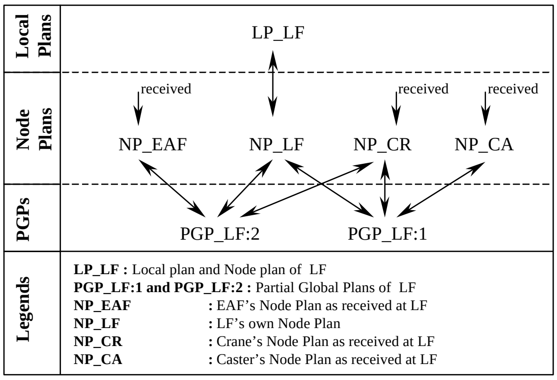

Fig. 6. Schedule Models at the LF

The partial global planning based turnaround co-ordination mechanism was programmed in the Stateflow® package of Matlab® software. In order to incorporate the co-ordination algorithms presented in section 4 within these simulations, the LF node was designated as the central co-ordinator rescheduling the PGPs for both node-groups. Further, only t_{LTS} was rescheduled to accommodate the changes in turnaround times. Fig.7 depicts a simulation case, demonstrating how the schedules evolve over time. At time C the turnaround is extended by 60 minutes from the initial situation (A, B). t_{LTS} was delayed by an amount such that the ladle is delivered within desired time of turnaround completion and the lost LF availability is minimized.

One critical issue not fully explored was that of deciding the times at which a node should update and exchange its NP and PGPs, such that other nodes can predict its behaviour more precisely. Co-ordination algorithms described in section 4 provide a possible solution to this problem.

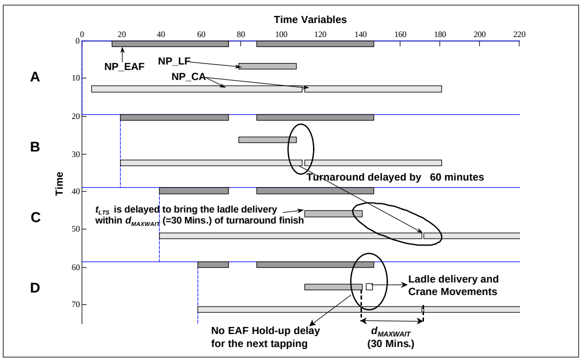

Fig. 7. Turnaround Co-ordination Using Partial Global Planning

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