RESOURCE-DRIVEN SCHEDULING FOR REPETITIVE PROJECTS: A PULL-SYSTEM APPROACH

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ABSTRACT

Having resources work continuously has long been the goal for scheduling repetitive projects. Waste (unforced idleness) in repetitive projects is observed when labor and equipment (resources) are waiting, being idle, because the preceding resources have not finished their jobs. In this paper we investigate the existence and influence of unforced idleness.

In contrast to the push-system approach used by traditional critical path method (CPM), we propose a pull-system scheduling system to eliminate unforced idleness in repetitive projects. We use the term pull in applying repetitive scheduling ideas to lean construction in a new way. The scheduling system is able to model general repetitive projects by relaxing impractical assumptions posted by previous models and provides a computational algorithm to generate planned and as-built graphical schedules. We also define the necessary elements of the scheduling system and describe the concept underlying a computational algorithm. A computer program, Repetitive Project Planner (RP2), is incorporated and a real-life pipeline project is implemented to demonstrate the application. The pull-system scheduling system can serve as a practical tool toward continuous work flow.

KEY WORDS

Repetitive scheduling, resource-driven scheduling, pull-system, just in time, continuous work flow

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INTRODUCTION

Repetitive activities are found commonly in the construction of multi-story buildings, pipelines, highways, and housing development projects. For such projects, similar activities are repeatedly performed from unit to unit. Projects comprising mostly repetitive activities are classified as repetitive projects.

Although the conventional critical path method (CPM) has been widely used in scheduling construction projects, it possesses various deficiencies in scheduling repetitive projects. Such deficiencies include the cumbersome repetition of similar activities and relationships, and the neglect of important production information, such as production rate and work location.

Lean production philosophy starts with the goal of avoiding waste (Shingo 1988). In lean construction, CPM has been attacked for its inability to model non-value adding activities (idleness), such as waiting, inspecting, and moving, let alone eliminate such idleness (Koskela 1992). When CPM is applied to schedule repetitive projects, the early start schedule may not be optimal because floats attached to repeating activities represent significant amount of waste, unforced idleness (Harris and Ioannou 1998). In this paper, we propose a pull-system approach that automatically pulls activities and/or activity segments to later start times so that unforced idleness can be eliminated. The term pull-system encompasses the pull concept in a kanban system or pull-driven scheduling (Tommelein 1998), which pulls upstream material and off-site work to match the progress on site.

UNFORCED IDLENESS

Within repetitive projects, scheduling is usually done by considering resources, labor and equipment, “flowing through” the whole project. Similar resources are repeatedly utilized through working units and hence can be modeled as they flow through the project site. This practice is similar to manufacturing assembly lines. However, in repetitive projects it is the labor and equipment that flow through the product (construction site) while in manufacturing assembly lines, it is the product flowing across stationary labor and equipment. In other words, in repetitive projects, the products being built tend to be stationary, whereas resources move from location to location and complete work that is prerequisite to starting work by the following resources (Tommelein et al. 1999). Riley and Sanvido (1997) called this production system a "parade of trades". Ideally, site managers wish that resources could flow through the site smoothly without any interruption. Unfortunately, this rarely happens. According to the interviews with project managers and the study conducted by Serpell et al. (1997), it is common to observe in repetitive projects that labor and equipment is idle and waiting because the preceding labor and equipment have not finished their jobs. This idleness is due to unbalanced production rates, uncertainty regarding the production rates during planning, and variability during execution. Since the idleness does not result from any forced causes, such as bad weather, labor accidents, or equipment breakdown, it is classified as unforced idleness.

Besides waiting, unforced idleness is also observed as lower productivity. Practitioners indicate that when crews expect they will run into the preceding crews, they intentionally slow down. Waiting and lower productivity make contractors suffer from higher costs and possible delays.

To avoid costs associated with unforced idleness, site managers either have resources perform out-of-sequence work elsewhere, or lay off resources and re-employ them later. The former alternative causes wastes in relocation and the discontinuity of work while the latter alternative leads to three problems. First, given the shortage of skilled labor and the difficulty for equipment transportation, releasing resources and re-employing them back are expensive and troublesome. This also diminishes the chance of having learning effects. Second, subcontractors that leave for another job often do not come back on time, which leads to serious delays (Ashley 1980). Third, it is never guaranteed that site managers can hire back the same crews who were laid off previously. Hence, it takes time and cost to train new crews to realize job requirements and cooperate with others. The problem of work discontinuity has been reported as a de-motivator for crew productivity by the Business Roundtable (1982).

Unforced idleness also causes problems for equipment utilization. In repetitive projects, on one hand, certain equipment requires long set-up and warm-up times. Hence, it is not feasible to turn on and off the equipment frequently. A good example is the diamond-grinding machine used as a highway re-surfacing tool. On the other hand, equipment may wear down if being turned on all the time. Site managers then encounter a dilemma of utilizing the equipment even when it is not necessarily productive to do so.

Unforced idleness is distinct from schedule buffers defined in (Ballard and Howell 1995), which serve the function of buffering downstream processes from upstream flow variation and uncertainty. In repetitive projects, schedule buffers are inserted behind activities as "expected" work interruption. Unforced idleness, in comparison, is "unexpected" work interruption.

CONTINUOUS WORK FLOW

Eliminating unforced idleness in the planning phase is the first step toward achieving uninterrupted work flow, which has long been proposed as an ultimate goal in the lean construction literature (Ballard and Tommelein 1999). Increasing work flow reliability in the execution phase will be critical for the success of implementing a schedule within which unforced idleness has been eliminated. An approach to increasing work flow reliability, shielding production, is described in (Howell and Ballard 1998).

Although having resources work continuously is often ideal for project managers, work interruption may be necessary or favorable in practice. Work interruption is necessary because of two types of technological constraints. First, an activity cannot start at the current location until its "successor" has been finished at the previous location (Russell and Wong 1993). For example, "formwork" for the second floor slab cannot start until "concrete placement and curing" on the first floor is finished assuming one set of slab form is available. Because "concrete placement and curing" has to succeed "formwork" on every floor, it is impossible to have the formwork crew work continuously. Second, specific activities may possess no-wait constraints. Such an activity must remain stop-and-go to follow its predecessor closely. For instance, initial tunnel support must be placed immediately following the penetration of a boring machine, it is therefore infeasible to postpone the start time of placing initial support to achieve work continuity. Work interruption may be favorable when violation of continuity leads to a shorter project duration. That is, bottleneck processes should start as soon as possible to allow the start of succeeding activities. Since interruption may be necessary or favorable, work continuity should not be recognized as a constraint but rather an option.

PULLING EFFECT OF WORK CONTINUITY

While work continuity has been discussed extensively in the literature, little is known about the pulling effect of work continuity. Traditional network scheduling techniques, such as CPM and PERT, represent push-systems, where every activity is pushed by its predecessors to the earliest position that maintains precedence relationships. This push-system approach cannot ensure the continuous utilization of resources because work continuity must also "pull" preceding activities or segments to eliminate gaps. Here we use the term pull in applying repetitive scheduling ideas to lean construction in a new way. For example in Figure 1, "pavement removal", shown as three bold lines, is performed with three segments in a 50-station highway maintenance project. The first segment is from station 20+00 to station 30+00 with a left-to-right direction. The second segment is from station 50+00 to station 30+00 with a right-to-left direction. The third segment is from station 0+00 to station 20+00 with a left-to-right direction. The duration for the first and second segments is two days while the duration for the third segment is three days. If project managers decide to postpone the start of segment (3) to day 7 because traffic control between station 0+00 and 20+00 is delayed, the continuity relationship, shown as lines including one long dash and two short dashes, should pull the previous segments to later positions shown as dashed lines, (1)' and (2)'. The delayed position of segment (3) is shown as (3)'.

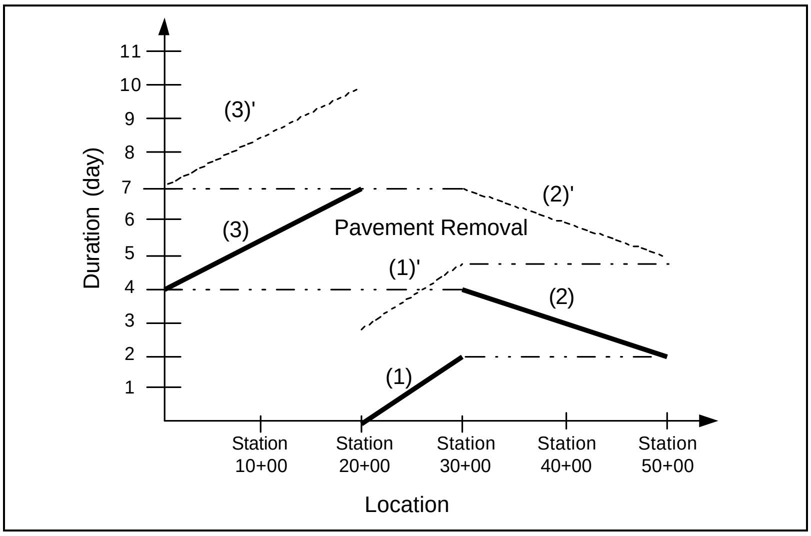

Figure 1. Pulling Effect of Work Continuity

GRAPHICAL SCHEDULE

The progress-against-time schedule presented in Figure 1 is identified as a graphical schedule. Unlike CPM networks or bar charts, graphical schedules depict a variety of important production information, such as work locations, production rates, and resource progress directions and sequences. Easy understanding of graphical schedules achieves another goal of lean production, making production information transparent to people involved with production, so as to enhance overall project performance (Howell 1999). However, an algorithm that can be implemented as a computer program to create graphical schedules is essential to make the use of graphical schedules acceptable to practice.

NATURE OF REPETITIVE PROJECTS

There are two basic categories of repetitive projects, one where progress units are discrete entities and another where progress is continuous and is expressed in terms of length or location. In the first category, units may be floors for multi-story buildings, houses for housing development projects, or apartments for remodeling projects. In the second category, progress is expressed in terms of meters, stations, or miles for highways, pipelines, tunnels and other similar projects. Projects in the first category are called "vertical repetitive projects" and progress is usually plotted vertically. In contrast, projects in the second category are called "horizontal repetitive projects" since progress is often plotted horizontally. They are also called "linear projects" because of the linear nature of the geometrical layout and work accomplishment. Since some vertical repetitive projects are not really constructed "vertically", vertical repetitive projects should be referred to as "discrete repetitive projects" to avoid confusion while the horizontal repetitive projects are referred to as "continuous repetitive projects".

A discrete repetitive project involves repetition of a unit network throughout the project. This unit network consists of the activities and their interrelationships that represent the work to be performed in each unit. Despite this repetition, the work quantities for an activity may not be the same in all units, however. Moreover, some activities may not even be present in all units. For example, a five-story building may require that only the first floor needs carpeting on the whole area; the second floor needs carpeting on only the west part of the floor, which is approximately equal to 60% of the floor area; and the remaining floors do not need carpeting at all. Besides, crews may have variable production rates due to the variation on 1) skill levels of crews, 2) weight and size of components, 3) fabrication and erection tolerances, etc. For instance, a carpeting crew can install 15 square meters of carpet per day. Because of the difficulty of moving material to higher floors, the crew may install only 10 square meters per day on the highest floor. In addition, activities in a discrete repetitive project do not necessarily start at the same location or follow the same sequence. Although some activities must start from lower levels and proceed upwards because of technological constraints, such as concrete pouring or shore erection, some activities can start anywhere, such as interior finishing or door installation.

A continuous repetitive project generally involves a number of activities following each other rather than the uniform repetition of a unit network. Planning decisions in continuous repetitive projects are to determine when and where activities should start in an orderly fashion so as to minimize disturbance. For example, installing granular sub-base will follow the activity of removing existing pavement in a highway rehabilitation project. Instead of considering a module network being repeatedly performed at every station, the scheduling concern is where and when these two activities should start so that the crew installing granular sub-base will not run into the crew removing existing pavement. In a continuous repetitive project, work quantity may vary at different locations and production rate may also change with progress. For example, earthmoving on the east segment of a road construction may require more work due to uneven ground level and equipment may have lower production rates because of adverse soil conditions. Activities in continuous repetitive projects are not necessarily present at all locations. For example, in a 100-station highway maintenance project, "dowel bar retrofit" is required only for the first 50 stations. Besides, activities in a continuous repetitive project may not start and finish at the same location. For example, "pavement removal" takes place at station 10+00 and finishes at station 25+00, while "dowel bar retrofit" starts at station 15+00 and finishes at station 20+00.

In both discrete and continuous repetitive projects, crews may undergo changes in composition, size, associated equipment, and work methods as a function of progress. For instance, constructing a trench may require both machine and manual excavation. Although machine excavation provides higher productivity, manual excavation is still favorable on the section that involves existing underground sewer and gas pipelines. In a multi-story building project, the number of available electricians may be five for the first month but decreases to three afterwards.

SCHEDULING REQUIREMENTS FOR REPETITIVE PROJECTS

A scheduling system to model repetitive projects with the ability of eliminating unforced idleness should provide generality and computational ability.

In terms of generality, the scheduling model must be able to handle real-life requirements and also be practical. Toward this goal, past research has contributed a number of observations in scheduling repetitive projects (Birrell 1980; Johnson 1981; Russell and McGowan 1993). These observations along with ours will be illustrated as the required attributes for a general scheduling system:

- Resources (labor and equipment) may have variable production rates and variable work quantity at different work locations. The choices of crew sizes and composition, equipment selections, and production rates may vary during work progress.
- An activity may utilize multiple crews simultaneously. A crew may perform multiple activities.
- Activities may have multiple predecessors and successors. There may be multiple relationships between each pair of predecessor and successor.
- The construction process, as defined by a set of activities and relationships, need not be the same at every work location.
- A full set of relationships (Finish-to-Start, Finish-to-Finish, Start-to-Start, and Start-to-Finish) should be available.
- One activity may link to another activity at non-contiguous locations. For example, a drywall activity on a specific floor should not start until the completion of two higher floors of the preceding glazing activity to ensure a weather-tight environment.
- Labor and equipment may change progress direction (east-to-west, up-to-down, etc.) or have complex work sequences.
- Activities may require space-buffer (lead-distance) in addition to time-buffer (lead-time). The space-buffer may be non-integer, e.g., 1.5 km or 1/2 houses.
- Activities may need resources that work back-and-forth in an area within a certain period, such as excavation or traffic control. Other resources may not work in this area at the same time.
- Work interruption should be allowed if desired.
- The non-repetitive portion of project work should be incorporated into the framework of repetitive scheduling.
- Cyclic relationships due to the pulling effect of work continuity should be allowed and treated as well as possible.

An example of cyclic relationships is depicted in Figure 2. Following the example shown in Figure 1, assume that segment (1) has a finish-to-start (FTS) relationship with activity A and activity A also has a FTS relationship with segment (3). Both FTS relationships are shown as horizontal arrow lines. Activity A, which is shown as a line with long dashes, is scheduled to be performed from station 0+00 to station 10+00 with the duration of five days. In this case, the continuity relationship between segment (1) and (2) must be broken to avoid a cyclic relationship. In other words, segment (1) must remain its original position whereas segment (2) and (3) are postponed to the dash lines, (2)' and (3)'. Otherwise, due to the continuity relationship, moving segment (3) will pull segment (2) and (1) upward. Since segment (1) moves upward, activity A will move upward to maintain the precedence. Then segment (3) needs to move upward again. Such a cycle will never stop and scheduling will fail.

In terms of computational ability, the scheduling system must provide a computational algorithm to automate the generation of graphical schedules. Without a programmable algorithm, the visual benefit of graphical schedules is lost because of tedious manual preparation. This algorithm is of great practical importance in that it can rapidly produce reliable graphical schedules for users to plan, schedule, update and modify the work. Moreover, users can test alternative strategy plans, such as adjusting crew sizes, changing production rates, or redesigning operations for individual tasks. During the course of construction, the algorithm can produce as-built schedules to help users model actual start and finish times and production rates for the activities that have occurred. On this basis, users can plan and schedule the remaining activities by modifying their production rates and/or their start time to handle deviations from planned.

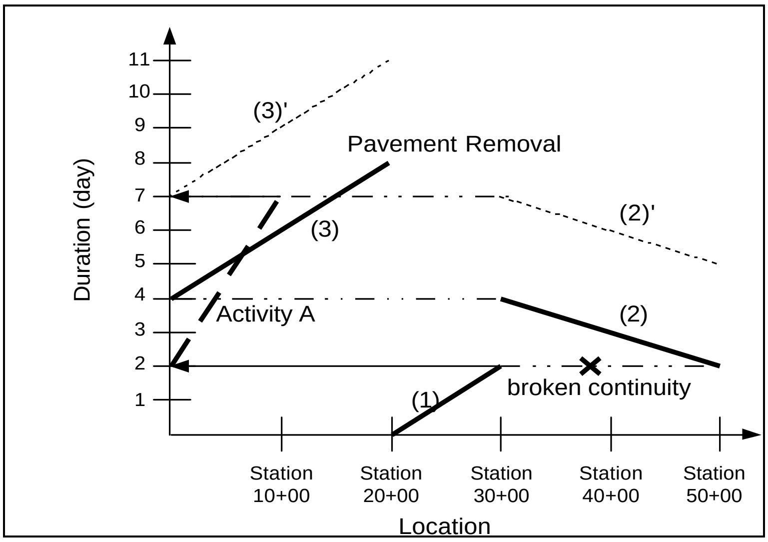

Figure 2. Cyclic Relationship

MODELING ELEMENTS

The scheduling system developed by the authors contains two sets of elements. The first set defines activity types and the second set defines relationships between activities. There are three general activity types: line, block, and bar activities, and three general relationship types: time-controlled, distance-controlled, and continuity relationships. In the existing literature, efforts were focused on the definition of activities whereas the interrelationships between activities were generally overlooked. Consequently, the pulling effect of work continuity was not modeled.

Line activities model the movement of resources with the slopes representing the production rates in discrete repetitive projects and the inverse of production rates in continuous repetitive projects. Block activities represent work that occupies a specific area over a certain period and often involve a space constraint against other activities. For example, when resources perform excavation, other resources cannot perform their jobs in the same area. Bar activities represent non-repetitive work that occurs at a certain location, such as a culvert construction underneath a repetitive highway project. The definitions of block and bar activities are adopted from (Vorster et al. 1992).

A time-controlled relationship uses lead-time (time-buffer) to control the relationship between two activities. For example, the activity "strip wall" must wait three days to start after the activity of "cast wall" is finished because concrete needs three days to dry. To simplify the input process, time-controlled relationships are further subdivided into global and local relationships. If the relationship between two activities applies at more than one location, users can employ a global time-controlled relationship to avoid unnecessary repetition. This relationship (e.g., finish-to-start) will exist in every unit both activities appear. A local time-controlled relationship links two activities at non-contiguous locations. For instance, in a building project it is required that the drywall activity on a specific floor should not start until the completion of two higher floors of the preceding glazing activity to ensure a weather-tight environment for drywall installation. Local time-controlled relationships are vital to describe resource sharing and multiple crew strategy. Both global and local relationships include four common overlapping relationships: finish-to-start (FTS), finish-to-finish (FTF), start-to-start (STS), and start-to-finish (STF).

A distance-controlled relationship uses lead-distance (space-buffer) to control the relationship between activities. Schedulers can specify how many units of work the preceding crew must finish before the succeeding crew can start at the same location. In other words, at any given point of time, the distance between activities must not be less than the lead-distance.

Lead-time and lead-distance are obvious means by which to describe the precedence details between activities. Schedulers may select either lead-time or lead-distance to provide enough buffers between two activities. Whether schedulers should choose lead-time or lead-distance depends upon how the precedence constraint is expressed. If the constraint is that the predecessor should maintain certain time buffer from the successor, schedulers should choose lead-time. For example, paint on walls needs 1 day to dry before carpets can be installed. No matter how fast the carpeting crew works, the lead-time must be 1 day. On the other hand, if the constraint is that the predecessor must maintain certain space from the successor, schedulers should employ lead-distance. For example, crews work for “granular sub-base” should maintain a distance of 2.5 stations from crews work for “sub-base trim” to provide enough space for labor and equipment. The distance must be maintained regardless of production rates. In addition to specifying either lead-time or lead-distance, schedulers can specify both and let the one governs determine the schedule.

A continuity relationship, as explained in the previous section, links activities when labor and equipment perform multiple activities or activity segments when labor and equipment change direction (sequence) to ensure continuous work flow.

PULL-SYSTEM ALGORITHM

The concept underlying the proposed computational algorithm is that upstream work should not start sooner than needed to ensure continuous downstream work. The concept is close to the just-in-time (JIT) approach in lean production. JIT, as its name suggests, represents the philosophy of making only what is needed, only when it is needed, and only in the amount that is needed. In manufacturing, JIT introduces a pull-system approach by pulling work through the factory to meet customer demands (O'Grady 1988). Here, the upstream work is pulled to assure the "demand" (continuity) from its customer, i.e., downstream work.

The procedure for the computational algorithm involves five steps. Due to the space limitation, the detailed algorithm cannot be presented here but can be found in (Yang and Ioannou 2001).

1. The shape of an activity is established. For a line activity, the shape is established by assuming that the line activity starts at time zero on the first unit where the activity starts. The best way to envision this is that the production line is like a bent piece of wire whose various slopes represent variability in the unit production rates for the activity. For a block activity, the shape has been determined by specifying the occupied units and duration. For a bar activity, the shape has been determined by specifying the location and duration.
2. The shift exerted by each predecessor at each unit to the activity being scheduled is calculated. The amount of shift refers to the required time or distance, which an activity must be shifted to satisfy various precedence constraints.
3. The maximum shift is selected over all units, all incoming relationships, and all predecessors.
4. The activity being scheduled is moved as a rigid body to the position, which results from the maximum shift.
5. If there is no cyclic relationship, a continuity relationship may pull the activity and its full successor set (including both immediate and remote successors) to move again to assure work continuity. If there is a cyclic relationship, the associated continuity relationship needs to be broken, as described in Figure 2.

COMPUTER PROGRAM

The present scheduling system has been incorporated in a computer program, Repetitive Project Planner (RP2). The program is a 32-bit windows application that runs on Microsoft 2000 and NT. Figure 3 depicts the main input window for project and activity information.

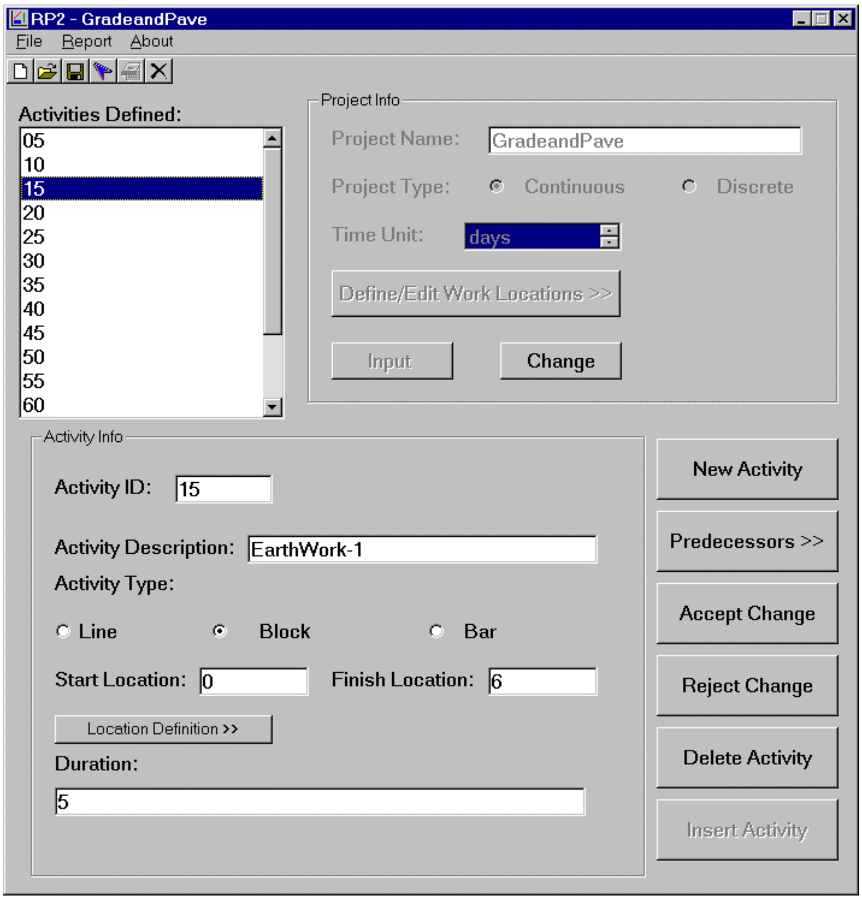

Figure 3: Project and Activity Information Window

EXAMPLE PROJECT

A real-life pipeline project is used to demonstrate the application of RP2. Interviews with the general contractor and project managers were conducted to realize the details of the project.

The project was to connect an existing pipeline to a water treatment plant with approximately 1,000 meters of steel pipes. Each steel pipe was 12 meters long with a diameter of 76.2 cm and a thickness of 7 mm. There were only a few turns so the number of elbows was less than 5. Pipes were installed in an open trench with the depth of 2 meters and the width of 1.8 meters. At each connection between pipes, the trench should be excavated wider, 1 meter more on each side, to provide extra space for welding crews. Total number of required pipes was 84. Due to the transportation difficulty, the pipe supplier preferred to ship all pipes together. The supplier also agreed to position pipes one after the other next to the progress line when they arrived the site. Since it was difficult to weld pipes inside the trench, pipes were preliminary welded outside. Because a sideboom could lift only two pipes at the same time, equivalent unit (EU), i.e., the end measure of progress selected by schedulers to quantify the production from different trades, was determined to be a pair of pipes.

The daily output for a backhoe to excavate the trench was estimated to be 840 cubic meters, which represents roughly excavating the trench for 288 meters (including extra space). This production for excavation was 12 pairs of pipes per day. The soil type was clay and rock was hardly found during the excavation.

Welders were divided into two crews. Each crew consisted of two welders, two helpers, and one sideboom. The outside-welding crew was responsible for welding pipes in pairs outside the trench and the inside-welding crew welded those pairs inside the trench. The production rates of outside-welding and inside-welding crews were 8 welds/day, (to connect 8 pairs/day) and 6 welds/day (to connect 12 pairs/day since each weld connected 2 pairs of pipes.) After pipes were welded in the trench, two painters applied epoxy paint at connections to prevent corrosion. The lead-time between the first and second paint coats was 1 day to assure the paint is dry. The duration to apply a coat of epoxy paint is 1 day.

Backfill and compaction was performed by eight laborers and one front-end loader. The daily output was estimated to be 220 cubic meters, which was converted to 3 pairs of pipes. "Trench excavation" and "outside welding" could start simultaneously because there was no conflict in the utilization of either resource or space. The lead-distance between "outside welding", "inside-welding", and "epoxy paint coat 1" is 4 pairs. The lead-time between epoxy paint coat 1 and 2, and "backfill and compaction" was 1 day.

The graphical schedule generated by RP2 is shown in Figure 4.

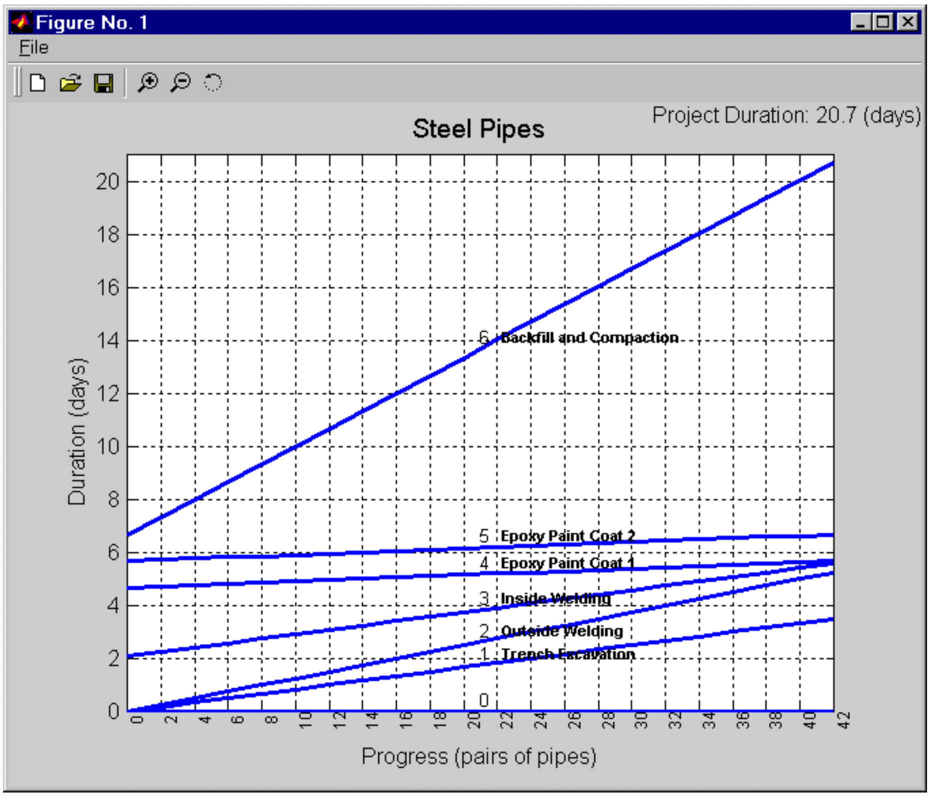

Figure 4: Steel Pipe Project

The steel pipe project is straightforward because a solution exists where all activities can be performed continuously, and hence does not require all the features defined in the scheduling system. Nevertheless, the graphical schedule answers the most important question in scheduling repetitive projects: when should labor and equipment start so they will not be idle at later locations? In the present project, inside-welding and painting crews are the ones whose start time is postponed to ensure continuous work flow. In the graphical schedule, work processes are presented in an easy-understood flow model. A variety of production information, which cannot be shown in a CPM network or bar chart, is now easy to perceive, such as work location, productivity, and progress direction. Non-value adding activities, e.g., stoppage and waiting, can also be captured.

CONCLUSIONS

The emphasis of this research is the elimination of unforced idleness (waste) in the planning and execution phase, so as to maintain continuous work flow. The developed system can help users analyze strategies for future work based on available information. Eliminating unforced idleness in the planning phase is the first step toward achieving continuous work flow. Other contributive steps in the planning and execution phase include eliminating variability and implementing lean thinking on supply chain management, performance management, and coordination among trades.

In contrast to the push-system approach of CPM, the research proposes a pull-system approach to achieve continuous work flow. Moreover, the research pioneers in investigating the pulling effect of work continuity and explaining possible cyclic relationships.

It is not new to postpone the start of an activity to achieve continuous work flow. Seasoned project managers estimate the necessary postponement when they suspect the occurrence of work discontinuity. However, this can be a time-consuming and error prone exercise when the size and complexity of a project increase. In real-life repetitive projects, progress does not follow neat and parallel production lines. Real challenges emerge when labor and equipment 1) skip certain work locations, 2) change progress directions, 3) work for multiple activities, 4) split and reunite during progress, 5) perform at different production rates, and 6) require travel or break time. It has been our intention to introduce a scheduling system that provides both generality and computational ability. Without these features, the elimination of unforced idleness in real-life projects must rely on arbitrary manual adjustments by project managers and would have remained an unattainable ideal.

RP2 can also serve as a test bed for analyzing buffer strategies. The strategies are to determine the amount and position of 1) in-line inventory buffers, 2) material delivery buffers, and 3) capacity buffers as suggested in (Ballard and Tommelein 1999). The means to place capacity buffers is called "underloading": making assignment to resource that absorbs less than 100% of its capacity (Lean Construction Institute 2000). Underloading is also recognized as "balancing production." A procedure for balancing production deserves detailed discussion. A number of examples can be found in the line-of-balance (LOB) literature (Lumsden 1968; Carr and Meyer 1974).

To better understand the influence of uncertainty on work continuity, start times calculated by RP2 can be used as external logic expressions to start activities in advanced simulation tools, such as STROBOSCOPE (Martinez 1996). Simulation tools by themselves cannot determine the start of an activity at certain location to ensure continuous work at later locations. The present scheduling system remedies this inadequacy.

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