The following publication Siu, M.F.F. (2019), "Resource budget for workface planning in industrial-construction", Facilities, Vol. 37 No. 5/6, pp. 292-312 is published by Emerald and is available at https://dx.doi.org/10.1108/F-04-2018-0057

RESOURCE BUDGET FOR WORKFACE PLANNING IN INDUSTRIAL-CONSTRUCTION

Francis Siu

Abstract.

Purpose

The purpose of this research is to develop a novel analytical approach for workface planning practice in industrial-construction sector such that the CWP (construction work package) resource budget can be sufficiently planned for delivering possible FIWP (field installation work package) schedules with work uncertainty.

Design/methodology/approach

The relationship between CWP resource budget and FIWP schedules is firstly elucidated based on workface planning practice. The literature of work packaging, workface planning, and project scheduling is reviewed. A novel analytical approach is then developed to quantify CWP resource budget based on a probability theory, in consideration of the probability of occurrence of feasible FIWP schedules formulated based on a resource scheduling approach. The results of case studies given by the new approach are cross-validated by using simulation and optimization techniques.

Findings

The new analytical approach can assist workface planning by quantifying the expected CWP resource budget to deliver the FIWP work scope with certain activities that are planned at project level and with uncertain activities that are found at workface level.

Practical implications

The new analytical approach helps project and workface planners to reliably deploy CWP resource budget for delivering FIWP schedules, instead of guessing the budget based on experience. An industrial-construction project for upgrading an oil-sands refinery facility is used to show the practical implications.

Originality/value

This research develops a new analytical approach for workface planning practice to determine sufficient CWP resource budget for delivering feasible FIWP schedules with work uncertainty.

Keywords: Workface planning, resource budgeting, resource scheduling, work uncertainty, oil-sands facility, industrial-construction.

1. Introduction

Industrial-construction projects focus on designing, constructing, maintaining, and upgrading industrial facilities (e.g., oil-sands plants). The work scope of this type of projects always features work uncertainty because industrial facilities are too technologically complicated to be constructed and the internal conditions of the facilities are not easy to inspect. To cope with its project complexity and work uncertainty, specialty trades such as experienced industrial installers and maintenance contractors should be sufficiently deployed to execute industrial works in mechanical, civil, and electrical engineer responsibilities. In practice, certain activities can be determined during project planning stage at project level while uncertain activities can only be realized during field execution stage at workface level. Project management techniques for work decomposition (e.g., WBS—work breakdown structure) and project scheduling (e.g., CPM—critical path method) may not be sufficient for planning and scheduling work scope with uncertainties such that the resource budget (measured in worker-hour) can be reliably determined to deliver the work on time and within budget.

Workface planning, as suggested by Construction Owners Association of Alberta (COAA), is currently used as one of the best practices for planning the execution of industrial-construction projects (COAA, 2014). COAA's definition of workface planning is "management of all related processes within a large (industrial-construction) project to deliver all elements necessary (e.g., workers), prior to the start of field execution, for enabling individual craft person of crew to perform quality field work in a safe, effective, and efficient manner." Research endeavors proved that this industrial practice significantly improves work productivity (Slootman, 2007; Lloyd et al., 2008; Jergeas, 2009).

During the project phase of conceptual design, WBS is constructed to represent the total work scope of a project and its lowest hierarchical level is work package (WP). A WP is formulated to represent work content to be performed by specialty trades at the construction work area (CWA). The sequencing of the CWA indicates the path of construction, which forms Level-1/2 project schedule (AACE, 2010). During the project phase of design basis memoranda, construction management and project owner progressively dissect WP work scope to construction work packages (CWP) by using advanced work packaging technique. A CWP indicates a construction deliverable produced by one or few trade disciplines as per each CWA. During project phase of engineering design, both engineering team and construction contractor create engineering work packages (EWP) based on a WP work scope by using advanced work packaging technique. An EWP defines the engineering information for supporting field construction in form of engineering drawings, procurement deliverables, design specifications, and vendor support. During project phase of detailed design, construction management and construction contractors collaborate for refining CWP definition by using the EWP information (O'Connor and Davis, 1988). Given the EWP and CWP information, Level-3 project schedule is formulated (AACE, 2010).

During the project phase of field execution, the workface planner, project scheduler, site superintendent and foreman cooperate to further dissect a CWP definition to field installation work packages (FIWP) constrained by CWP resource budget (CII, 2013). A FIWP work scope, along with its field constraints, is created. Examples of field constraints are availability of resources, readiness of material supply, availability of tool and technique, and availability of safe working space. A FIWP presents an activity list (i.e., certain activities and uncertain activities) and activity sequence for a trade discipline to comprehend and execute in coming weeks. Then, the scheduler is responsible for formulating Level-4/5 project schedule (AACE, 2010) in line with FIWP release sequence. From the perspective of project scheduling, a FIWP definition can be equivalent to a single activity as denoted in

Level-4 project schedule or a set of activities as denoted in Level-5 project schedule (FIWP schedule).

In essence, the beauty of using workface planning practice for delivering the industrial-construction projects is to put emphasis on the completion of preparatory works in compliance with engineering and construction requirements, and identifying, checking, and removing field constraints before allocating field workers to execute the field operations at workface level. As such, skilled workers would be able to execute the works in a productive manner.

In practice, project and workface planners determine the CWP resource budget for delivering the FIWP schedules solely based on planners' experience. If the CWP is under-budgeted, the FIWP schedules may be delayed. If the CWP is over-budgeted, the project resource may be wasted. Although project scheduling techniques were advanced for formulating project schedules constrained by limited resources, the schedule is formulated based on the information given at project level such as project WP definition, activity definition, activity relationship, resource demanded by activities, and resource supply for project (Kelley and Walker, 1959). In the existing knowledge of workface planning practice, there is no discussion on how to determine the expected CWP resource budget for delivering the FIWP work scope on time and within budget, given the probability of occurrence of FIWP schedules with work uncertainty.

To advance the knowledge, a novel approach is proposed to characterize the expected CWP resource budget driven by the optimum FIWP schedules formulated with certain and uncertain activities by using a resource scheduling approach and a probability theory. In the following sections, literature review is first given to discuss state-of-the-art project management techniques of work packaging, workface planning, and project scheduling. Next, the novel approach is proposed. Then, an example case study is given to demonstrate the calculation procedure. The proposed methods are validated by using operations simulation approach and simulation-based optimization approach. An industrial-construction project for upgrading an oil-sands facility is used to illustrate its method application in practice.

2. Literature review

2.1 Project management technique—work packaging

In 1962, NASA (National Aeronautics and Space Administration) and DOD (Department of Defense) proposed the use of work breakdown structure (WBS) to organize project work information (CII 2013; PMI 2006). Project work scope is decomposed into manageable pieces named as work packages (WP). Previous research studies of work packaging were focused on (i) defining WBS for construction projects and (ii) examining WP definitions for field execution.

To define project WBS, CSI and CSC (2014) suggested a standard filing system, named as MasterFormat, for decomposing project work scope and organizing work information in facility construction. The divisions for building elements of construction facility were standardized. For example, Division 40-00-00 denotes "process interconnections", its sub-division 40-01-00 denotes "operation and maintenance of process interconnections", and its sub-division 40-01-10 denotes "operation and maintenance of gas and vapour process piping". As such, project planners can compare the work content of WP with the same division across different projects. Globerson (1994) emphasized the importance of developing a project WBS in connection with the WBS level, organizational structure and culture, organizational needs, work package sizes, activity relationships, and economic benefit. He illustrated the above concept by using a restaurant construction project.

He found that it is impossible to quantify sufficient resource budget and generate proper activity network without establishing project WBS. Kim and Ibbs (1995) suggested the use of long-term and short-term WP for managing industrial projects. WP was defined by considering information flow of work process in a company. They used data flow diagrams to visualize information flow. A petrochemical facility construction project was used to demonstrate the definition of short-term WP based on the availability of field information such as labor supply in the field. Jung and Woo (2004) proposed flexible WBS to organize project work information. Essentially, key facet was used to group WP. For instance, "work section" was used as the key facet of plastering work while "floor level" was used as the key facet of concreting work. The authors claimed that flexible WBS reduces overhead effort of collecting and maintaining information. Siami-Irdemoosaa et al. (2015) deployed neural computing technique for defining WBS and WP automatically. Underground construction projects were used to illustrate the proposed method. They firstly collected WBS and WP data based on 20 completed tunnel projects with 3433 activities. Project attributes such as project time and tunnel length were next defined. Back-propagation neural network was then used to establish the relationships between project attributes and associated WBS and WP. As such, the planners can be assisted by making an informed choice of WBS and WP for their projects.

Previous researchers examined the effectiveness of using WP definitions to inform the field works. Choo et al. (1999) realized that "should-be-completed" WP does not provide appropriate support to advise field workers what they are actually able to do. It is because the WP definition does not consider field constraint such as resource availability. Therefore, they developed "WorkPlan" system for defining "can-be-completed" WP constrained by contract, engineering, material, labour, equipment, and prerequisite work. Kim et al. (2008) discovered that project WBS and WP are not associated with resource budget. Thus, they integrated WBS with cost breakdown structure (CBS). Project cost performance can be tracked by using earned value analysis. They claimed that this approach could save time for project planning. Sivaraman and Varghese (2016) discovered that the productivity of pipe fabrication shop is highly dependent on time efficiency of information flow between engineering, procurement, and construction so as to advise the readiness of WP execution. As such, they developed an information platform to facilitate information exchange, updates, and communication between project teams of engineering design, material procurement, and field construction.

In short, the definition and application of project WBS is essential for organizing work information in order to assign WP to workers for field execution. However, the use of WP definition to inform field execution is not effective because the definition does not consider any field constraint at workface level.

2.2 Project management technique—workface planning

In the Year 2010, Construction Owners Association of Alberta (COAA) formally proposed workface planning practice for planning industrial-construction projects. The practice recommended that project WP should be further dissected to EWP, CWP, and FIWP for field execution such that work productivity can be improved (CII, 2013). Related research studies can be grouped as to (i) examine practical need of workface planning practice, (ii) facilitate workface planning practice by visualization, and (iii) measuring workface productivity by conducting activity analysis.

To examine the needs of workface planning practice, Fayek and Peng (2013) proposed to identify the modifications of standard procedure of workface planning made by contractors. They examined the modification rate of industry standards of workface planning for company adaptation. They contrasted industry standard procedure and organization-specific procedure at organization level, and organization-specific procedure and actual implementation on case study projects. Kim et al. (2014) studied the interrelationships between work planned at project level and the one executed at workface level. Based on the project data obtained from 50 electrical projects, they examined the correlations between the work planned and executed. They concluded that a strong linkage between planned and executed activities leads to a high project performance. Caldas et al. (2014) developed best productivity practices implementation index for industrial projects. The index is used to identify potential knowledge area for productivity improvement when delivering the projects. They found that one of the areas for improving worker productivity is the application of workface planning practice.

To facilitate workface planning by visualization, Sacks et al. (2009) developed a software system by integrating BIM system with Last Planner system to visualize work process constrained by field constraints. They visualized work process of both commercial and residential construction projects to improve the workflow of workers. Grau et al. (2014) observed that the uncertainties of work scope disrupt the workflow of workers on site. Therefore, they proposed to combine both BIM visualization and workface planning practice in order to stabilize the workflow. They applied the proposed method to deliver a health care facility construction project and found that the variation of workflow is reduced.

To measure productivity at workface level, Pregenzer et al. (1999) conducted activity analysis based on 9 heuristic rules, which are proposed to classify if a worker is productive on site. A project constructing masonry wall in a hospital is used to demonstrate the method. Gong et al. (2010) conducted productivity studies based on 123 construction projects in Austin, Texas. They used work sampling technique to benchmark the utilization rate of the workers in delivering direct work, and found that productivity could be adversely influenced if there is little emphasis on workface planning. Gouett et al. (2011) suggested guidelines for conducting activity analysis to benchmark the productivity. 16 industrial projects for constructing power, petroleum, and petrochemical plants were used to benchmark the productivity. Peng et al. (2012) observed that the application of workface planning practice improves labour productivity. They proposed the use of "variance in labour productivity" metric for quantifying productivity improvement.

In summary, research endeavours proved that work productivity can be improved by applying workface planning practice to deliver industrial-construction projects. The FIWP is released to inform the workers of field execution once the field constraints are removed. A typical example of field constraint is limited availability of field workers. However, there is no discussion of formulating FIWP schedules in particular with the consideration of both certain and uncertain activities.

2.3 Project management technique—project scheduling

Project scheduling techniques were proposed for scheduling resource-constrained projects. The techniques were operations simulation, evolutionary optimization, and mathematical programming.

By taking advantage of computer's power, operations simulation technique is used to model the work process of construction projects at operational level. The duration of work process can be modelled as probability distribution. A particular duration is sampled for each work process. Project duration can be simulated for each simulation run. By conducting multiple runs, a probability distribution of project duration can be developed. For instance, McCahill and Bernold (1993) proposed resource-oriented approach to simulate resource workflows. They declared the resources and their attributes as variables, such that, different sizes of resources for an activity can be deployed. An earthmoving project was used to illustrate the approach. AbouRizk and Shi (1994) simulated an earthmoving operation to determine the impact of limited availability of resource on project unit cost, production rate, and resource matching. Park et al. (2005) investigated the relationships between long-lead time in resource acquisition and project performance. They used system dynamics to simulate optimum resource coverage for improving project time and cost performance. Chen et al. (2012) simulated the operations of three construction projects to determine the distributions of manpower, equipment, material, and space.

Project schedule constrained by resource limit can be optimized in order to minimize the project time. Brucker et al. (1999) and Liao et al. (2011) reviewed the mathematical programming and evolutionary approach for optimizing resource-constrained project schedules. In general, the duration of work process can be modelled as deterministic value for formulating the schedules. As such, optimal completion time of the project can be determined. For example, Pritsker et al. (1969) suggested a mathematical programming model for formulating optimum project schedules constrained by limited resources. Karaa and Nasr (1986) developed another model for formulating optimum schedules of multiple projects constrained by limited resources. Both Pritsker et al. (1969) and Karaa and Nasr (1986) used postulated examples to illustrate the formulations.

Evolutionary technique is used to optimize project schedules by changing priorities of individual activities for allocating limited resources. For example, Zhang et al. (2006) utilized particle swarm algorithm for changing activity priorities in order to minimize project time in consideration of resource break constraints. They found that particle swarm algorithm outperforms genetic algorithm in terms of computational efficiency. Concrete placement operation was given as an example to illustrate the method application. Kim (2009) embedded “elitist roulette wheel selection operator” in genetic algorithm to reduce the time for iterating optimal solutions. To illustrate the improvement of time efficiency for iterating optimal solutions by using proposed approach, 90 projects selected from project scheduling problem library were used.

In brief, scheduling technique is advanced to optimize resource-constrained project schedules efficiently by using advanced computer power. However, there is no discussion of formulating optimum FIWP work schedules with work uncertainty.

Given the above literature review of work packaging, workface planning, and project scheduling, in context of workface planning practice, no research study has attempted to determine CWP resource budget for delivering FIWP schedules with work uncertainties. As such, the author is motivated to propose an analytical approach for quantifying the expected CWP resource budget given the probability of occurrence of possible FIWP schedules with work uncertainties by combining the use of a scheduling technique and a probability theory. More specifically, this research provides analytical methods to (i) formulate optimum FIWP work schedules factoring in work uncertainty, (ii) formulate optimum FIWP work schedule featuring minimum resource budget, and (iii) quantify expected CWP resource budget for delivering FIWP work schedules.

3. Research methodology

In this section, an analytical approach for workface planning, which consists of four steps, is proposed. Step 1 defines FIWP work scope with consideration of certain activities and uncertain activities. Step 2 formulates FIWP schedule based on a resource scheduling approach. Step 3 characterizes probability of occurrence of feasible FIWP schedule. Step 4 quantifies expected CWP resource budget based on a probability theory.

3.1. Step 1: Define FIWP work scope with consideration of certain activities and uncertain activities

First, WP is defined to represent work scope in particular CWA throughout project duration at project level. Next, EWP and CWP are created by dissecting the WP to present engineering deliverable and construction deliverable respectively associated with one or few trade disciplines.

Prior to field execution (i.e., few hours or days before field execution), FIWP is defined by identifying the certain activities and uncertain activities. In industrial-construction, uncertain activities are classified as unexpected work and additional work (Lenahan, 2006). Unexpected work is found when executing certain activity, while additional work is inserted when delivering schedule that is not part of the original plan. Resource requirement and precedence relationship of certain and uncertain activities are indicated.

3.2. Step 2: Formulate feasible optimum FIWP schedules

Given the combinations of certain activities with or without uncertain activities, feasible FIWP schedules can be formulated by using any scheduling approach. The RSDMP (resource supply-demand matching problem) scheduling approach (Siu et al., 2015; Siu et al., 2016) is selected to formulate an optimum FIWP schedule featuring the minimum resource budget (the shortest completion time, and minimum resource supply). The RSDMP formulation is classified as mixed integer linear programming model. The model is expressed as Equations (1–9) in context of workface planning practice.

Decision variables are declared as FIWP activity end time, FIWP end-activity end time, and FIWP resource supply. The FIWP end-activity is a fictitious activity with zero duration and used to indicate the completion of FIWP schedule. The objective function is uniquely designed to minimize FIWP activity end time, FIWP end-activity end time, and FIWP resource supply as Equation (1). Equation (2) declares technological constraints for maintaining precedence relationship between FIWP activities. Equation (3) expresses technological constraints for maintaining precedence relationship between FIWP activities and FIWP end-activity.

Equation (4) defines resource constraints for ensuring resource demand aggregated from all activities at any time point is less than resource supply of particular time period in the field. Equation (5) estimates the quantity of deployed resources in a range of lower bound and upper bound. Equation (6) ensures that FIWP activity is completed at a particular time point. Equation (7) ensures that FIWP end-activity is completed at a particular time point. Equation (8) declares binary variables that represent FIWP activity end time. Equation (9) declares binary variables that represent FIWP end-activity end time.

$$\text{minimize}\, f = \sum_{\text{FIWP-Act}}\sum_{\text{t=0}}^{\text{T}}(\alpha_{\text{FIWP-Act}}\,\text{t}x_{\text{FIWP-Act}}^{\text{t}}) + \left[\begin{array}{l}\sum_{\text{t=0}}^{\text{T}}(\beta_{\text{FIWP-End}}\,\text{t}x_{\text{FIWP-End}}^{\text{t}}) + \\ \sum_{\text{FIWP-Res}}(\gamma_{\text{FIWP-Res}}R_{\text{FIWP-Res}})\end{array}\right] \tag{1}$$

$$\sum_{\text{t=0}}^{\text{T}}[(\text{t}x_{\text{FIWP-Act}}^{\text{t}})]_{\text{Pred}} \le \sum_{\text{t=0}}^{\text{T}}[(\text{t}-d_{\text{Suc}})x_{\text{FIWP-Act}}^{\text{t}}]_{\text{Suc}}\,, \quad \forall \text{ Precedence relationship between FIWP activities} \tag{2}$$

$$\sum_{\text{t=0}}^{\text{T}}[(\text{t}x_{\text{FIWP-Act}}^{\text{t}})]_{\text{Pred}} \le \sum_{\text{t=0}}^{\text{T}}[(\text{t}x_{\text{FIWP-End}}^{\text{t}})]_{\text{Suc}}\,, \quad \forall \text{ Precedence relationship between FIWP activity and FIWP end-activity} \tag{3}$$

$$\sum_{\text{t=t}}^{\text{t}+d_{\text{FIWP-Act}}}(r_{\text{ActRes}}^{\text{t}}x_{\text{FIWP-Act}}^{\text{t}}) \le R_{\text{Res}}\,, \ \forall \text{ Resource type}, \ \forall \text{ Time point} \tag{4}$$

$$lb_{\text{Res}} \le R_{\text{Res}} \le ub_{\text{Res}}\,, \ \forall \text{ Resource type} \tag{5}$$

$$\sum_{t=0}^{T} x_{\text{FIWP-Act}}^{t} = 1,\ \forall\ \text{FIWP activity} \tag{6}$$

$$\sum_{t=0}^{T} x_{\text{FIWP-End}}^{t} = 1,\ \forall\ \text{FIWP end-activity} \tag{7}$$

$$x_{\text{FIWP-Act}}^{t} = \{0,\ 1\},\ \forall\ \text{FIWP activity} \tag{8}$$

$$x_{\text{FIWP-End}}^{t} = \{0,\ 1\},\ \forall\ \text{FIWP end-activity} \tag{9}$$

where f, objective function; $\alpha_{\text{FIWP-Act}}$,weight of FIWP activity end time; $\beta_{\text{FIWP-End}}$,weight of FIWP end-activity end time; $\gamma_{\text{FIWP-Res}}$, weight of resource supply; t, time unit from start time 0 to end time T; $x_{\text{FIWP-Act}}^{t}$, binary variable with 1 representing FIWP activity completed at time t or 0 otherwise; $x_{\text{FIWP-End}}^{t}$, binary variable with 1 representing FIWP end-activity completed at time t or 0 otherwise; $R_{\text{FIWP-Res}}$, deployed resource; d_{Suc}, duration of FIWP activity's successor; $d_{\text{FIWP-Act}}$, duration of FIWP activity; r_{ActRes}^{t}, resource requirement of FIWP activity; lb_{Res}, lower bound of resource supply; ub_{Res}, upper bound of resource supply.

3.3. Step 3: Estimate probability of occurrence of feasible FIWP schedules

During field execution, only one feasible FIWP schedule with a particular combination of certain activities with or without uncertain activities is used. The probability of occurrence of feasible FIWP schedule is determined with four discrete probability classes. They are $P_{\text{FIWP (Certain)}}$, $P_{\text{FIWP (Unexpected)}}$, $P_{\text{FIWP (Additional)}}$, and $P_{\text{FIWP (Unexpected-Additional)}}$.

$P_{\text{FIWP (Certain)}}$ denotes the probability of occurrence of FIWP schedule formulated by certain activities. $P_{\text{FIWP (Unexpected)}}$ defines the probability of occurrence of FIWP schedule formulated by certain activities with unexpected work. $P_{\text{FIWP (Additional)}}$ declares the probability of occurrence of FIWP schedule formulated by certain activities with additional work. $P_{\text{FIWP (Unexpected-Additional)}}$ expresses the probability of occurrence of FIWP schedule formulated by certain activities with both unexpected and additional work. As the events of using feasible FIWP schedules are independent and mutually exclusive, the summation of probability is equal to one (Equation 10).

$$\begin{bmatrix} P_{\text{FIWP (Certain)}} + P_{\text{FIWP (Unexpected)}} + \\ P_{\text{FIWP (Additional)}} + P_{\text{FIWP (Unexpected-Additional)}} \end{bmatrix} = 1 \tag{10}$$

3.4. Step 4: Determine expected CWP resource budget

Workface planning practice suggests that resource budget can be effectively managed at CWP level by rolling up resource budgets of its associated FIWP. Built upon RSDMP model, Equation (11) quantifies FIWP resource budget by multiplying the FIWP resource supply and its deployed duration.

Based on probability theory, Equation (12) calculates the expected FIWP resource budget by summing the probable resource budgets of feasible FIWP schedules. The probable FIWP resource budget is calculated by multiplying the probability of occurrence of FIWP schedule and its FIWP resource budget.

Equation (13) determines the expected CWP resource budget by accumulating the expected FIWP resource budgets associated with the CWP.

$$\text{Resource budget}_{\text{FIWP}} = \sum\nolimits_{\text{FIWP-Res}} tx^{t}_{\text{FIWP-End}} \times R_{\text{FIWP-Res}}, \quad \forall \text{ FIWP feasible schedule} \tag{11}$$

$$\text{E}(\text{Resource budget}_{\text{FIWP}}) = \begin{bmatrix} P_{\text{FIWP (Certain)}} \times \text{Resource budget}_{\text{FIWP (Certain)}} + \\ P_{\text{FIWP (Unexpected)}} \times \text{Resource budget}_{\text{FIWP (Unexpected)}} + \\ P_{\text{FIWP (Additional)}} \times \text{Resource budget}_{\text{FIWP (Additional)}} + \\ P_{\text{FIWP (Unexpected, Additional)}} \times \text{Resource budget}_{\text{FIWP (Unexpected-Additional)}} \end{bmatrix} \tag{12}$$

$$\text{Resource budget}_{\text{CWP}} = \sum\nolimits_{\text{FIWP} \in \text{CWP}} \text{E}(\text{Resource budget}_{\text{FIWP}}) \tag{13}$$

4. Results and discussion

4.1. Example case study for showing calculation procedures

This section demonstrates the calculation procedures of applying the proposed approach using a postulated example. As shown in Figure 1, one project level WP_1 is defined at CWA_1. Based on WP_1, *n* EWP are defined for *n* trade disciplines. Given *n* EWP, *n* CWP are defined for *n* trades disciplines. The CWP_1 is dissected for defining workface level FIWP_1 and FIWP_2, which are sequentially released to field workers for execution. Figure 2 gives the task lists of FIWP_1 and FIWP_2 putting into consideration uncertain activities. FIWP_1 defines Activities A, B, C, and D. FIWP_2 defines Activities E, F, and G. An unexpected work Activity B_U may occur when performing Activity B, and an additional work Activity H_A may incur when delivering FIWP_2.

<Figure 1>

<Figure 2>

4.1.1. Step 1

The available workers of a trade discipline consists of five units of Resource A and five units of Resource B. Table I shows activity precedence, work durations and demanded resources to complete FIWP_1 and FIWP_2 activities. For example, two units of Resource A and two units of Resource B are required to execute Activity A for five hours. Activity duration and resource demand of Activity B_U and Activity H_A are also specified.

<Table I>

4.1.2. Step 2

Activity combinations for formulating FIWP_1 schedule are (i) FIWP_1 activities without Activity B_U, and (ii) FIWP_1 activities with Activity B_U. Activity combinations for formulating FIWP_2 schedule are (i) FIWP_2 activities without Activity H_A, and (ii) FIWP_2 activities with Activity H_A. Based on RSDMP approach (using Equations 1–9), optimum solutions for FIWP schedules featuring the shortest duration and leanest resource supply were iterated by use of CPLEX (IBM, 2016). Figure 3 show the optimum FIWP_1 and FIWP_2 schedules along with resource supply-demand profiles.

< Figure 3>

4.1.3. Step 3

Probability of occurrence of feasible FIWP schedules is determined. It is estimated that FIWP_1 schedule with certain activities will be delivered with a 70% chance while FIWP_1 schedule with uncertain activities will be delivered with the remaining 30% chance. Besides, FIWP_2 schedule with certain activities will be delivered with a 50% chance while FIWP_2 schedule with uncertain activities will be delivered with the difference, a 50% chance. The summation of probability of occurrence of FIWP_1 schedules is equal to one, and the summation of probability of occurrence of FIWP_2 schedules is equal to one (using Equation 10). That is:

- $P_{\text{FIWP}_1\text{(Certain)}} + P_{\text{FIWP}_1(\text{B}_\text{U})} = 70\% + 30\%$
- $P_{\text{FIWP}_2\text{(Certain)}} + P_{\text{FIWP}_2(\text{H}_\text{A})} = 50\% + 50\%$

4.1.4. Step 4

Resource budgets, measured in worker-hour (whr), of FIWP_1 schedule and FIWP_2 schedule are calculated (using Equation 11).

- Resource budget for FIWP_1 schedule with certain activities is 50 whrs:
  $\sum_{\text{FIWP}_1\text{-ResA\&B}} \left(tx^{\text{t}}_{\text{FIWP}_1\text{-End}} \times R_{\text{FIWP}_1\text{-ResA\&B}} \right) = 3\times10+2\times10$
- Resource budget for FIWP_1 schedule with uncertain activities is 60 whrs:
  $\sum_{\text{FIWP}_1\text{-ResA\&B}} \left(tx^{\text{t}}_{\text{FIWP}_1\text{-End}} \times R_{\text{FIWP}_1\text{-ResA\&B}} \right) = 3\times12+2\times12$
- Resource budget for FIWP_2 schedule with certain activities is 32 whrs:
  $\sum_{\text{FIWP}_2\text{-ResA\&B}} \left(tx^{\text{t}}_{\text{FIWP}_2\text{-End}} \times R_{\text{FIWP}_2\text{-ResA\&B}} \right) = 2\times8+2\times8$
- Resource budget for FIWP_2 schedule with uncertain activities is 48 whrs:
  $\sum_{\text{FIWP}_2\text{-ResA\&B}} \left(tx^{\text{t}}_{\text{FIWP}_2\text{-End}} \times R_{\text{FIWP}_2\text{-ResA\&B}} \right) = 3\times8+3\times8$

Expected resource budgets for performing FIWP_1 schedule and FIWP_2 schedule are calculated (using Equation 12).

- Expected resource budget for FIWP_1 schedule is 53 whrs:
  $\begin{pmatrix} P_{\text{FIWP}_1\text{(Certain)}} \times \text{Resource budget}_{\text{FIWP}_1\text{(Certain)}} + \\ P_{\text{FIWP}_1(\text{B}_\text{U})} \times \text{Resource budget}_{\text{FIWP}_1(\text{B}_\text{U})} \end{pmatrix} = 70\%\times50+30\%\times60$
- Expected resource budget for FIWP_2 schedule is 40 whrs:
  $\begin{pmatrix} P_{\text{FIWP}_2\text{(Certain)}} \times \text{Resource budget}_{\text{FIWP}_2\text{(Certain)}} + \\ P_{\text{FIWP}_2(\text{H}_\text{A})} \times \text{Resource budget}_{\text{FIWP}_2(\text{H}_\text{A})} \end{pmatrix} = 50\%\times32+50\%\times48$

Expected CWP resource budget is calculated (using Equation 13).

- Expected CWP resource budget is 93 whrs:
  $\begin{pmatrix} \text{Resource budget}_{\text{CWP}} = \\ \text{E(Resource budget}_{\text{FIWP}_1}) + \text{E(Resource budget}_{\text{FIWP}_2}) \end{pmatrix} = 53+40$

4.2. Validation of analytical results by using operations simulation and simulation-based optimization

Analytical results provided by the proposed methods are cross-validated and contrasted based on simulation approach and simulation-based optimization approach. The results are validated by simulating CWP resource budget based on RSDMP-based FIWP schedule (Validation I), simulation-based FIWP schedule (Validation II), and PSO-based (particle swarm optimizer) FIWP schedule (Validation III):

- Validation I optimizes all feasible FIWP schedules by using mathematical approach (RSDMP approach), and simulates CWP resource budget by using simulation approach.
- Validation II simulates all feasible FIWP schedules by using simulation approach, and simulates CWP resource budget by using simulation approach.
- Validation III optimizes all feasible FIWP schedules by using simulation-based optimization approach, and simulates CWP resource budget by using simulation approach.

Notably, all simulation and simulation-based optimization models were newly developed for validating the proposed analytical approach.

For Validation I, the CWP resource budget is simulated by using Simphony.NET 4.6 (AbouRizk et al., 2015), given the RSDMP-optimized FIWP schedules. During simulation runs, an entity is generated by “Circle” element. The entity passes through “Branch” element that controls the probability of occurrence of routing succeeding FIWP. Then, it passes through one possible “Square” element that represents FIWP event. The duration of the FIWP event is determined by RSDMP approach. For example, the event “$FIWP_1$” represents $FIWP_1$ schedule with certain activities, while the event “$FIWP_{1U}$” represents $FIWP_1$ schedule with uncertain activities (i.e., Activity B_U). The entity is removed by “Trapezoid” element. Expected CWP resource budgets can be simulated. By conducting 10,000 simulation runs, the CWP resource budget is simulated as 93 whrs. This validates the proposed approach because the CWP resource budget given by simulation approach (simulate the probability of occurrence of feasible FIWP schedules) is consistent with the one given by the proposed analytical approach (93 whrs).

For Validation II, the CWP resource budget is determined based on simulated FIWP schedule using Simphony.NET 4.6 (AbouRizk et al., 2015). “First-in-first-out” priority rule is used to sequence FIWP activities. “Resource” element and “Queue” element are used to create available resource pool (i.e., five units of Resource A and five units of Resource B). During simulation runs, the entity is generated from “Circle” element. The entity is then transferred to “Composite” elements that simulate the workflows of $FIWP_1$ schedule and $FIWP_2$ schedule. “Capture” element captures demanded resources to perform FIWP activities, while “Release” element frees the captured resources after delivering FIWP activities. “Branch” element indicates the probability of occurrence of routing the succeeding FIWP activity. The entity is removed by “Trapezoid” element. After performing 10,000 simulation runs, the CWP resource budget is simulated as a constant of 180 whrs. This validates the proposed approach because the simulation approach does not optimize FIWP schedules such that the CWP resource budget given by simulation approach is less than the one given by the proposed analytical approach.

For Validation III, the CWP resource budget is determined based on FIWP schedules optimized based on particle swarm optimizer (PSO) using SDESA 1.0 (Lu et al., 2008). PSO is used for adjusting activity priorities of allocating limited resources to formulate the schedules such that the FIWP completion time can be minimized. “Diamond” element creates flow entity. “Rectangle” element represents FIWP activity. Captured resource for executing FIWP activity is denoted at top-left corner of “Rectangle” element, while released resource after completing FIWP activity is denoted at top-right corner of “Rectangle” element. After performing FIWP activities, a completion signal is generated as denoted at bottom-right corner of “Rectangle” element. The CWP resource budget is simulated as 93 whrs. This validates the proposed approach because the simulation-based optimization approach optimizes the FIWP schedules such that the CWP resource budget is consistent with the one given by the proposed analytical approach.

4.3. Practical case study

To illustrate a practical application of the proposed analytical approach, a real-world operation and maintenance project for upgrading an oil sands facility in Alberta, Canada is used. As stipulated in general contract, this project is managed by applying workface planning practice. The facility is upgraded to maintain its reliability and expand its capability for producing oil. The project goal is to deliver an upgraded facility in providing a reliable five-year run length.

Total work scope includes (i) regenerator cyclone replacement, (ii) reactor cyclone and riser replacement, (iii) regenerator overhead system upgrade, (iv) stack and slide valve hydraulic system replacement, (v) spent slide valve replacement, (vi) normal catalyst withdrawal line upgrade, and (vii) regenerator and reactor structure elevator replacement. As oil is not produced during the maintenance period, the project must be completed on time. Otherwise, liquidated damages will be incurred.

During project phase of conceptual design, 2 level-1, 18 level-2, 105 level-3, 110 level-4, 1 level-5, and 2 level-6 WPs are defined. Each WP is coded with CWA number. For instance, a WP name of "CCR01-Reactor" represents the work scope of upgrading a reactor. During project phases of design basis memoranda, engineering design and detailed design, the WP is dissected to progressively develop the EWP and CWP in line with Level-3 project schedule. During project phases of field execution, EWP and CWP are progressively refined to FIWP in line with Level-5 project schedule. Project and workface planners regularly review and determine CWP resource budget with consideration of work scope for releasing FIWP during weekly meetings based on their experience.

Notably, before releasing FIWP task lists to the crew for field execution, project and workface planners are responsible for identifying and removing field constraints as per each FIWP. For example, a 3D model and field photo were used to identify the field constraints of "the maximum number of craft persons that can be allocated to execute WP "CCR01-Reactor" at a particular time". After site superintendent's sign off and approval of FIWP, trade specialities are allocated to deliver the FIWP schedules.

In this case study, the work scope is narrowed down to consider the CWP associated with the WP of "CCR01-Reactor" for approximately three weeks. Trade disciplines are limited to a crew of boilermakers, boilermaker welders, pipefitters, and pipefitter welders. In delivering this CWP, six FIWP are progressively released to upgrade the reactor (Figure 4). Table II show the task lists (i.e., certain activities planned at project level, and uncertain activities found at workface level) and activity-resource requirements of $FIWP_1$ to $FIWP_6$. Activity identifier with Subscript "A" denotes additional work, while activity identifier with Subscript "U" denotes unexpected work. Table III presents feasible FIWP schedules along with its work scope and probability of occurrence.

Given the proposed analytical approach, the optimum completion time and resource budget of the feasible FIWP schedules are calculated. The expected resource budgets of FIWP schedules are shown in Table III. The expected CWP resource budget is quantified as 3,166.4 whrs. As such, rather than guessing CWP resource budget based on experience, the planners could reliably allocate 3,166.4 whrs as the CWP budget resource for executing the FIWP schedules with work uncertainties.

<Figure 4>
<Table II>
<Table III>

5. Conclusion

Workface planning practice is commonly used for effectively informing limited workers to execute the fieldwork in industrial-construction sector. However, the project and workface planners are struggled in determining sufficient CWP (construction work package) resource budget to deliver its associated FIWP (field installation work package) schedules on time and within budget.

The literature reviewed that the project WP (work package) developed by work packaging technique is not effective for informing work execution in the field, the work schedule formulated by project scheduling technique only considers the certain activities at project level but not the uncertain activities at workface level, and the FIWP developed by workface planning practice does not provide work schedules with uncertainties. As such, there is a need to provide an analytical method for determining the CWP resource budget by formulating feasible FIWP schedules with consideration of certain activities and uncertain activities found.

A new analytical approach for workface planning practice is thus proposed to reliably quantify the expected CWP resource budget for delivering the FIWP work scope consists of certain activities and uncertain activities. This approach consists of four steps. Step 1 determines the FIWP work scope with certain activities and uncertain activities. Step 2 formulates the feasible FIWP schedules by using scheduling approach. For instance, RSDMP (resource supply-demand matching problems) approach was selected for schedule optimization. Step 3 estimates the probability of occurrence of feasible FIWP schedules. Step 4 determines the CWP resource budget by using probability theory. The results can be cross-validated by using operations simulation and simulation-based optimization approach. As demonstrated, the CWP resource budget can be simulated based on the FIWP schedules formulated by RSDMP approach, operations simulation, and particle swarm optimizer.

The academic contributions of this research study are as follow: the FIWP work scope can be defined with consideration of certain activities planned at project level and uncertain activities (with the features "unexpected" and "additional") found at workface level, the FIWP schedules can be optimized to minimize its resource budget, the feasible FIWP schedule can be associated with certain probability of occurrence, and the expected CWP resource budget can be quantified by rolling up the resource budget of its associated FIWP schedules.

The practical contributions of this research study are illustrated based on a practical case of upgrading an oil-sands plant facility. Rather than guessing the CWP resource budget for delivering the FIWP schedules of reactor upgrading work factoring in work uncertainty, the new approach assists the project and workface planners for reliably determining sufficient resource budget to deliver CWP on time and within budget. The application of this new approach is repeatable for assisting the planners to determine the resource budget for other industrial projects in a simple and easy fashion.

The approach assumes that the information of certain activities and uncertain activities (i.e., activity name, activity duration, resource demanded for activities, and resource supplied in field) is available, the probability of occurrence of all feasible FIWP schedules can be quantified (e.g., based on past records), the expected CWP resource budget is used for executing direct work without overhead expense. The scope of this research is also limited to plan the resource budget for workface planning practice in industrial-construction. Other approach for planning resource budget, if any, is not investigated. Future research shall be done to examine the feasibility and effectiveness of applying the proposed approach for planning general construction projects such as civil infrastructure and building construction.

References

AACE (Association for the Advancement of Cost Engineering International) (2010), *Schedule levels of detail—as applied in engineering, procurement and construction*, International recommended practice, Morgantown, West Virginia, United States.

AbouRizk, S., Hague, S. and Ekyalimpa, R. (2015), *Construction simulation: an introduction using Simphony*, University of Alberta, Edmonton, Alberta, Canada.

AbouRizk, S. and Shi, J. (1994), "Automated construction simulation optimization", *Journal of construction engineering and management*, Vol. 120 No. 2, pp. 374–385.

Baldwin, A. and Bordoli, D. (2014), *A handbook for construction planning and scheduling*, John Wiley and Sons, Ltd. Hoboken, New Jersey, United States.

Brucker, P., Drexl, A., Mohring, R., Neumann, K. and Pesch, E. (1999), "Resource-constrained project scheduling: notation, classification, models and methods", *European journal of operational research*, Vol. 112, pp. 3–41.

Caldas, C., Kim, J., Haas, C., Goodrum, P. and Zhang, D. (2014), "Method to assess the level of implementation of productivity practices on industrial projects", *Journal of construction engineering and management*, Vol. 141 No. 1, pp. 04014061.

Chen, S., Griffis, F., Chen, P. and Chang, L. (2012), "Simulation and analytical techniques for construction resource planning and scheduling", *Automation in construction*, Vol. 21, pp. 99–113.

Choo, H., Tommelein, I., Ballard, G. and Zabelle, T. (1999), "WorkPlan: constraint-based database for work package scheduling", *Journal of construction engineering and management*, Vol. 125 No. 3, pp. 151–160.

Construction Owners Association of Alberta (COAA) (2014), *COAA workface planning rules*, Edmonton, Alberta, Canada.

Construction Industry Institute (CII) (2013), *Advanced work packaging: design through workface execution*, Implementation resource 272–2, Version 3.0. Construction Industry Institute, Austin, Texas, United States.

CSI (Construction Specifications Institute) and CSC (Construction Specifications Canada) (2014), *MasterFormat 2014*, Construction Specifications Institute, 110 South Union Street, Suite 100, Alexandria, Virginia, United States, 22314; Construction Specifications Canada, 120 Carlton Street, Suite 312, Toronto, Ontario, Canada, M5A4K2.

Fayek, A. R. and Peng, J. (2013), "Adaptation of workface planning for construction contexts", *Canadian journal of civil engineering*, Vol. 40 No. 10, pp. 980–987.

Globerson, S. (1994), "Impact of various work-breakdown structures on project conceptualization", *International journal of project management*, Vol. 12 No. 3, pp. 165–171.

Gong, J., Borcherding, J. and Caldas, C. (2010), "Assessment of direct work utilization at the workface in the U.S. construction industry (1972–2008)", *Construction research congress 2010*, Banff, Alberta, Canada, May 8–10, 2010, pp. 960–969.

Gouett, M., Haas, C., Goodrum, P. and Caldas, C. (2011), "Activity analysis for direct-work rate improvement in construction", *Journal of construction engineering and management*, Vol. 137 No. 12, pp. 1117–1124.

Grau, D., Abbaszadegan, A., Tang, P., Ganapathy, R. and Diosdado, J. (2014), "A combined planning and controls approach to accurately estimate, monitor, and stabilize work flow", *Computing in civil and building engineering 2014*, Orlando, Florida, Jun 23–25, 2014, pp. 105–112.

IBM. (2016), *IBM ILOG CPLEX Optimization studio V12.6.1 documentation*, IBM Corp. 1987, 2016, Armonk, North Castle, New York, United States.

Jergeas, G. (2009), *Improving construction productivity on Alberta oil and gas capital projects*. University of Calgary, Calgary, Alberta, Canada.

Jung, Y. and Woo, S. (2004), "Flexible work breakdown structure for integrated cost and schedule control", *Journal of construction engineering and management*, Vol. 130 No. 5, pp. 616–625.

Karaa, F. and Nasr, A. Y. (1986), "Resource management in construction", *Journal of construction engineering and management*, Vol. 112 No. 3, pp. 346–357.

Kelley, J. E. and Walker, M. R. (1959), "Critical-path planning and scheduling." *Proceedings of the eastern joint computer conference*, pp. 160–173.

Kim, D., Menches, C. L. and O'Connor, J. T. (2014), "Stringing construction planning and execution tasks together for effective project management." *Journal of construction engineering and management*, Vol. 31 No. 3, pp. 04014042.

Kim, J. and Ibbs, C. (1995), "Work-package–process model for piping construction", *Journal of construction engineering and management*, Vol. 121 No. 4, pp. 381–387.

Kim, J.L. (2009), "Improved genetic algorithm for resource-constrained scheduling of large projects", *Canadian journal of civil engineering*, Vol. 36 No. 6, pp. 1016–1027.

Kim, S., Park, C., Lee, S. and Son, J. (2008), "Integrated cost and schedule control in the Korean construction industry based on a modified work-packaging model", *Canadian journal of civil engineering*, Vol. 35 No. 3, pp. 225–235.

Koskela, L. (1992), *Application of the new production philosophy to construction*, Technical Report 72, Center for integrated facility engineering, Department of civil engineering, Stanford University, California, United States.

Lenahan, T. (2006), *Turnaround, shutdown and outage management: effective planning and step-by-step execution of planned maintenance operations*. Oxford, Elsevier/Butterworth-Heinemann, Linacre House, Jordan Hill, Oxford, United Kingdom, 0X28DP.

Liao, T. W., Egbelu, P. J., Sarker, B. R. and Leu, S. S. (2011), "Metaheuristics for project and construction management—A state-of-the-art review", *Automation in construction*, Vol. 20 No. 5, pp. 491–505.

Lloyd, K. R., Slootman, T. and Jergeas, G. F. (2008), "The industry's perspective on workforce planning for major projects", *AACE international transactions*, Vol. 12, pp. 1–12.

Lu, M., Lam, H. C. and Dai, F. (2008), "Resource-constrained critical path analysis based on discrete event simulation and particle swarm optimization", *Automation in construction*, Vol. 17 No. 6, pp. 670–681.

McCahill, D. and Bernold, L. (1993), "Resource-oriented modeling and simulation in construction", *Journal of construction engineering and management*, Vol. 119 No. 3, pp. 590–606.

O'Connor, J. T. and Davis, V. (1988), "Constructability improvement during field operations", *Journal of construction engineering and management*, Vol. 114 No. 4, pp. 548–564.

Park, M., Lee, H., Son, B. and Ryu, H. (2005), "Dynamic resource management", *Computing in Civil Engineering (2005)*, Cancun, Mexico, Jul 12–15, 2005, pp. 1–12.

Peng, J., Fayek, A., Mohamed, A. and Kennett, C. (2012), "Exploring the impact of workface planning on labor productivity variance mitigation on industrial construction projects: a mathematical framework", *Construction research congress 2012*, West Lafayette, Indiana, May 21–23, 2012, pp. 376–385.

Pregenzer, L., Seppanen, P., Kunz, J. and Paulson, B. (1999), "Value-added assessment of construction plans", *Journal of construction engineering and management*, Vol. 125 No. 4, pp. 242–248.

Pritsker, A. B., Waiters, L. J. and Wolfe, P. M. (1969), “Multiproject scheduling with limited resources: a zero-one programming approach”, *Management science*, Vol. 16 No. 1, pp. 93–108.

Project Management Institute (PMI) (2006), *Practice standard for work breakdown structures*, Newtown Square, Pennsylvania, United States.

Sacks, R., Treckmann, M. and Rozenfeld, O. (2009), “Visualization of work flow to support lean construction”, *Journal of construction engineering and management*, Vol. 135 No. 12, pp. 1307–1315.

Safa, M., Shahi, A., Haas, C. and Hipel, K. W. (2016), “Construction contract management using value packaging systems”, *International journal of construction management*, Vol. 17 No. 1, pp. 50–64.

Siami-Irdemoosaa, E., Dindarloob, S. R. and Sharifzadehc, M. (2015), “Work breakdown structure (WBS) development for underground construction”, *Automation in construction*, Vol. 58, pp. 85–94.

Siu, M. F. (2016), *Development of quantitative methods for project scheduling and workface planning under time-dependent resource constraints*, University of Alberta, Edmonton, Alberta, Canada.

Siu, M. F., Lu, M. and AbouRizk, S. (2015), “Resource supply-demand matching scheduling approach for construction workface planning”, *Journal of construction engineering and management*, Vol. 142 No. 1, pp. 04015048.

Siu, M. F., Lu, M., AbouRizk, S. and Tidder, V. (2016), “Quantitative assessment of budget sufficiency and resource utilization for resource-constrained project schedules”, *Journal of construction engineering and management*, Vol. 142 No. 6, pp. 04016003.

Sivaraman, A. and Varghese, K. (2016), “Pull planning system to coordinate the engineering procurement and construction on process plant projects”, *Construction research congress 2016*, San Juan, Puerto Rico, May 31–Jun 2, 2016, pp. 1720–1730.

Slootman, T. (2007), *Planning of mega-projects: Influence of execution planning on project performance*, University of Twente, Enschede, Netherlands.

Zhang, H., Tam, C., Li, H. and Shi, J. (2006), “Particle swarm optimization-supported simulation for construction operations.” *Journal of construction engineering and management*, Vol. 132 No. 12, pp. 1267–1274.

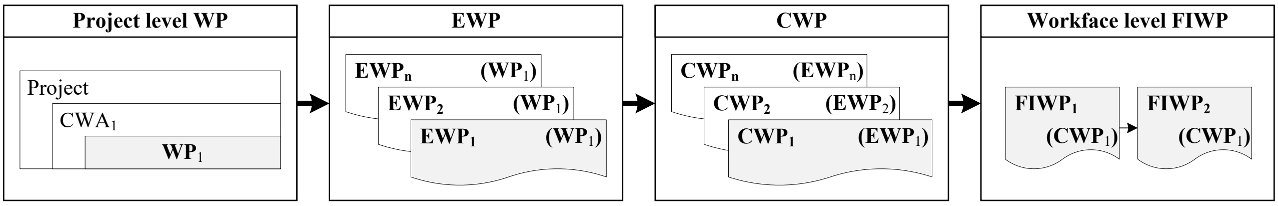
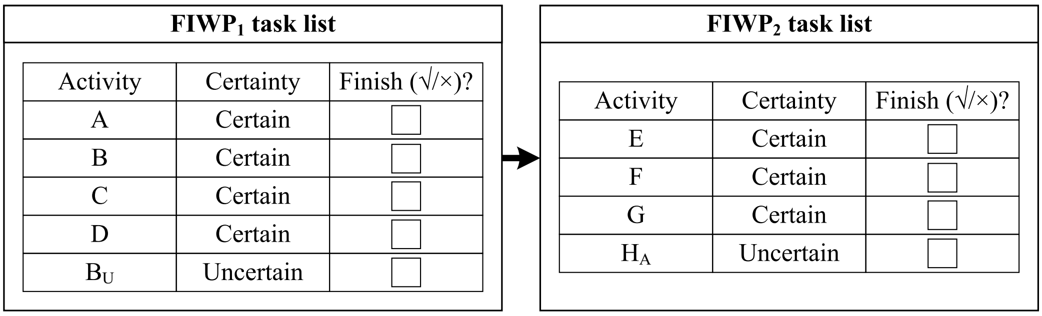


Figure 1. Development of WP, EWP, CWP, FIWP



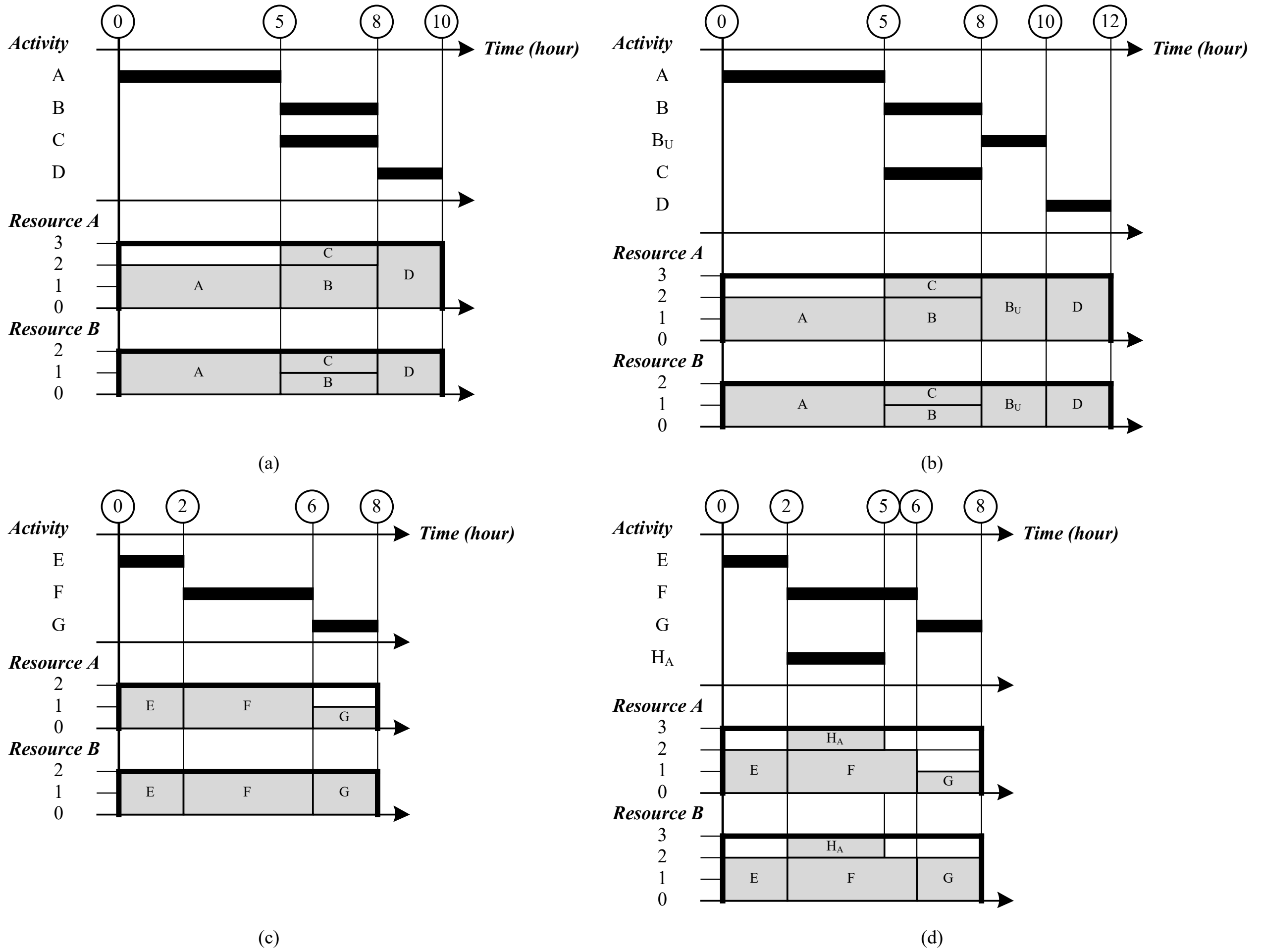
FIWP$_1$ task list

Activity	Certainty	Finish (√/×)?
A	Certain	☐
B	Certain	☐
C	Certain	☐
D	Certain	☐
B_U	Uncertain	☐

FIWP$_2$ task list

Activity	Certainty	Finish (√/×)?
E	Certain	☐
F	Certain	☐
G	Certain	☐
H_A	Uncertain	☐

Figure 2. FIWP task lists



(a) (b) (c) (d)

Figure 3. Optimum FIWP$_1$ schedules (a) without uncertain activities and (b) with unexpected work, and FIWP$_2$ schedules (c) without uncertain activities and (d) with additional work

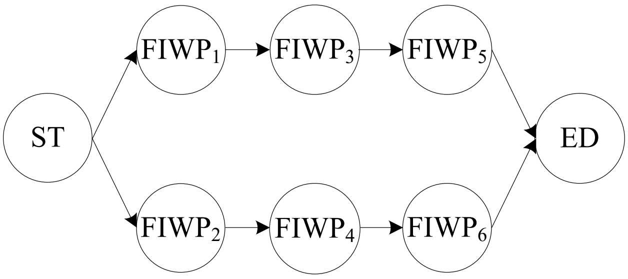


Figure 4. FIWP releasing sequence

Table I. FIWP activity-resource requirement

FIWP	Activity	Successor (Certain)	Successor (Uncertain)	Duration (hour)	Resource A	Resource B
1	A	B, C		5	2	2
1	B	D	B_U	3	2	1
1	C	D		3	1	1
1	D	-		2	3	2
1	B_U			2	3	2
2	E	F, G	H_A	2	2	2
2	F	G		4	2	2
2	G	-		2	1	3
2	H_A	G		3	1	1

Table II: Activity-resource requirements for practical case study

FIWP	Identifier	Activity name	Suc.	Dur. (hour)	Res A	Res B	Res C	Res D
1	A	Shed Row 18, patch repair shed on N side of riser as per WPR-128	B	20	2	1	0	0
1	B	Shed Row 18, patch repair shed on S side of riser as per WLR-128	E	20	2	1	0	0
1	C_A	Reinstall horse collar	-	30	2	1	0	0
1	D	Riser—prep cut line on old riser	-	4	1	1	0	0
1	E	Shed Row 19, patch repair shed on NE side of riser as per WLR-128	F	20	2	1	0	0
1	F	Shed Row 20, patch repair shed on W side of riser as per WLR-128	-	20	2	1	0	0
2	G	M2 Cover (76” Main)—install new sections of termination ring per WLR-115	G_U	20	1	1	0	0
2	G_U	M2 Cover (76” Main)—install anchors in manway cover areas (35 sqft×4 anchors/sqft)	-	10	1	2	0	0
2	H	Spent Riser—install plate ring and retaining plates around spent line	-	20	1	1	0	0
2	I	Overflow well—install plate ring and retaining plates around overflow line	-	20	1	1	0	0
3	J	Shed Row 20, patch repair shed on E side of riser as per WLR-128	J_{U1}	20	2	1	0	0
3	K	Weld out new reactor head to existing reactor shell (25%)	M, N	20	3	3	0	0
3	L	Lower riser into position, fit and tack	O	20	4	1	0	0
3	J_{U1}	Shed Row 20, repair the bolting on shed on N side of riser as per WPR-128	J_{U2}	20	2	1	0	0
3	M	Weld connect pressure tap piping from riser to shell located just below riser outlet horn	-	10	0	0	2	1
3	N	Weld out new reactor head to existing reactor shell (50%)	S, T	20	3	3	0	0
3	O	Weld out new riser duct to existing lower riser section	-	40	2	2	0	0
3	P	Cut back sheds that are at hot spot locations flush with the refactory	-	10	2	1	0	0
3	Q	Weld connect pressure tap piping from riser to shell located above level “A” riser bracing	-	10	0	0	2	1
3	J_{U2}	Shed Row 22, 23, 24 repairs to teeth and sheds in 4 areas per WPR-128	-	20	2	1	0	0
3	R	Install refractory anchors in reactor cone section RHI to layout pattern—160 anchors	Y	12	2	2	0	0
3	S	Weld out new reactor head to existing reactor shell (75%)	-	20	3	3	0	0
3	T	Backgouge reactor weld of new shell to existing shell	W	10	4	2	0	0
3	U	Install refractory anchors for refractory repairs at large manway	X	10	2	1	0	0
3	V	Weld connects to piping from riser to shell. located above level “A” riser bracing	-	10	0	0	2	1
3	W	Weld inside of new shell to existing shell	-	20	4	2	0	0
3	X	Demo old steam coil, inside vessel	-	10	0	0	3	0
3	Y	Install refractory anchors in stripper cone section RHI to layout pattern—80 anchors	-	10	2	2	0	0
4	Z	Spent riser—install shroud on spent bellows	-	10	3	0	0	0
4	AA_A	Grid—clean off grid before pouring grid refractory	-	5	4	0	0	0
4	AB	Overflow well—install shroud on overflow bellows	-	10	3	0	0	0
4	AC	Torch oil—shop to replace tips on 4 torch oil assemblies	AD	10	0	0	1	1
4	AD	Torch oil—install new assemblies 4 to ensure the “T” mark at the top position	-	20	0	0	2	0
5	AE_A	Steam sparger—grind remove old sparger nozzles	AN	50	2	1	0	0
5	AF_A	Layout and install refractory anchors on reactor head weldout area—288 anchors	-	20	2	2	0	0
5	AG	Install riser manway and seal weld	AI	8	2	1	0	0
5	AH	Install Platform 1, Section 0-90 from rector to regenerator	-	30	3	1	0	0
5	AI	NDE on riser manway cover	-	1	2	1	0	0
5	AJ_A	Final cleaning of ACB	-	4	2		0	0
5	AK	Close Reactor MW—MX-4 (ACB)—install refractory plug	AL	6	1	1	0	0
5	AL	Close Reactor MW—MX-5 (ACB)—install refractory plug	AM	6	1	1	0	0
5	AM	Close Reactor MW—MX-6 (ACB)—install refractory plug	AO	6	1	1	0	0
5	AN	Steam sparger—install new sparger nozzles	-	50	2	1	0	0
5	AO	Close Reactor MW—MX-7 (ACB)—install refractory plug	-	6	1	1	0	0
6	AP	Grid—install grid floor manway	-	10	1	1	0	0

A=boilermaker; B=boilermaker welder; C=pipefitter; D=pipefitter welder, Suc.=successor, Dur.=duration.

Table III: FIWP schedules for practical case study

FIWP Schedule	Work scope uncertainty	Probability of occurrence	Completion time	Resource budget (whr)	Expected resource budget (whr)
$FIWP_1$	Without uncertain activity	30%	84	252	411.6
$FIWP_1$	With Activity C_A	70%	80	480	
$FIWP_2$	Without uncertain activity	60%	60	120	156.0
$FIWP_2$	With Activity G_U	40%	70	210	
$FIWP_3$	Without uncertain activity	5%	70	1400	1628.5
$FIWP_3$	With Activity J_{U1}	30%	80	1600	
$FIWP_3$	With Activity J_{U2}	30%	80	1600	
$FIWP_3$	With Activities J_{U1}, and J_{U2}	35%	90	1710	
$FIWP_4$	Without uncertain activity	30%	30	180	201.0
$FIWP_4$	With Activity AA_A	70%	30	210	
$FIWP_5$	Without uncertain activity	10%	59	413	749.3
$FIWP_5$	With Activity AE_A	10%	139	695	
$FIWP_5$	With Activities AE_A, and AF_A	30%	159	795	
$FIWP_5$	With Activities AE_A, AF_A, and AJ_A	50%	100	800	
$FIWP_6$	Without uncertain activity	100%	10	20	20.0