CONSTRAINT MODELING AND BUFFER MANAGEMENT WITH INTEGRATED PRODUCTION SCHEDULER

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ABSTRACT

Constraint modeling is a necessary step in construction planning. The basic CPM approach provides a simple and practical means for resolving time-related precedence constraints between activities. However, most CPM-based tools do not support dealing with the constraints regarding resource and information availabilities at the production-level planning phase. When these constraints are concealed in the work plan, it is difficult to assure that they are removed in time so that work takes place as planned. Consequently, the reliability of work plans/assignments will be reduced. This paper presents a scheduling tool called integrated production scheduler (IPS) to handle the non-precedence constraints in supply chain and information flow. The IPS has three main objectives to be fulfilled. The first is to promote work plan reliability. The second is to increase resource utilization and throughput based on the estimated resource profile. The third is to maintain a stable work flow through reducing uncertainties in the supply chain and information flow. To further facilitate reliable planning, a set of schedule buffers are established to help manage the constraints. Specifically, the working buffer and the shielding buffer ensure quality assignments by removing resource conflicts and supply chain uncertainties. The pulling buffer and the screening buffer increase resource and information availabilities by managing the delivery issues in advance. With the proposed schedule buffer management, it is feasible to enhance the reliability of look-ahead plans and consequently achieve lean process management.

KEY WORDS

Constraint, buffer management, lean construction, look-ahead planning, Integrated Production Scheduler.

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INTRODUCTION

Constraint management is the core issue in production planning and control during the course of project. It involves identifying the constraints (e.g. manpower, materials, machines, and information prerequisites) and eliminating them to achieve fewer disruptions in production processes and higher throughput against limited available resources. The CPM/PERT-based network scheduling approaches have been extensively employed to identify prerequisite activities and determine activity start/finish times. Although simple to use and capable of solving sophisticated problems, the basic CPM/PERT methodologies have been criticized for lacking the ability of dealing with non-precedence constraints, e.g. resource constraints. These constraints generally account for the resource and information availabilities that are crucial in determining the actual activity start times. It is necessary to recognize and resolve such non-precedence constraints through effective constraint modeling and management otherwise production plans will be unreliable.

Most available methodologies for resolving the non-precedence constraints, or resource constraints in particular, may fall into one of the following categories, namely heuristic (Davis 1973, Elsayed et al. 1986, Shanmuganayagam 1989, and Tsai 1996), optimal (Elmaghraby 1993, Yang et al. 1993, Chan et al. 1996, and Schniederjans et al. 1996) and simulation (Andersen 1995, and Chan 1997) approaches. These methodologies help find optimal or near-optimal solutions on the constrained resource allocation problems, thus overcome the weakness of the basic CPM/PERT approaches. A major difficulty in applying these methodologies, however, is that a predetermined resource profile must be supplied first. The profile contains key resource constraints to be satisfied so that any changes on it may affect the schedule subsequently. For this reason, the validity of the schedule is largely dependent on the reliability of the resource profile which comprises a set of variables, rather than constants, changing from period to period. If the profile is subjected to high uncertainties from the supply chain and work flow, it is unlikely to obtain 'optimal' results based on the above methodologies.

As a matter of fact, reliable planning often requires more details on the resource and information delivery issues at the production time. These issues represent the 'hidden' constraints regarding resource and information availabilities, which are insignificant in the master schedule, important in the look-ahead plans, and essential when assignments are given. Managing these constraints is related to the management of supply chain and information flow, respectively. If they could be explicitly identified and removed in the look-ahead plans, fewer uncertainties would exist and a stable work flow would be achievable. Consequently, the project manager may focus on optimizing resource utilization, reducing excessive inventories, and increasing throughput.

In order to maintain the simplicity of the CPM while modeling more kinds of constraints in the look-ahead plan, Chua et al. (1999) and Shen et al. (2000) proposed a tool, namely Integrated Production Scheduler (IPS), to manage two types of integrated constraints (i.e. RESOURCE and INFORMATION constraints) in addition to PROCESS constraints in production processes. The IPS contributes to reducing the uncertainties of resource and information deliveries through pull-driven production control and messaging systems. This paper further discusses the determination of the adjusted activity start times under the influence of non-precedence constraints. To facilitate reliable look-ahead planning, a set of schedule buffers are established, specifically working, shielding, pulling, and screening buffers. These buffers help achieve quality assignments (Ballard and Howell, 1998) through removing constraints in advance and shielding assignments from most foreseen process uncertainties. Eventually, this would help achieve lean process management.

A PRODUCTION VIEW ON CONSTRUCTION PROCESSES

Construction processes have many similarities with manufacturing processes. *Table 1* shows one brief comparison between each other. From the production point of view, crew tasks within construction activities have equivalent roles as machine tasks in manufacturing processes. Accordingly, many production theories could be applied to construction processes under similar principles.

Table 1: Comparison between Construction and Manufacturing Processes

	Construction	**Manufacturing**
Elements in Process	Crew tasks	Machine tasks
Input	Time, money, resources, space and information	Time, money, resources, and information
Output	Finished structures	Finished parts
Capacity utilization	Percent Plan Complete (PPC)	Throughput
Bottlenecks	Tasks on critical path	Constraint machines
Principle	No delay on critical path	No idle on constraint machine
Disruption	Task delay	Machine breakdown (or idle)
Prevention	Reliable planning	Maintenance
Management of Work in progress	Supply chain management	Buffer management

According to the theory of constraints (TOC) (Goldratt 1990), any production system is restricted by one or a few constraint machines. The capacity of the constraint machine determines the overall system throughput. In order to maximize the throughput against limited resources, the constraint machine should be protected with a certain level of work in progress (WIP), which is defined as a constraint buffer. The size of the constraint buffer should be kept big enough to avoid starvation on the constraint machine and, meanwhile, relatively small to cut down the WIP inventories.

When TOC is adopted in the construction processes, crew tasks on critical path can be viewed as machine tasks on constraint machines. If some key prerequisites have not been sufficiently supplied, the critical path tasks may be unduly delayed, which is analogous to machine breakdown (or idle) in the manufacturing processes. In the same way, a protection buffer should be placed in front of the critical path tasks to ensure adequate resource (and information) availabilities. This concept has evolved into a constraint-management-based approach for the look-ahead planning with the IPS, which is illustrated in the following sections.

CONSTRAINT MODELING WITH THE IPS

Integrated constraints can be described as any indispensable resource and/or information prerequisites associated with a production process. They play important roles in determining whether a process is ready to be executed. Not all kinds of integrated constraints are worthwhile to be considered in the IPS look-ahead plan but must be resolved at the assignment level. Some shared common resources (e.g. general workers), for example, are not significant to be modeled unless they are limited and competed for by more than two processes concurrently. In this case, coordination nearer the time of work to take place is required, typically just before the assignment is made. Those that require timely deliveries (e.g. concrete, pre-cast components, and drawings), on the other hand, should receive earlier attention. The purpose of constraint modeling is to fulfill three major objectives. The first is to achieve reliable work plans where constraints of resource and information availability issues have been resolved and quality assignments can be made. The second is to increase resource utilization in the plan and consequently boost throughput in production. The third is to maintain a stable work flow via reducing uncertainties in the supply chain and information flow. In essence, managing constraints helps develop appropriate buffers to protect bottleneck activities from the uncertainties related to resource and information availabilities.

As shown in the Fig. 1, each IPS activity consists of two types of 'integrated constraints'. The RESOURCE constraints represent the availability of physical resources, e.g. materials, manpower, equipment, and space etc. The information constraints represent the availability of information prerequisites, e.g. request for information, shop drawing, and design approvals, etc. Among various constraints, only a few deserve special attention depended on their availabilities on site or the history of the suppliers' performance. They are considered as the 'key' constraints to processes, which are conflicted or subject to higher uncertainty from the supply chain, or both. Therefore these constraints must be highlighted and properly managed in the look-ahead plan. The rest, however, may not necessarily be monitored in the IPS but will be resolved by the superintendent before assignments are made.

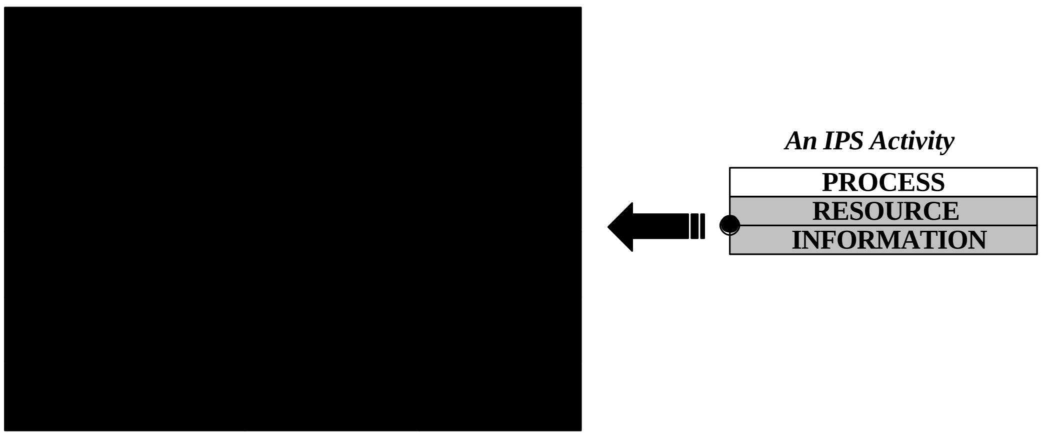

Fig. 1: Integrated Constraints in an IPS Activity

For each integrated constraint item, a time attribute called estimated available time (*EAT*) is added to evaluate its availability by comparing the *EAT* to the activity's start time. When the *EAT* is later than the activity's start time, either the constraint item would be expedited or the activity would be rescheduled (or delayed). The *EAT* is the key to determine both the actual activity's start time and the resource/information delivery time. It is valuable for controlling the WIP so that an appropriate size of the constraint time buffers may be established.

According to the basic CPM procedure, the scheduled start time S_j for any activity A_j in the project P is determined by the following condition to avoid delay in project completion:

$$ES_j \le S_j \le LS_j, \qquad \forall A_j \in P \tag{1}$$

where $ES_j = \underset{all\ \ i}{\text{MAX}}\begin{Bmatrix} INITIAL \quad TIME \\ EF_i + FS_{ij} \end{Bmatrix}$ is the early start time of A_j, in which $EF_i = ES_i + D_i$ is the early finish time of A_i, A_i being the predecessors of A_j; $LS_j = LF_j - D_j$ is the late start time of A_j, in which $LF_j = \underset{all\ \ k}{\text{MIN}}\begin{Bmatrix} TERMINAL \quad TIME \\ LS_k - FS_{jk} \end{Bmatrix}$ where LS_k is the late start time of A_k, the successors of A_j. *FS* denotes the finish-to-start precedence constraints.

In consideration of the integrated constraints, the basic CPM approach is augmented with the *EAT* constraints so that the modified activity start time is now determined by both the precedence and the integrated constraints:

$$ES_j^{'} \le S_j \le LS_j \qquad \forall A_j \in P \tag{2}$$

where $ES_j^{'}$ is the modified early start time of activity A_j to account for reliable plan,

$$ES_j^{'} = \text{MAX}\begin{Bmatrix} \underset{all\ \ i}{\text{MAX}} \begin{Bmatrix} INITIAL \quad TIME \\ EF_j + FS_{ij} \end{Bmatrix} \\ \underset{all\ \ l}{\text{MAX}}(EAT_{jl}) \end{Bmatrix} \tag{3}$$

in which EAT_{jl} represents the estimated available time for the l^{th} constraint of activity A_j.

The *EAT* brings a 'new dimension' on modeling resource/information delivery time to adjust the CPM activity start time. Fig. 2 shows that the *EAT* may affect activity float and would even alter the actual activity start time if it were delayed beyond the S_j. If activity J is on the critical path, this will cause schedule delay in the downstream.

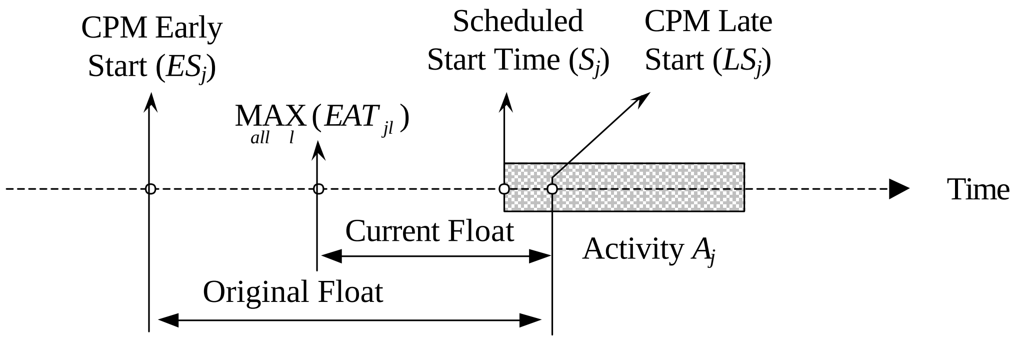

Fig. 2: Determination of Activity Start Time with the Consideration of EAT

The late delivery time (LDT) is another attribute determining the minimum time buffer to protect bottleneck activities from being delayed due to resource/information delivery problems (see Fig. 3):

$$LDT_{jl} = EAT_{jl} - (1 + a)t_{jl} \tag{4}$$

where LDT_{jl} is the late delivery time for the l^{th} constraint of activity A_j, t_{jl} is the setup time for the l^{th} constraint of A_j (if applicable), and a is a disturbance variable accounting for the deviation of t_{jl} under certain degree of confidence (e.g. 90%). A confirmation on LDT_{jl} should be received from the relevant project participant to make sure delivery will be timely.

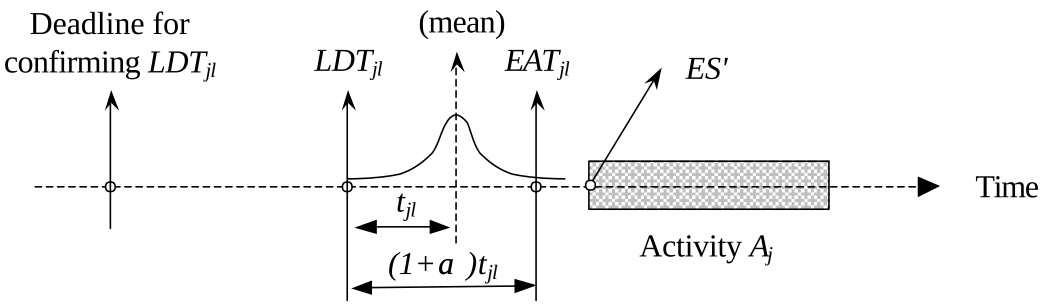

Fig. 3: Determination of Late Delivery Time for the l^{th} Constraint of A_j

With the integrated constraints, it is now possible to improve the reliability of work plans because the uncertainties surrounding the resource and information prerequisites of activities can be managed. The modified early start time can reinforce quality assignments since the key resource and information constraints have been identified and possibly resolved by the following schedule buffer management.

SCHEDULE BUFFER MANAGEMENT

The IPS has established a series of schedule buffers to facilitate the management of constraints. Specifically, they are working buffer, shielding buffer, pulling buffer, and screening buffer described subsequently (see Fig. 4). The concept of schedule buffers is different from that of constraint buffers. A constraint buffer is either a volume buffer or a time buffer placed in front of a constraint machine (or process) for managing the WIP, whereas a schedule buffer is a specific time frame in the IPS look-ahead plan in which deliveries of resource and information prerequisites are controlled and assured to avoid disruptions at bottleneck processes.

At the look-ahead planning level, activities in the master schedule are decomposed into smaller activities where key resource and information constraints can be identified. These activities maintain the original precedence relationships but reveal greater details. They will be further decomposed into tasks (or work assignments) shortly before construction work is executed. Confirming the status of constraints is the first step toward schedule buffer management. Accordingly, suppliers are requested to confirm the estimated available time of their constraint items, i.e. EAT_{jl}. This will eventually determine the position of an activity in the IPS schedule.

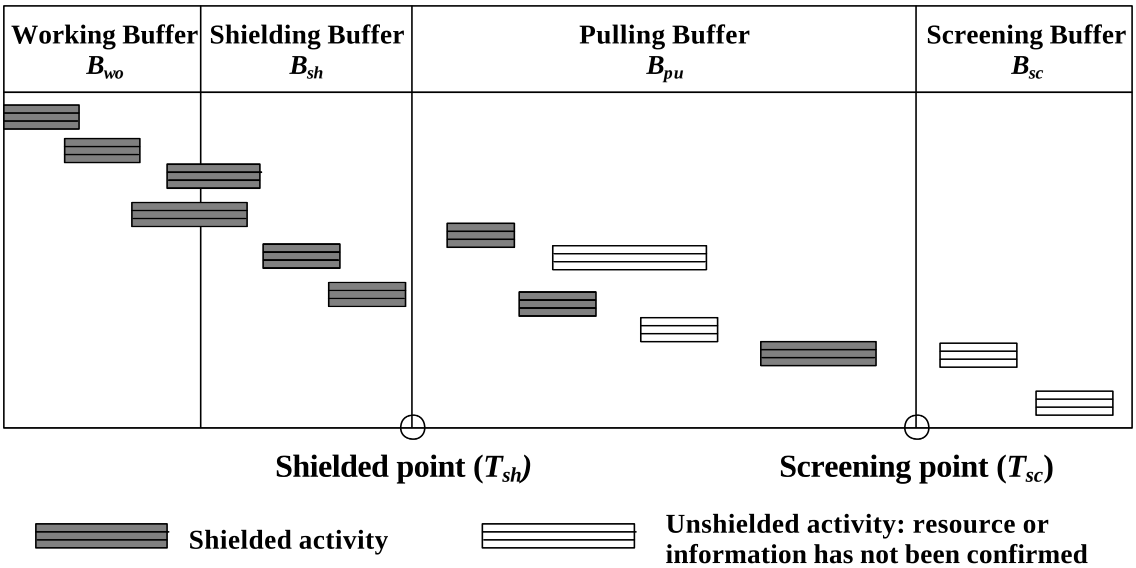

Fig. 4: Schedule Buffer Management in the IPS Look-ahead Plan

Working buffer (B_{wo}): Activities in this buffer are scheduled to work in the present week. They can be further decomposed to a series of work assignments. These activities have been shielded from foreseen supply chain uncertainties before work assignments are made. A 'shielded' activity would satisfy the following condition:

$$\begin{cases} ES'_j \le S_j \le LF_j \quad , \text{ and} \\ C_{jm} = 1 \qquad\qquad \forall C_{jm} \in C_j \end{cases} \tag{5}$$

where $C_{jm} = 1$ denotes that the m^{th} integrated constraint in activity A_j is confirmed by the organization in charge, or 0, otherwise. C_j denotes all the prerequisites for activity A_j as represented by the integrated constraints. Since the constraints have all been resolved, the concern that remains is to make good work assignments and ensure efficient production control so as to achieve high plan completion.

Shielding buffer (B_{sh}): The shielding buffer contains activities that will directly feed into the working buffer. In other words, it builds up a workable backlog for the assignment planning. Activities in this buffer must have been shielded as in Eq. (5) and also satisfy the buffer limits:

$$S_j < T_{sh}, \qquad \forall A_j \in B_{sh} \tag{6}$$

where T_{sh} is the time of the shielding point, and B_{sh} the set of shielded activities. The shielding buffer thus only contains activities that have all their prerequisites satisfied to enable reliable planning. The main objective for managing this buffer is to resolve the constraints so that a good size buffer of activities can be achieved. This will ensure a constant flow of work that can be scheduled for the working buffer.

Pulling buffer (B_{pu}): This buffer is the focus of supply chain management and information flow coordination. Activities inside should satisfy the following condition:

$$T_{sh} \le S_j^{'} < T_{sc}, \qquad \forall A_j \in B_{pu} \tag{7}$$

where T_{sc} is the time of screening point, and B_{pu} the set of activities within the pulling zone; the start time $S_j^{'}$ of activity A_j in this buffer may be uncertain because the EAT_{jl} of constraint l may not have been confirmed. These uncertainties are resolved by requesting confirmations of delivery dates for the prerequisite information and resources/materials from the respective suppliers, subcontractors or other project participants through a messaging system described in a later section. In this way, the activities can be shielded before proceeding to the shielding buffer. Another objective is to assist the project manager in identifying key constraints that cause project delays and making appropriate decisions, e.g. expediting certain constraints instead of allowing them to be delayed.

Screening buffer (B_{sc}): Some activities in the preceding buffer may be delayed beyond the screening point T_{sc} because of the non-availability of prerequisites:

$$ES_j < T_{sc}, \qquad \forall A_j \in B_{sc} \tag{8a}$$

$$\underset{\text{all } l}{\mathrm{MAX}}(EAT_{jl}) \ge T_{sc} \qquad \forall A_j \in B_{sc} \tag{8b}$$

where B_{sc} is the set of activities in the screening buffer, and ES_j the early start time of A_j according to Eq. 1. Eq 8(a) implies that the start times of the activities as determined by the precedence relationship would put them within the screening point. However, the starts of these activities have been delayed by some late arrivals of the prerequisites as suggested by Eq. 8(b). The objective is to minimize this buffer by expediting the integrated constraints so that resource flow issues do not unduly delay the project.

In essence, the proposed schedule buffer management provides a framework for improving the reliability of the CPM-based look-ahead plans. This has been achieved using the integrated constraints so that the reasons for delays can be explicitly attributed, and these constraints can be expedited if needed.

PROTOTYPE

The prototype demonstrated below illustrates how the IPS functions with its buffers and how the integrated constraints may be resolved through pulling information from project participants so that reliable work plans can be made. Fig. 5 shows the prototype of an IPS look-ahead plan with one-week working buffer, one-week shielding buffer, and two-week pulling buffer. Each activity inside is composed of three bars denoting the three types of constraints described previously.

A color scheme is adopted, according to which BLUE means that all underlying constraints have been resolved or confirmed. GREEN indicates that at least one integrated constraint has not been confirmed, for example, activity G shows a GREEN status for the information constraint contributed by "Workshop drawing 07-02". Finally, RED reveals that the activity has uncertainties in its schedule caused by predecessor(s) that have not been completely assured, for example, activity H whose predecessor G has unresolved information constraint.

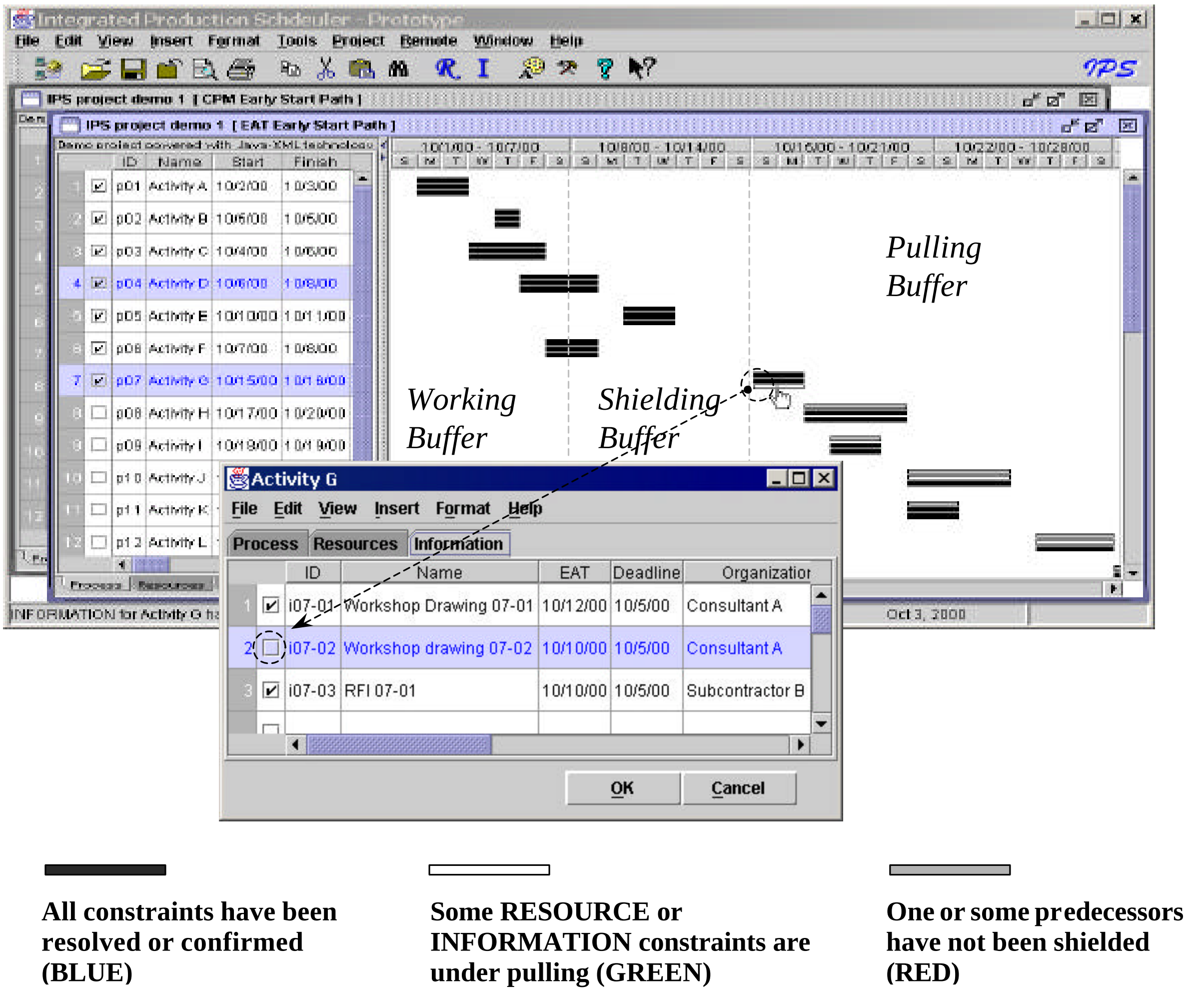

Fig. 5: Pulling Information and Shielding Activities with the IPS Prototype

The position of an activity in schedule determines the level of details required for the planning. The closer to the working buffer, the more details will be presented. As shown in Fig. 5, all activities in the working buffer and shielding buffer have been assured. The pulling buffer contains activities with unconfirmed constraints which prevents it from advancing into the shielding buffer. The start of Activity G, for example, has been delayed to the shielding point because the *EAT* of its "Workshop drawing 07-02" has not been confirmed even though it could be scheduled earlier according to its precedence. In this instance, a request for confirmation would be sent to consultant A. Activity G has been kept out of the shielding buffer otherwise its uncertainty may cause unreliable plans in the following week. Item i07-02 becomes a key constraint that should be expedited. Once this constraint is resolved, Activity G would have been shielded and would proceed into the shielding buffer.

CONCLUSIONS

Reliable work plans are important in achieving high productivity and continuous work flow. The basic CPM/PERT approaches do not deal with the 'hidden' constraints regarding resource and information availabilities associated with delivery. However, these constraints may determine whether quality assignments can be made. The Integrated Production Schedule (IPS) is a tool used for managing two additional types of constraints, namely RESOURCE constraints and INFORMATION constraints, in the look-ahead plan. It helps increase the reliability of the work plan through managing resource delivery and information acquisition. A set of schedule buffers are employed to facilitate the management of integrated constraints and achieve more reliable work plans. By resolving key constraints at bottleneck activities, the project manager may maintain a steady work flow and focus on increasing resource utilization and throughput. This would eventually contribute to fulfill lean processes in project management.

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