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# A simulation-based method for effective workface planning of industrial construction projects

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#### ABSTRACT

The generation of well-defined and moderately sized field installation work packages for the construction workforce, referred to as workface planning, has been recently employed to plan large-scale industrial construction projects under tight schedules. However, traditional CPM-based scheduling of several thousand work packages (e.g. 5000 activities multiply by 10 work packages per activity on average) is a tedious, error prone process. Defining proper logics and controlling congestion among work packages crossing several work areas, and also effective resource allocation over time are other major challenges in workface planning. This paper presents a novel simulation-based framework to implement workface planning for large-scale industrial construction projects. This framework proposes a time-stepped discrete event simulation-based modelling for dynamic resource allocation based on congestion and other constraints on the job site. The proposed method is demonstrated and tested against traditional CPM-based solutions based on an actual case study.

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# 1. Introduction

Mega projects in Heavy Industrial industry pose huge challenges for general contractors due to its sheer size and complexity. The Alberta Economic Development Authority (AEDA 2004) summarized a few figures for mega projects based on the oil sands projects built in the province of Alberta, Canada. For a project of \$2.5 billion, it requires around 3.5 million engineering man-hours and 15 million construction man-hours and generates 40,000 to 50,000 design drawings and 10,000 to 20,000 vendor and shop drawings.

Workface Planning (WFP) was introduced by Construction Owners Association of Alberta (COAA) in the last decade to enhance planning and organizing mega construction projects. WFP can be defined as the process of breaking down the project into well-defined Field Installation Work Packages (FIWP) to facilitate field crews to perform quality work safely and efficiently. The size of FIWP in one discipline usually does not exceed one rotation of work, ranging from 5 to 10 working days (Ryan 2009). The project team must review the FIWPs to make sure all perquisites are ready prior to releasing them on the job site (Construction Industry Institute 2011).

Implementing WFP on mega-projects with traditional CPM-based software (e.g. Primavera, Microsoft Project) is an onerous exercise as the schedule generally involves 2000 to 6000 activities, each of which can be broken into five to thirty work packages. The addition of work packages to the schedule is an on-going exercise since work packages are built about four weeks before construction begins on field. The schedule will continuously grow in activity count as work packages are added since large scale projects take several years to execute. Some other major limitations of CPM scheduling to implement WFP include fixed logic among activities, fixed activity durations and fixed resource allocation levels. This rigidity is not a precise presentation of how FIWPs are executed on the job site. More often, fictitious logics are entered as hard constraints among FIWPs, while most of these logics are soft constraints that can be variable over time. For example, the level of congestion in often manipulated by an added logics to delay some of FIWPs. Based on the experience of the authors in industrial projects, the traditional CPM method of scheduling work packaging has several key drawbacks which led to this research project.

 Variable logic among work packages resulting from sharing resources (e.g. working crews) cannot be automated.

- (2) Resource level during the execution of work packages is variable and their durations are not fixed.
- (3) Work packages do not necessarily require the full size crew to perform the work.
- (4) Limits on how many and which trades can simultaneously work in a work area cannot be performed.
- (5) Congestion issue is challenging to be controlled particularly if work packages cross several work areas.

This paper presents a novel simulation-based framework to implement workface planning for large-scale industrial construction projects. This framework dissects work packages into segments based on time unit (i.e. hour, day, week or month) and simulate the execution of these segments by using time-stepped simulation. Such resource allocation not only satisfies the resource limit at certain time, but also limits congestion at certain work area based on work package priorities. FIWPs are allowed to be interrupted and also changed in durations given the resource limits and task priorities. Priority is an input to the simulation which can be either calculated based on heuristics or overridden by managers/superintendents. The simulation also respects hard constraints such as predecessor/successor dependency, imposed start/finish dates, work calendars for different trades.

# 2. Industrial projects supply chains

Many of heavy industrial projects have complex supply chains. They are built in remote areas where local labour availability is not sufficient and a substantial workforce needs to be relocated from somewhere else. The on-site labour cost could be very expensive. One solution to this is to pre-fabricate most construction components (e.g. piping and steel members) in a factory like shop environment off-site. Some of these fabricated components are shipped directly to site for final installation, others are synthesized with other pre-fab components into a unit called module. A module is a building block for a pipe rack or a plant that includes a steel structure, piping, equipment, cable tray, instruments and other electrical components. Modules are sized within the limitations of transportation so that they could be shipped from assembly yards to the construction site. The proportion of shop fabrication and module assembly used in industrial projects has significantly increased over the past 20 years (Haas *et al.* 2000).

In a perfect scenario, both shop fabrication and module assembly should be driven by site construction. However, during the course of construction, the site schedule is prone to changes due to many factors such as scope/ design changes, site conditions or constructability issues. This variability originates at the end of the supply chain and ripple back to all proceeding stages (Wang 2006). It manifests in the form of rush orders, change orders or order cancelations (Figure 1) and causes rework, work stoppage and priority change in shop fabrication and module assembly, which in turn disrupt the site construction in the form of late or out-of-sequence supply. The disruption is further amplified when the supply of IFC (Issue for Construction) drawings and raw materials are unreliable.

Fast tracking is another contributor to variability. Fast tracking forces overlap between design, procurement, fabrication, module assembly and site installation. As a result, pre-fabrication, pre-assembly and even site construction start well before the design is completed. As project progresses, the incomplete design is usually translated into a large number of drawing revisions, which in turn disrupt shop fabrication, module assembly and site construction (Williams 1995).

Uniqueness in industrial project components (especially in piping) makes it extremely difficult to mitigate the late



Figure 1. Work areas and congestion limit.

or out-of-sequence supply from fabrication shops or module yards. A petroleum refinery can require as many as 10,000 piping inventory codes, each of which represents a unique piping component (Wyss 2009).

Based on authors' experience, high level of variability instantly changes the "workable" work fronts for site crews and requires that site mangers/superintendents/ planners quickly respond to the changes and make adjustments accordingly. This is performed by site management through detailed weekly lookahead schedules modified daily as needed. It is usually done through re-directing/re-distributing limited work force to focus on those "workable" and "high priority" work fronts. For example, resources are released from in-progress work packages due to pending issues (e.g. Request for Information) and are re-allocated to other "workable" work packages. Other times, priority on work packages changes to reflect the new construction sequence. Work packages can be started with a reduced resource level. Work packages with higher priority more likely receive full amount of resources while work packages with lower priority end up with a lower resource level or are completely delayed. As a result, their durations are either shortened or extended and the scheduled dates are either advanced or delaved. The resource level is also not invariable during the execution of work packages.

The resource limit, the total available resource, is often not fixed at the same level throughout project duration. A resource (i.e. especially manpower) usually starts at a relatively low level, peaks somewhere in the middle of the project and gradually declines towards the end. The availability of resources can vary from one period to another and be at different levels during the project life cycle. This is usually referred to as Time-dependent Resource Availability (Hartmann 2013, Castro *et al.* 2014).

Work packages in industrial projects often are linear and cross multiple work areas, which tend to cause congestion issues. Workspace congestion can be affected by different factors such as number of workers in a given work area, product space, equipment space, material storage space, space used by temporary structures, space for workers and equipment paths (Akinci et al. 2002, Mallasi 2006). Congestion in this paper is strictly limited to the number of workers who are working in the same work area during the same period of time. Congestion is a common issue in mega projects when many work packages are performed concurrently in the same area. Since congestion diminishes productivity and increases the risk of safety incidents, it is necessary to impose congestion constraints on these areas so that it can be controlled. This congestion constraint, in turn, affects the amount of resources (especially workers) that could be allocated to work packages in the area. Work Packages are often not constrained to one work area, thus a mechanism called Work-Area-Work-Package was built to handle this issue.

Both resource availability level and resource utilization level can vary over time, even in the middle of the execution of work packages. This issue has been dealt with in the form of morning superintendent meetings where superintendents and managers sit together to review the current project status and allocate or re-allocate the limited resource at hand to mitigate the negative effect of changes on the project schedule.

#### 3. Literature review

Traditional critical-path-method- (CPM) based project scheduling techniques (e.g. Program Evaluation and Review Technique, Activity-On-Node, Activity-On-Arrow and Precedence Diagram Method) are limited in terms of practicality for their unrealistic assumption that resources are unlimited. Recognition of this limitation motivated intensive research in regards to the resource-constrained project scheduling problem (RCPSP). There are two major topics in this domain: resource allocation and resource levelling. The former aims to find the shortest project duration within the resource availability constraints, while the latter seeks to reduce the fluctuation in resource usage with assumptions such as unlimited resource availability and fixed project duration (Hegazy 1999). Since this research is more related to the former topic, literature related to resource allocation is reviewed herein.

Many researchers have attempted to formulate the RCPSP as a mathematical programming problem using various optimization techniques such as linear programming, branch-and-bound, and enumerative branch-and-cut (Karshenas and Haber 1990, Demeulemeester 2002, Jiang and Shi 2005). These techniques can only find a global optimal solution, if the RCPSP problem is solvable. However, these techniques are computationally impractical for most real-life projects (Moselhi and Lorterapong 1993, Hegazy 1999, Kim and de la Garza 2005).

Another approach to tackle the RCPSP problem is through heuristic techniques. Heuristics provide criteria for prioritizing concurrent work packages that are competing for the same resource. Commonly used heuristics include the least total float (LTF), the minimum latest finish (LFT) and resource scheduling method (RSM) (Davis and Patterson 1975). Moselhi and Lorterapong (1993) devised another heuristic technique, "least impact", which allocates resources to a set of activities rather than to an individual activity, as in most heuristic techniques. Lu and Li (2003) proposed a new heuristic called "work content" and argue it has comparable performance with LTF in terms of finding the shortest project duration.

Meta-heuristic-based project scheduling techniques became popular recently. These algorithms perform stochastic searches on populations of solutions which evolve over a number of iterations (Lu et al. 2008, Elbeltagi et al. 2005). Genetic algorithm (GA) has also been adopted to solve RCPSP problems (Chan et al. 1996, Hegazy 1999, Kandil and El-Rayes 2006). Unlike mathematic and heuristic techniques, these algorithms are usually designed to achieve more than one objective simultaneously (e.g. the minimum project duration, the least resource utilization variation and the least cost). GA has been used widely to optimize various construction problems, such as fleet configuration for earthmoving (Marzouk and Moselhi 2004), and location selection for crane lifting (Al-Hussein et al. 2005). GA limitations have also been identified, e.g. long processing time and tendency to be trapped in local optima (Elbeltagi et al. 2005, Ng and Zhang 2008). This motivated researchers to explore other meta-heuristic techniques. Particle swarm optimization (PSO) and ant colony optimization (ACO) are the two algorithms recently introduced to the construction scheduling domain (Lu et al. 2008, Ng and Zhang 2008, Christodoulou 2010).

Most previous RCPSP research is focused on finding more efficient and more effective scheduling optimization techniques. Scheduling optimization aside, they all assume that the work package can only start when all required resources are available throughout its duration and that, once captured, the resource levels stay constant for the duration of the work package. For example, if a piping work package requires a crew of 10 pipe fitters to perform the work, it is allowed to start only when there are 10 or more pipe fitters available. Otherwise, it would be simply delayed or interrupted until this condition is satisfied again. In practice, the work package might be carried out even if there are only 8 pipe fitters available. The resource level allocated to a work package could be any value within the range (minimum, normal, and maximum). In addition, resource level allocated to a work package could also change during the course of execution. For example, when a work area is congested, the number of skilled workers assigned to work packages might be reduced to alleviate the congestion. Or, skilled workers might be diverted from lower priority, in-progress work packages to higher priority ones so that they can be started. The dynamic characteristics of resource allocation, due to changing site conditions, are ignored in most previous RCPSP research, although it may have substantial impact on work packages' performance and need to be considered in the scheduling process.

Hegazy and Menesi (2010) proposed a new critical path analysis method called Critical Path Segment (CPS), which decompose activities into a group of segments based on days. This method converts the complicated precedence relationships (such as Start-to-Start and Finish-to-Finish) into Finish-to-Start. However, as for resource allocation, it holds the same deterministic view point.

Jobsite congestion has been approached mainly in two different ways: (1) space scheduling or space-time conflict, and (2) productivity loss due to site congestion. The former takes space as one of the pre-conditions (as a resource constraint) to perform a work package and returns a space-loaded construction schedule (Beliveau and Thabet 1994, Riley and Sanvido 1997, Tommelein and Zouein 2001, Akinci et al. 2002). A main goal of this line of research is to discover the mapping between space requirements of work packages and the physical space in 2D or 3D format, and then to detect and resolve the space conflict between work packages in close proximity. Recent work related to this line of research includes Location Based Scheduling (LBS). In this work, physical locations of activities are included in the planning and scheduling process. This method allows more control of the workflow to maintain continuity of work for different crews and to eliminate interference of trades in the same location, which consequently improves production efficiency (Lowe et al. 2012). It should be noted that LBS terminology that describes construction activities and workspace refer to concepts very similar to ones used in this paper. For example, LBS tasks refer to the same concept of work package and LBS locations refer to the same concept of work area. However, there is another type of congestion - overcrowding. It only reflects a degree of how crowded a work area is but not necessarily amounts to a space conflict. Jobsite crowding is believed to be one of the major causes of productivity loss and safety hazards (Nandakumar and Ahuja 1985, AbouRizk et al. 1993, Beliveau and Thabet 1994, Ovararin and Popescu 2001). Many researchers attempted to quantify the impact of site congestion on crew productivity (Thomas and Smith 1990, AbouRizk et al. 1993, Beliveau and Thabet 1994, Horner 1995, Ovararin and Popescu 2001).

Few researchers attempted to incorporate the impact of jobsite overcrowding into the schedules of work packages. Zouein and Tommelein (2001) suggested that space congestion issue can be solved, in addition to delaying the start of a work package, by lowering the resource level of work packages, believing that the space requirement can be reduced as its resource level declines. Although recognizing the relationship between the resource level and the degree of congestion, they did not fully make use of dynamic resource allocation. Instead, they assumed that the resource level, whether it is decreased or at the normal level, is determined at the start of a work package and stays constant throughout its duration. Thabet and Beliveau (1994) also recognized that work space crowding lengthens the duration of work packages and attempted to reflect this in the schedules of work packages. However, they suggested that instead of lowering resource level, the production rate should be reduced, due to multiple work packages taking place concurrently in the same work area, and consequently, increased congestion. This means that work packages can still hold the normal amount of resources, regardless of how crowded the work area is, and only get penalized by decreased production rates. In reality, however, this is not the case, since overcrowding not only causes reduction in productivity, but also brings about safety hazards and should be restricted with a maximum limit.

A gap exists between the project-scheduling-related research and industry practice. Little attention has been paid to the dynamic nature of resource availability, resource requirement and resource level of work packages. Instead, a deterministic point of view dominates most previous research. Meanwhile, jobsite overcrowding is seldom considered and integrated during the scheduling process.

Since absolute schedule optimization is not the focus of this paper, heuristic technique is selected to implement in the proposed framework.

Heuristic-based resource constrained project scheduling has two components: a scheduling scheme and a priority rule (Kolisch 1996). Scheduling scheme can be categorized into two different modes: serial scheduling scheme and parallel scheduling scheme. Serial scheduling scheme determines a sequence of activities, ordered by their priority (based on whatever priority rule is used). This sequence of activities is then scheduled one at a time and at the earliest time when both dependency and resource availability constraints can be met. Parallel scheduling scheme, on the other hand, assigns and releases resources at every time unit. Likewise, at the beginning of each time unit, a list of eligible activities (those whose predecessors have been completed) is updated and ordered by priority. Activities that create no resource over-allocation are scheduled and others are delayed or interrupted. This procedure repeats until all activities are scheduled. The major difference between the two scheduling schemes is that the serial mode releases resources only at the completion of activities while the parallel mode releases resources at the end of every time unit (Lu and Li 2003). Considering the flexibility that is required by dynamic resource allocation in this study, the parallel scheduling scheme is used.

#### 4. Proposed simulation-based framework

Congestion issues are associated with "work area," a concept that does not directly correspond to work packages. This is especially the case in industrial projects where many work packages are linear and cross a number of work areas, while each work area might involve more than one work package. Figure 1 shows a situation where several work packages take place concurrently in the same work area (e.g. WorkArea101) and a work package (e.g. WP2) can extend across several work areas (e.g. WorkArea100, 101 and 102). As a result, the execution of WP2 should comply with both resource limit and congestion constraints of all three work areas that it crosses.

Congestion constraint can be treated as a type of resource that is expressed as how many skilled workers can be present in the same work area. For example, assume that WP2 normally requires 10 skilled workers. However, due to the congestion status of WorkArea101, it could only get work space to accommodate 8 skilled workers. This can be modelled as it captures 8 skilled workers from a certain trade and meanwhile takes work space for 8 skilled workers from WorkArea101. A dilemma arises when WorkArea100 and WorkArea102 differ from WorkArea101. For example, WorkArea100 allows 10 skilled workers while WorkArea102 can only accommodate 7 skilled workers. Since WP2 also crosses these two work areas, it is then inaccurate to assign 8 skilled workers to the entire work package WP2 (Figure 2(a)). When WP2 is being performed in WorkArea101, it does not involve congestion limits in WorkArea100 and WorkArea102, and vice versa.

Figure 2(b) presents a new way of implementing congestion constraint. Work packages are further broken down into smaller elements called Work-Area-Work-Packages (WAP). Each WAP represents a portion of the work package in a specific work area. In this way, congestion constraints can act, respectively, on individual WAPs instead of on the whole work package. Since work packages are already at the lowest level of project planning and scheduling, WAPs need to be automatically created before simulation commences. The creation of WAPs can be viewed as part of pre-simulation data processing. The details and assumptions about the creation process are described as follows.

#### 4.1. Definition of WAP

In order to define WAPs, it is necessary to know in which work area(s) a work package is going to take place. Each work package/work area pair defines a WAP. A link is established between WAP and its parent work package. In this way, WAPs have access to the properties of their parent work packages, e.g. discipline, total man-hours, total quantity, unit of measurement, etc.

#### 4.2. Size of WAP

The size of WAPs is roughly derived from dividing the total man-hours (or total quantity) of the parent work package by the number of work areas it crosses. This is merely an approximation, but accurate enough for the



(a) Traditional way of implementing congestion limit



Figure 2. Work-area-work-package and congestion constraint.

work-area-work-package level. For example, sizes of piping WAPs can be determined by the length of pipe spools or the number of ISOs in each work area.

#### 4.3. Sequence of WAP

WAPs inherit all precedence relationships from parent work packages. For example, if work package A is a predecessor to work package B, all WAPs of A (A1, A2, ..., An) are predecessors to all WAPs of B (B1, B2, ..., Bn). Both the type of precedence relationship and the time lag remain the same. No sequence exists between WAPs from the same work packages.

This study assumes that each WAP is performed continuously once it has been started. However, on the work package level, child WAPs are not necessarily performed in a continuous fashion. This assumption makes sense in the context of industrial projects, since stoppage between WAPs can happen due to the time required to set up scaffolding in each work area when the work takes place at higher elevations.

# 5. Time-stepped discrete event simulation (DES)

The heuristic resource allocation approach can be implemented and automated through the use of DES. Simulation has long been used to model and analyse various construction processes, with the objective of improving long-term performance. For the last two decades, it has increasingly been used for planning and scheduling day-to-day operations. It is usually referred to as simulation-based scheduling (Senior and Halpin 1998, Lu et al. 2008, Mohamed et al. 2007, Taghaddos et al. 2012). Compared to traditional CPM method, DES is able to explicitly model resource interactions such that the resulting schedule is automatically levelled to the availability of resources. Another major advantage of using DES is that it provides a cost-effective laboratory environment where various alternatives can be tested and compared and the best one can be selected, without interrupting the real system. Many researchers have investigated the use of DES to solve construction planning and scheduling problems (Martinez et al. 1994, Senior and Halpin 1998, Zhang et al. 2002, Song and

AbouRizk 2006, Mohamed *et al*. 2007, Hu and Mohamed 2010, Taghaddos *et al*. 2012).

However, previous research depends heavily on the event-driven type of discrete event simulation (DES). Event-driven DES uses two events (start and/or end event) to represent the beginning and the completion of a work package. Once the duration is sampled from a statistic distribution, the execution of the work package (including resource level) is determined and stays the same throughout its duration. It then skips the interval between these two events. Time-stepped simulation is another type of DES where time advances in equal increments. At each step, the event list is checked to see whether an event is scheduled to occur. If yes, the system state is updated accordingly; otherwise, the simulation advances to the next time step and the system state remains unchanged. Future events are also scheduled in response to events occurring at the current time. This procedure continues until either there are no more events in the event list or a pre-defined time limit has been reached (Banks 1998).

Generally speaking, event-driven simulation is much more efficient, from a computing-time point of view. However, it lacks the granularity for capturing changes that might happen in-between key events. The time-stepped DES (also referred to as time-slicing) (Robinson 2004) is preferred over the event-driven DES to use in this research because it dissects the execution of a work package into subsequent segments and carries them out individually. This level of granularity allows for the incorporation of schedule changes during work package execution and the analysis of its possible effects on other work packages. In the proposed method, simulation is designed to advance time 24 h per day and 7 days per week. Each time step represents an hour, but could easily be scaled up or down to other time units. The major reason to choose a 24/7 time advance is that work calendars for different trades vary from one work package to another (e.g. piling work packages use the 10/5 calendar, i.e. 10 h per day and 5 days per week, while steel structure work packages use the 8/6 calendar). The 24/7 calendar offers a common foundation on which different calendars can be incorporated in the simulation model.

Time-stepped simulation requires a routine procedure in every time step, which includes the steps shown in Figure 3: (1) if this is the beginning of the simulation, move to step 2 immediately; otherwise, update the progress for WAPs that successfully captured resources in the last time step, release all the resources and update the resource availability limit at the current time; (2) identify eligible WAPs (i.e. those that satisfy all prerequisites, e.g. drawings, materials, time constraints, as well as precedence dependency); (3) prioritize eligible WAPs and allocate resources to them considering the limited availability and congestion conditions in each work area; (4) advance the simulation to the next time step unless all WAPs have been completed already or a pre-defined time limit has been reached.

# 6. Identify eligible work packages

Work packages should not be released to field until all the preconditions have been met. It is necessary to check the eligibility of every work package before it can be scheduled. This also applies to WAPs, each of which represents a portion of its parent work package. Various constraint checks are built into the simulation, including predecessor status check, time constraints check, and prerequisites check, as defined below.

#### 6.1. Predecessor WAPs check

It is the precedence relationships that drive the schedule to move forward. As predecessor WAPs progress or are completed, the succeeding WAPs become eligible to be executed. The proposed method incorporates all four types of precedence relationships: (1) start-to-start (SS); (2) startto-finish (SF); (3) finish-to-start (FS); and (4) finish-to-finish (FF). Both positive and negative time lags are allowed to complement the four relationship types in order to model the logic relationship between WAPs. More than one relationship can exist between a pair of WAPs.

#### 6.2. Time constraint check

A work package may have time constraints that govern its start time or/and finish time. These constraints also apply to child WAPs of this work package. Simulation converts the current simulation time into date-time format and compares with these constraints to determine the eligibility of WAPs.

#### 6.3. Prerequisite check

Material and drawing availability are the most frequent reasons to delay work packages. In fast-tracked industrial projects, construction and procurement starts way before the design is completed. Since scope is either undetermined or prone to change, the delivery of material and drawings becomes the major issue to hamper project progress. The start of WAPs is checked against delivery dates of required material and drawings.

Only WAPs that have successfully passed all three checks are schedulable or eligible. Others are sent back to the WAP pool, and checked in future time units.



Figure 3. Routine procedure for every time step.

# 7. Dynamic resource allocation algorithm

A two-round resource allocation algorithm is designed to allow for dynamic resource allocation while maintaining the continuity of WAPs as shown in Figure 4. First, all eligible WAPs are divided into two categories: (1) in-progress WAPs, and (2) newly-included WAPs. The first round of resource allocation is active if the number of in-progress WAPs is not equal to zero. It allocates resources to all in-progress WAPs up to their respective minimum-manpower-level requirements. The purpose is to guarantee that all in-progress WAPs can be continuously performed. The resource level may or may not be the same as in the previous time units. After the first round is done, all WAPs (in-progress and newly-added) are combined in a single list and sorted by their priority, given a particular priority rule (e.g. least total float, earliest late finish or current float). The second round of resource allocation is active if resources are not depleted in the first round. The second round adopts greedy firstfit criteria when allocating resources to work packages. This means that it attempts to fulfil the resource requirements of higher-priority WAPs. The allocation is successful when the sum of resources that a WAP has obtained from both rounds is more than the minimum manpower level. Otherwise, the WAP has to be delayed. If resources are abundant, the resources allocated to a WAP could sum up



Figure 4. Dynamic resource allocation algorithm.

to the WAP's normal resource level. In this case, the amount of resources captured in the second round is equal to the normal resource level minus the amount captured in the first round. For example, if a piping WAP normally requires 10 pipe fitters and has already captured 8 pipe fitters in the first round of resource allocation. It can capture another two pipe fitters in the second round of resource allocation if two or more than two pipe fitters are still available. If resources are insufficient, all the remaining resources are allocated to this WAP. For example, if there is only one pipe fitter left in the second round. The piping work package will still capture this pipe fitter and the total manpower level is 9. Resource allocation is also constrained by congestion conditions of related work areas. The amount of resources that can be allocated to a WAP is the minimum of both the availability of the resource it requires and the number of people that can be present in the work area.

# 7.1. Variable resource level and variable durations

Although WAPs that are in progress are guaranteed to be performed continuously, their resource levels are not necessarily constant. Resource levels of a WAP might change under a few circumstances. First, in cases where a higher-priority WAP that requests the same type of resource is added to the eligible list, and it successfully captures resources in the second round of resource allocation, the resource level of the in-progress WAP might be reduced. Likewise, in cases where a higher-priority WAP that takes place in the same work area becomes schedulable and it manages to take some congestion resources in the second round, the resource level of the in-progress WAP might be decreased. Another reason for change in WAP resource levels could simply be a decrease in the availability of the resource (due to time-dependent resource limit). The resource level could also be increased when all aforementioned situations are inversed. Traditional CPMbased scheduling tools such as MS Project also allow for variations in resource allocation, but the variation is restricted to either the normal resource requirement, or nothing. Completely stopping work on a WAP that has already started is very rare in real-life projects due to extra costs for protecting work-in-process, mobilizing equipment, double-handling materials and associated set-up time. Given the fixed work quantity of a WAP, its duration is bound to change as the resource level changes. It is assumed that the production rate has a linear relation with resource level.

#### 7.2. Update the progress of work packages

All WAPs that have successfully captured resources in the current simulation time are collected in a list. The progress of these WAPs is updated accordingly at the end of the current simulation time. For example, if a piping WAP captures 8 pipe fitters, the man-hours that it has gained are equal to 8 times the time unit. If the time unit is an hour, 8 manhours are gained. If the time unit is a day, then the total man-hours obtained depend on the calendar of the work package. Assuming that it uses the 10/5 calendar, 80 manhours are then obtained. If a WAP has fulfilled the total man-hours, it is added to the completed work package list.

At the end of the current simulation time step, two additional tasks are performed. First, all resources captured in the current step are released to replenish the resource pool. Second, the availability limit of each type of resource is updated according to the pre-defined, time-dependent value.

#### 8. Implementation

Since the time-stepped simulation advances time in a 24/7 manner, it requires more computing time than other event-driven simulations. The simulation efficiency is then an issue that has to be addressed. Most work packages or WAPs will not be performed 24 h per day or 7 days per week. There are certain time units that are non-working time for all work packages. A check is performed at the beginning of each time unit to see if it is a working time for any eligible WAPs. If yes (i.e. some packages are working), the standard procedure will be carried out (identify eligible work packages→allocate resources→advance simulation time→update the progress). Otherwise, this procedure is skipped and the simulation time is advanced one time unit forward. This significantly reduces the required time to run the simulation model.

The proposed method requires a variety of information from different information sources. The current implementation automatically reads data from a database, constructs and runs the simulation model, and eventually writes the generated schedule back to the database. Figure 5 shows an outline of the implementation used in the sample case. The simulation code also interfaces with other information systems at a database level. For example, material and drawing availability information can be exchanged via a database between a material management system and a simulation database. As-built information is pulled from a progress tracking system so that simulation can start construction activities from the current time instead of from the beginning of the project. Meanwhile, some, of the work packages can be extracted directly from a 3D model of the project, depending on how much information is embedded. Manual input is still required to populate some data tables (e.g. dependency relationships between parent work packages, man-hour requirements of work packages, and time dependent availability limits of resources) that may not be available in existing systems. The system has been implemented using Visual Basic.Net, Simphony. Net 4.0 (AbouRizk and Mohamed 2000), Microsoft Access 2007 as the data base management system, and Microsoft Project 2007 for schedule representation.

#### 9. Case study

In order to demonstrate and test the practicality of the proposed method, a real case is used from a general contractor operating in Canada and the United States. The contractor provides services from pipe spool pre-fabrication,



Figure 5. Outline of implementation architecture.

module pre-assembly, to field construction. The project is an oil sands project designed to produce 110,000 barrels of bitumen processing capacity per day. The capital investment is approximately \$10.9 billion. The project is a typical mega oil-sand project that is being constructed in the province of Alberta, Canada. The full scope of the project is beyond the purpose of the case study. As such, only a portion of pipe rack area is focused on here. This portion is marked by arrows in Figure 6.

The major work in this area is to install a number of pipe-rack modules in a stacked configuration. These modules are pre-assembled in a module yard and shipped to the construction site for final installation. Other disciplines involved include piling, support structure, piping (for interconnecting modules), silencer installation, hydro-testing, insulation, and electrical cable tray. Fifty one work packages are identified with quantity, work areas, dependency relationships, and resource requirements data. A sample of these work packages is shown in Table 1. As a typical oil and gas project, overlap between work packages (e.g. work packages 38 to 42 and work packages 44 to 49 in Table 1) exists as insulation can be started before hydrotesting (specifically reinstate) is completed to achieve shorter schedule duration. This overlap can lead to congestion issues that impact safety and productivity of workers. Five trades are required to perform these work packages, which

results in about 250 activities taking place where these work packages are located. Daily availability limit for each trade is shown in Table 2. The pipe-rack module packages are selected here as they suffer the most from overlaps between trades in the same work area and therefore are subject to congestion constraints.

Multi-tier pipe rack areas are usually highly congested with various pipes and cable trays running (horizontally or vertically) on the steel structures. Given that many work packages have to be performed concurrently in these areas and the work space is quite limited, the congestion issue is unavoidable. Table 3 shows the congestion constraint for each work area.

#### 9.1. Pre-simulation calculations

As discussed earlier, input related to resource, dependency and congestion limits is done on work package and work area levels and aggregated in one database either through manual input or through import from existing information systems. Pre-simulation stage begins after loading this information into program. The main task of this stage is to translate the information to the WAP level. For work-quantity-related information (e.g. total man hours), it is simply divided by the number of work areas that the work package crosses. This could be improved in the future by better



Figure 6. Pipe-rack area of case study project.

#### Table 1. Case study data.

					Craft personnel requirements			
Work package No. (1)	Description (2)	Quantity (man hours) (3)	Work areas (4)	- Predecessors (FS) (5)	Trade (6)	Normal crew size (7)	Min crew size (8)	
38	HydrotesingBet- w011AB012ABC	30	011AB	29(-2 days)	PF	10	8	
39	HydrotesingBet- w012ABC005AB	30	012ABC	30(-2 days)	PF	10	8	
40	HydrotesingBet- w005AB006AB	30	005AB	31(-2 days)	PF	10	8	
41	HydrotesingBet- w006AB007ABC	30	006AB	32(-2 days)	PF	10	8	
42	HydrotesingBet- w007ABC014AB	30	007ABC	33(-2 days)	PF	10	8	
43	HydrotestingSilencer- OnTopOf007AB- C014AB	80	007ABC, 014AB	36,37	PF	10	8	
44	InsulationBet- w011AB012ABC	20	011AB	38(-1 day)	INS	10	8	
45	InsulationBet- w012ABC005AB	20	012ABC	39(-1 day)	INS	10	8	
46	InsulationBet- w005AB006AB	20	005AB	40(-1 day)	INS	10	8	
47	InsulationBet- w006AB007ABC	20	006AB	41(-1 day)	INS	10	8	
48	InsulationBet- w007ABC014AB	20	007ABC	42(-1 day)	INS	10	8	
49	InsulationSilencerOn- topOf007ABC014AB	40	014AB	43(-1 day)	INS	10	8	

measurement e.g. the number of pipe spools in each area or the linear length of cable tray. WAPs inherit resource requirement information (e.g. trade, crew size) from their parent work packages. WAPs also inherit all logic-dependency relationships from their parent work packages. Excessive constraints should be removed in this step. For example, Figure 7 shows a situation where work package A is one of predecessors of work package B, and both take place in work area 1 and work area 2. One of the predecessors to B1 (the portion of work package B in work area 1) is A1 (the portion of work package A in work area 1), but not A2. Likewise, there is no dependency relationship between B2 and A1.

Table 2. Daily trade availability limit.

Trade (1)	Start date (2)	End date (3)	Available amount (4)
EL (Electrician)	01-Sep-12	31-Jan-13	20
INS (Insulation)	01-Sep-12	31-Jan-13	20
IW (Iron worker)	01-Sep-12	31-Jan-13	20
PF (Pipe fitter)	01-Sep-12	31-Jan-13	16
PIL (Piling)	01-Sep-12	31-Jan-13	20

Table 3. Congestion constraint of each work area.

Work area (1)	Max craft persons (2)
011AB	16
012ABC	16
005AB	16
006AB	16
007ABC	16
014AB	16

# 9.2. Simulation details

The simulation processes 51 work packages, including eight processes: piling, module base structure, module setting, piping, silencer installation, hydrotesting, insulation and cable tray, which are further broken into 60 WAPs (many of work packages like module setting cannot be further broken up). There are two work crews, each with 10 craft workers, available for each trade (piling, pipe fitters, iron workers, and insulation workers) to perform these work packages. Some of these work packages require the same craft workers, e.g. both piping and hydrotesting work packages require pipe fitters. Normally, each work package requires a 10 workers size crew but can be carried out with 8 workers if available. These work packages cross 6 work areas, each of which cannot accommodate more than 16 workers at the same time.



Figure 7. Remove excessive dependency relationship between WAPs.

After the basic information is determined for WAPs, a CPM calculation is carried out before the simulation starts. The only purpose is to create initial priority value for work packages based on certain heuristics (e.g. the least total float, the least free float, early start or early finish) This priority can be overridden by users if necessary, but it has to be done before the simulation kicks off.

The simulation strictly follows all constraints such as precedence relationship, resource availability level, different shifts for trades, time constraint, and congestion limit. It dynamically assigns resource to WAPs depending on available craft workers at the moment, congestion status in work areas and work package priorities. The least total float is used as main heuristic to prioritize work packages in the pre-simulation CPM calculation.



Figure 8. Congestion status before (a) and after (b) simulation run.

At the end of simulation, the start times and finish times of WAPs are rolled up to the work package level, It is assumed that the work starts on 10 September 2012. The simulation result shows that it can be completed by 7 January 2013.

Congestion issues exists in every work area (as in Figure 8(a), as the darker bars indicate that the congestion constraint has been exceeded) when the congestion constraint is not imposed. After running the simulation, the resulting schedule shows that all congestion situations have been resolved (Figure 8(b)).

#### 9.3. Comparison to MS Project and Primavera

Literature on simulation model development links the validity of a model to the purpose of its development and its intended application (Balci 1998, Sargent 2013). The main objective of the proposed method is to generate a schedule for a number of work packages taking into account logical dependency constraints between activities, dynamically changing resource level constraints, and congestion limits constraints. As such, validating the developed model is done by examining its output in comparison to main stream scheduling solutions widely acceptable by the industry

and making sure that none of the standard constraints are violated. To conduct the comparison, the same case study is also scheduled using CPM-based scheduling software tools (MS Project and Primavera 6). The experiment has two steps: (1) schedule all WAPs with standard constraints only (i.e. only with precedence dependency and calendar constraints); (2) schedule under both resource availability limit and congestion constraint. Tabular results of the two steps are provided in Appendix 1. When only considering precedence dependency and calendar constraint, CPM based scheduling software and the proposed method result in the same project completion date – November 26th, 2012. All three generated schedules are identical, which indicates proper handling of dependency constraints by the proposed method and complete alignment with industry acceptable scheduling tools under normal conditions.

The proposed method shows a departure from MS Project and Primavera 6 when both resource limit (Table 2) and congestion constraint (Table 3) come into play. It returns a project completion date of 7 January 2013. The simulation results satisfy all the constraints of the activities. To model the resource limits and congestion constraints under the other two tools we can only use the available resource levelling functions provided in these tools and

compare the project finish date in the generated schedules. MS Project, after resource levelling, reaches a project finish date of 24 January 2013. Since MS Project is using its own proprietary algorithm, there is no other resource allocation algorithm to choose. The only variation that can be made is to allow the program to create splits in activities (i.e. allow interruption). Although guite impractical in reality (as mentioned before), this option was enabled, and the result was still 24 January 2013. Primavera 6, on the other hand, allows users to experiment with various heuristics (early start/finish, late start/finish, total float, free float, etc.). When using total float as the main heuristic (i.e. the same as used in the simulation) to allocate resources, the program results in a project finish date of 24 January 2013. Other heuristics have been tried and most of them return an even later project completion date, except for free float heuristic. When adopting free float heuristic, the program returns a project finish date of 22 January 2013. However, this result is still not as desirable as the one also returned by the simulation - 7 January 2013.

# 9.4. Discussion of results

The major difference between the proposed method and traditional CPM scheduling methods is the way resources are allocated. The proposed method allows adjustment of resource allocation at any point during the execution of work packages where methods used in traditional scheduling tools use the same resource allocation throughout the execution of work packages. If allowed to create splits in work packages, MS Project interrupts the work package and allocates no resources to it. The simulation tool, on the other hand, can assign work packages any amount of resources within the normal and the minimal range. This is illustrated in Figure 9, which focuses on four work packages, work package 37 to 40. Work packages 37 and 38 are to install the pipe spools that are used to connect silencers on the top of pipe rack modules, while work package 39 and 40 are to install the silencers. All four work packages require the same type of craft workers – pipe fitters. The background bar chart shows the original schedule when there is no resource limit or congestion constraint. Overlap



Figure 9. Comparison between the simulation tool, MS Project and Primavera.

between these work packages leads to a situation where a higher-priority work package starts during the execution of a lower-priority work package. For example, work package 38 and 40 both have overlap with work package 39. The resource limit for pipe fitters is 20 and each work package normally requires a crew of 10 pipe fitters. During the overlap, the total resource requirement could surge to 20, which exceeds the congestion limit of 16. Figure 9 also shows the total float of each work package (i.e. the number of days on the right of the bars), e.g. work package 37 and 39 have 1 day total float, while work packages 38 and 40 have zero total float, and thus, have higher priority than the former two work packages. Although work package 39 starts before work package 38 and 40, resource is re-allocated when work package 38 and 40 start.

MS Project and P6 assign either the full amount of required resources or nothing to work packages. Therefore, if the aforementioned situation occurs, it completely postpones one work package or the other. Figure 9 shows that MS Project and P6 can only perform one work package at a time, though the sequence might be different. However, the proposed method allows these work packages to be performed concurrently. When work package 38 starts, it can use some resources redirected from work package 39, even though 39 is still in progress. The two-round resource allocation algorithm allocates 8 pipe fitters to work package 39 in the first round. In the second round of resource allocation, it allocates the remaining 8 pipe fitters to work package 38 since it has higher priority. In this way, the continuity of work package 39 is maintained and work package 38 can be started immediately without delay. The same process happens when work package 40 starts. In the case of the proposed method, all four work packages can be completed within 10 working days (i.e. from 7 November to 20 November 2012). The duration of work package 39 is also changed from 6 days to 7.5 days. In contrast, it takes 15 working days and 26 working days to complete these work packages in MS Project and P6, respectively.

#### 10. Limitations and future work

There are a number of limitations of the proposed system that need to be addressed in future work. First, Congestion in this paper is restricted to the number of workers to work at the same work area at the same time. Other factors that contribute to congestions such as conflicts between product space, storage areas, equipment spaces and paths are not addressed in a direct way in this work but can be modelled indirectly by reducing the maximum number of workers allowed in a certain work area based on usage and available space in that area. A 2D/3D model could be of help to implement congestion limits but it is not a must-have. A project plot plan would be sufficient for this purpose. Congestion limit can be better implemented by measuring the total "workable" area in each work area and calculating the minimal work area requirement for each trade. Using the total available area as congestion limit might be more accurate than using the total number of workers can be present in the same area as area requirement might vary from one trade to another.

The size of WAPs can be improved by better measurements. For example, for piping, it can be measured as the number of pipe spools in each work area. For steel structure, it can use total weight of steel members to be installed in each work area.

The cost associated with resource allocation has not been considered in the simulation. The schedule is improved only in terms of overall project duration but if the overall project cost is also reduced is a question to be answered. This is especially important when it is a lump sum project, but might not as important when it is a reimbursable project and the client is willing pay the cost to obtain the shorter project duration.

Priority of work packages are calculated based on the "least total float" heuristic. The simulation should also be able to use priority values that overridden by field superintendents and managers and compare the results. This is advantage of using simulation to test multiple "what-if" scenarios.

Finally, a limitation of the proposed system is that it requires more input than a traditional CPM scheduling tool. Therefore, integration with other information systems used by contractors is crucial to facilitate practical use. A standalone database is used for this study. All data are manually imported into database. Manpower levels for work packages can be linked to estimating systems and part of the precedence dependency information can be derived automatically from 3D models based on the physical constraints. Detailed comparison between the proposed method and location based scheduling methods can also be pursued in future work to investigate differences and similarities, and the potential of integration between the two methods.

# 11. Conclusions

This paper presents a time-stepped simulation-based scheduling method that dissects work packages into smaller time unit based (daily/weekly/monthly) segments. It simulates the execution of work packages for each time step and allows for variable resource allocation to these work packages if either the resource limit or the congestion limit is reached. Both resource availability levels and utilization levels can be variable during the course of work packages. Work packages can also be performed/started in an understaffed scenario and do not always require the full crew size. It also accounts for all traditional constraints

of work packages such as precedence relationships, calendars and hard time constraints. A real industrial construction case was used to test the practicality of the method. The advantage of using simulation for scheduling is the capability of handling a large number of activities and work packages at high level of granularity and the ability to guantify the impact of resource allocation and congestion limits decisions. The schedules generated from the proposed method were compared with those produced by popular CPM-based project scheduling tools. The proposed framework returns shorter overall project duration compared to two other scheduling tools as it has more flexible resource allocation mechanism which allows for work packages to be carried out concurrently. This flexibility is frequently utilized in real-life construction practice but rarely addressed by prior scheduling research. Another advantage of the proposed framework is that it can take as-built data and run simulation from current time of the project instead of having to start over from the very beginning. The simulation allows for experimenting with various priority scenarios for work packages.

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# Appendix 1. Simulation vs. P6 vs. MS. Project results

Case1: No congestion or resource limits

		Simulat	Simulation result		ra result	MS project	
ID	WAPName	WAPSimStart	WAPSimFinish	Start	Finish	Start	Finish
1	Piling011AB	9/10/2012	9/11/2012	9/10/2012	9/11/2012	9/10/2012	9/11/2012
2	Piling012ABC	9/10/2012	9/11/2012	9/10/2012	9/11/2012	9/10/2012	9/11/2012
3	Piling005AB	9/12/2012	9/13/2012	9/12/2012	9/13/2012	9/12/2012	9/13/2012
4	Piling006AB	9/12/2012	9/13/2012	9/12/2012	9/13/2012	9/12/2012	9/13/2012
5	Piling007ABC	9/14/2012	9/17/2012	9/14/2012	9/17/2012	9/14/2012	9/17/2012
6	Piling014AB	9/14/2012	9/17/2012	9/14/2012	9/17/2012	9/14/2012	9/17/2012
7	ModuleSupportStructure@011AB	9/12/2012	9/17/2012	9/12/2012	9/17/2012	9/12/2012	9/17/2012
8	ModuleSupportStructure@012ABC	9/12/2012	9/17/2012	9/12/2012	9/17/2012	9/12/2012	9/17/2012
9	ModuleSupportStructure@005AB	9/14/2012	9/19/2012	9/14/2012	9/19/2012	9/14/2012	9/19/2012
10	ModuleSupportStructure@006AB	9/14/2012	9/19/2012	9/14/2012	9/19/2012	9/14/2012	9/19/2012
11	ModuleSupportStructure@007ABC	9/18/2012	9/21/2012	9/18/2012	9/21/2012	9/18/2012	9/21/2012
12	ModuleSupportStructure@014AB	9/18/2012	9/21/2012	9/18/2012	9/21/2012	9/18/2012	9/21/2012
13	1600-PR-011A	9/18/2012	9/19/2012	9/18/2012	9/19/2012	9/18/2012	9/19/2012
14	1600-PR-011B	9/20/2012	9/21/2012	9/20/2012	9/21/2012	9/20/2012	9/21/2012
15	1610-PR-005	9/24/2012	9/25/2012	9/24/2012	9/25/2012	9/24/2012	9/25/2012
16	1600-PR-012A	9/26/2012	9/27/2012	9/26/2012	9/27/2012	9/26/2012	9/27/2012
17	1600-PR-012B	9/28/2012	10/1/2012	9/28/2012	10/1/2012	9/28/2012	10/1/2012
18	1600-PR-012C	10/2/2012	10/3/2012	10/2/2012	10/3/2012	10/2/2012	10/3/2012
19	1610-PR-004	10/4/2012	10/5/2012	10/4/2012	10/5/2012	10/4/2012	10/5/2012
20	1600-PR-005A	10/9/2012	10/10/2012	10/9/2012	10/10/2012	10/9/2012	10/10/2012
21	1600-PR-005B	10/11/2012	10/12/2012	10/11/2012	10/12/2012	10/11/2012	10/12/2012
22	1610-PR-002	10/15/2012	10/16/2012	10/15/2012	10/16/2012	10/15/2012	10/16/2012
23	1610-PR-003	10/17/2012	10/18/2012	10/17/2012	10/18/2012	10/17/2012	10/18/2012
24	1600-PR-006A	10/19/2012	10/22/2012	10/19/2012	10/22/2012	10/19/2012	10/22/2012
25	1600-PR-006B	10/23/2012	10/24/2012	10/23/2012	10/24/2012	10/23/2012	10/24/2012
26	1610-PR-001	10/25/2012	10/26/2012	10/25/2012	10/26/2012	10/25/2012	10/26/2012
27	1600-PR-007A	10/29/2012	10/30/2012	10/29/2012	10/30/2012	10/29/2012	10/30/2012
28	1600-PR-007B	10/31/2012	11/1/2012	10/31/2012	11/1/2012	10/31/2012	11/1/2012
29	1600-PR-007C	11/2/2012	11/5/2012	11/2/2012	11/5/2012	11/2/2012	11/5/2012
30	1600-PR-014A	11/6/2012	11/7/2012	11/6/2012	11/7/2012	11/6/2012	11/7/2012
31	1600-PR-014B	11/8/2012	11/9/2012	11/8/2012	11/9/2012	11/8/2012	11/9/2012
32	PipingBetw011AB012ABC	10/4/2012	10/12/2012	10/4/2012	10/12/2012	10/4/2012	10/12/2012
33	PipingBetw005AB012ABC	10/15/2012	10/22/2012	10/15/2012	10/22/2012	10/15/2012	10/22/2012
34	PipingBetw006AB005AB	10/25/2012	11/1/2012	10/25/2012	11/1/2012	10/25/2012	11/1/2012
35	PipingBetw007ABC006AB	11/6/2012	11/13/2012	11/6/2012	11/13/2012	11/6/2012	11/13/2012
36	PipingBetw014AB007ABC	11/12/2012	11/19/2012	11/12/2012	11/19/2012	11/12/2012	11/19/2012
37	PipingOnTopOf007C	11/6/2012	11/7/2012	11/6/2012	11/7/2012	11/6/2012	11/7/2012
38	PipingOnTopOf014B	11/12/2012	11/13/2012	11/12/2012	11/13/2012	11/12/2012	11/13/2012
39	Silencer@007ABC	11/8/2012	11/15/2012	11/8/2012	11/15/2012	11/8/2012	11/15/2012
40	Silencer@014AB	11/14/2012	11/16/2012	11/14/2012	11/16/2012	11/14/2012	11/16/2012
41	HydrotesingBetw011AB012ABC	10/11/2012	10/15/2012	10/11/2012	10/15/2012	10/11/2012	10/15/2012
42	HydrotesingBetw012ABC005AB	10/19/2012	10/23/2012	10/19/2012	10/23/2012	10/19/2012	10/23/2012
43	HydrotesingBetw005AB006AB	10/31/2012	11/2/2012	10/31/2012	11/2/2012	10/31/2012	11/2/2012
44	HydrotesingBetw006AB007ABC	11/12/2012	11/14/2012	11/12/2012	11/14/2012	11/12/2012	11/14/2012
45	HydrotesingBetw00/ABC014AB	11/16/2012	11/20/2012	11/16/2012	11/20/2012	11/16/2012	11/20/2012
46	HydrotestingSilencerOnTopOf007ABC	11/16/2012	11/21/2012	11/16/2012	11/21/2012	11/16/2012	11/21/2012
4/	HydrotestingSilencerOnTopOf014AB	11/19/2012	11/22/2012	11/19/2012	11/22/2012	11/19/2012	11/22/2012
48	InsulationBetw011AB012ABC	10/15/2012	10/16/2012	10/15/2012	10/16/2012	10/15/2012	10/16/2012
49	InsulationBetwoll2ABC005AB	10/23/2012	10/24/2012	10/23/2012	10/24/2012	10/23/2012	10/24/2012
50	InsulationBetw005AB006AB	11/2/2012	11/5/2012	11/2/2012	11/5/2012	11/2/2012	11/5/2012
51	InsulationBetw006AB00/ABC	11/14/2012	11/15/2012	11/14/2012	11/15/2012	11/14/2012	11/15/2012
52	InsulationBetw00/ABC014AB	11/20/2012	11/21/2012	11/20/2012	11/21/2012	11/20/2012	11/21/2012
53	InsulationSilencerOntopOf00/ABC	11/21/2012	11/22/2012	11/21/2012	11/22/2012	11/21/2012	11/22/2012
54	InsulationSilencerOntopOf014AB	11/22/2012	11/23/2012	11/22/2012	11/23/2012	11/22/2012	11/23/2012
55	ElectricalCableTray@011AB	10/17/2012	10/17/2012	10/1//2012	10/1//2012	10/17/2012	10/17/2012
56	ElectricalCableTray@012ABC	10/1//2012	10/1//2012	10/1//2012	10/1//2012	10/1//2012	10/1//2012
5/	ElectricalCableTray@005AB	11/26/2012	11/26/2012	11/26/2012	11/26/2012	11/26/2012	11/26/2012
58		11/26/2012	11/26/2012	11/26/2012	11/26/2012	11/26/2012	11/26/2012
59		11/26/2012	11/26/2012	11/26/2012	11/26/2012	11/26/2012	11/26/2012
00	ElectricalCableTray@014Ab	11/20/2012	11/20/2012	11/20/2012	11/20/2012	11/20/2012	11/20/2012

# Case2: With congestion and resource limits

		Simulation Result		Primavera Result		MS Project	
ID	WAPName	WAPSimStart	WAPSimFinish	Start	Finish	Start	Finish
1	Piling011AB	9/10/2012	9/11/2012	9/10/2012	9/11/2012	9/10/2012	9/11/2012
2	Piling012ABC	9/10/2012	9/11/2012	9/10/2012	9/11/2012	9/10/2012	9/11/2012
3	Piling005AB	9/12/2012	9/13/2012	9/12/2012	9/13/2012	9/12/2012	9/13/2012
4	Piling006AB	9/12/2012	9/13/2012	9/12/2012	9/13/2012	9/12/2012	9/13/2012
5	Piling007ABC	9/14/2012	9/17/2012	9/14/2012	9/17/2012	9/14/2012	9/17/2012
6	Piling014AB	9/14/2012	9/17/2012	9/14/2012	9/17/2012	9/14/2012	9/17/2012
7	ModuleSupportStructure@011AB	9/12/2012	9/17/2012	9/12/2012	9/17/2012	9/12/2012	9/17/2012
8	ModuleSupportStructure@012ABC	9/12/2012	9/17/2012	9/12/2012	9/17/2012	9/12/2012	9/17/2012
9	ModuleSupportStructure@005AB	9/18/2012	9/21/2012	9/18/2012	9/21/2012	9/18/2012	9/21/2012
10	ModuleSupportStructure@006AB	9/24/2012	9/27/2012	9/24/2012	9/27/2012	9/24/2012	9/27/2012
11	ModuleSupportStructure@007ABC	9/28/2012	10/3/2012	9/28/2012	10/3/2012	9/28/2012	10/3/2012
12	ModuleSupportStructure@014AB	10/4/2012	10/10/2012	10/4/2012	10/10/2012	10/4/2012	10/10/2012
13	1600-PR-011A	9/18/2012	9/19/2012	9/18/2012	9/19/2012	9/18/2012	9/19/2012
14	1600-PR-011B	9/20/2012	9/21/2012	9/20/2012	9/21/2012	9/20/2012	9/21/2012
15	1610-PR-005	9/24/2012	9/25/2012	9/24/2012	9/25/2012	9/24/2012	9/25/2012
16	1600-PR-012A	9/26/2012	9/27/2012	9/26/2012	9/27/2012	9/26/2012	9/27/2012
17	1600-PR-012B	9/28/2012	10/1/2012	9/28/2012	10/1/2012	9/28/2012	10/1/2012
18	1600-PR-012C	10/2/2012	10/3/2012	10/2/2012	10/3/2012	10/2/2012	10/3/2012
19	1610-PR-004	10/4/2012	10/5/2012	10/4/2012	10/5/2012	10/4/2012	10/5/2012
20	1600-PR-005A	10/9/2012	10/10/2012	10/9/2012	10/10/2012	10/9/2012	10/10/2012
21	1600-PR-005B	10/11/2012	10/12/2012	10/11/2012	10/12/2012	10/11/2012	10/12/2012
22	1610-PR-002	10/15/2012	10/16/2012	10/15/2012	10/16/2012	10/15/2012	10/16/2012
23	1610-PR-003	10/17/2012	10/18/2012	10/17/2012	10/18/2012	10/17/2012	10/18/2012
24	1600-PR-006A	10/19/2012	10/22/2012	10/19/2012	10/22/2012	10/19/2012	10/22/2012
25	1600-PR-006B	10/23/2012	10/24/2012	10/23/2012	10/24/2012	10/23/2012	10/24/2012
26	1610-PR-001	10/25/2012	10/26/2012	10/25/2012	10/26/2012	10/25/2012	10/26/2012
27	1600-PR-007A	10/29/2012	10/30/2012	10/29/2012	10/30/2012	10/29/2012	10/30/2012
28	1600-PR-007B	10/31/2012	11/1/2012	10/31/2012	11/1/2012	10/31/2012	11/1/2012
29	1600-PR-007C	11/2/2012	11/5/2012	11/2/2012	11/5/2012	11/2/2012	11/5/2012
30	1600-PR-014A	11/6/2012	11/7/2012	11/6/2012	11/7/2012	11/6/2012	11/7/2012
31	1600-PR-014B	11/8/2012	11/9/2012	11/8/2012	11/9/2012	11/8/2012	11/9/2012
32	PipingBetw011AB012ABC	10/4/2012	10/15/2012	10/4/2012	10/12/2012	10/4/2012	10/12/2012
33	PipingBetw005AB012ABC	10/19/2012	10/29/2012	10/19/2012	10/26/2012	10/19/2012	10/26/2012
34	PipingBetw006AB005AB	10/29/2012	11/7/2012	10/29/2012	11/5/2012	10/29/2012	11/5/2012
35	PipingBetw007ABC006AB	12/12/2012	12/20/2012	12/4/2012	12/12/2012	11/27/2012	12/4/2012
36	PipingBetw014AB007ABC	11/29/2012	12/7/2012	1/8/2013	1/16/2013	12/5/2012	12/12/2012
37	PipingOnTopOf007C	11/7/2012	11/9/2012	11/14/2012	11/15/2012	11/6/2012	11/7/2012
38	PipingOnTopOf014B	11/12/2012	11/14/2012	11/30/2012	12/4/2012	11/12/2012	11/13/2012
39	Silencer@007ABC	11/9/2012	11/20/2012	11/16/2012	11/26/2012	11/14/2012	11/21/2012
40	Silencer@014AB	11/14/2012	11/20/2012	12/17/2012	12/20/2012	11/22/2012	11/26/2012
41	HydrotesingBetw011AB012ABC	10/11/2012	10/16/2012	10/15/2012	10/17/2012	10/15/2012	10/17/2012
42	HydrotesingBetw012ABC005AB	10/25/2012	10/30/2012	11/9/2012	11/13/2012	12/13/2012	12/17/2012
43	HydrotesingBetw005AB006AB	11/2/2012	11/8/2012	11/6/2012	11/8/2012	12/18/2012	12/20/2012
44	HydrotesingBetw006AB007ABC	12/18/2012	1/2/2013	12/12/2012	12/17/2012	12/21/2012	1/3/2013
45	HydrotesingBetw00/ABC014AB	12/5/2012	12/11/2012	1/16/2013	1/21/2013	1/10/2013	1/14/2013
46	HydrotestingSilencerOnTopOf00/ABC	11/23/2012	11/30/2012	11/26/2012	11/30/2012	1/4/2013	1/9/2013
4/	HydrotestingSilencerOnlopOf014AB	11/20/2012	11/26/2012	12/20/2012	1/4/2013	1/15/2013	1/18/2013
48	InsulationBetw011AB012ABC	10/15/2012	10/1//2012	10/18/2012	10/19/2012	10/18/2012	10/19/2012
49		10/29/2012	11/1/2012	11/0/2012	11/15/2012	12/18/2012	1/19/2012
50	InsulationBetw005AB006AB	11///2012	1/9/2012	11/9/2012	11/12/2012	12/21/2012	1/2/2013
51		12/21/2012	1/3/2013	1/21/2012	1/12/19/2012	1/4/2013	1/1/2013
52		12/10/2012	12/12/2012	1/21/2013	1/23/2013	1/15/2013	1/10/2013
53 E /	InsulationSilencerOntopOt00/ABC	11/29/2012	12/3/2012	1/30/2012	1/9/2012	1/1//2013	1/18/2013
54 55		11/23/2012	10/10/2012	1/4/2013	1/0/2013	1/21/2013	1/22/2013
22 56		10/18/2012	10/18/2012	10/22/2012	10/22/2012	10/22/2012	10/22/2012
20		1/2/2012	10/18/2012	1/22/2012	1/24/2012	1/22/2012	1/22/2012
5/ 50	ElectricalCableTray@005AB	1/3/2013	1/4/2013	1/23/2013	1/24/2013	1/23/2013	1/23/2013
20	ElectricalCableTray@007APC	1/3/2013	1/4/2013	1/23/2013	1/24/2013	1/23/2013	1/23/2013
59 60	ElectricalCableTray@014AP	1/4/2013	1///2013 1/7/2012	1/24/2013 1/24/2012	1/25/2015	1/24/2013 1/2//2012	1/24/2013
00	LICCITCAICADIEITAY@UT4AD	1/4/2013	1///2015	1/24/2013	1/23/2013	1/24/2013	1/24/2013