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Resource Scheduling and Planning for Tunneling with a New Resource Model of the Decision Aids for Tunneling (DAT)

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Abstract

Resource scheduling and planning are the strategies required to determine the sequence of activities and resource allocation during tunnel construction. Resource scheduling and planning have been implemented in a new resource model of the Decision Aids for Tunneling (DAT), which are a computer based tool used to simulate tunnel construction. Tunneling plans obtained with the new resource model of the DAT take into account the technical precedence of activities, the resource/space availability, the dynamic status of the process, and the work continuity. In particular, the new resource model of the DAT can provide the optimal tunneling plan**,** which produces the shortest construction time and the smallest construction cost, and satisfies the special characteristics of tunnel construction such as excavation methods, distance requirements between the headings, and preempting activities (e.g., blasting).

The paper attempts to contribute to both theory and practice: Optimization of the construction process considering time, cost and resources is particularly complicated in tunneling where activities and resource availability have to be appropriately sequenced and interference has to be avoided. The paper addresses this fundamental problem with the development of different schematic tunneling plans that consider the relevant activities and optimizes them with regard to

overall cost and time, also considering uncertainties. Equally important is to make the theoretical development practically useable. This is done through implementation of the resource optimization in the DAT and, very importantly, by demonstrating the practical use with an application to a real tunnel case.

1. Introduction

The Decision Aids for Tunneling (DAT) are a computer based method with which distributions of tunnel construction time and cost as well as required and produced resources can be estimated considering uncertainties in geologic conditions, construction processes and resources (e.g. Einstein, 2002). The results of the DAT in turn can be used for various decision making processes. One of the notable recent developments of the DAT is the implementation of a resource management model with which resource usage and -flows during tunnel construction can be modeled. The DAT essentially consist of three modules called “geology module”, “construction module” and “resource module”. The resource module of the DAT uses the resource model to represent resource usage and - flows during tunnel construction. The core computer code of the DAT to perform the simulations is C/C++, and the graphical user interface and the resource model in the DAT are programmed in JAVA.

From the point of view of simulation strategy, the DAT can be categorized as an activity-based model. In an activity-based model, simulation parameters such as those characterizing resources, move from activity to activity during the simulation. Allocating a resource to a successor may involve decisions depending on the amount of resources available for the successors, and the number of successors that demand the same resources. If the same resources are required by multiple immediate successors, and the amount of resources is limited, selecting a recipient is important because the decision may affect part of or even the entire process. In this regard, resource scheduling and planning are crucial to the success of a project.

The resource model of the DAT that existed up to now had, however, several drawbacks and limitations. The scheduling and planning for resource allocation and -flows satisfied the technical constraints (e.g., technical precedence of the activities) and resource constraints (e.g., resource availability) while they did not guarantee the optimal resource allocation to complete the projects within schedule and budget. In dealing with resource allocation, the DAT set only the predefined heuristic rules for prioritizing activities, which may result in resource overshooting and process interruptions. Considering these shortcomings, a new resource model for the DAT was developed to overcome the identified problems and implement optimal resource scheduling and planning features (Min, 2008).

This paper first presents problems and limitations of the previous/current resource models of the DAT and of other construction simulation tools for resource modeling. This is followed by a discussion of possible methodologies and solutions to overcome the identified problems and limitations. The major improvements and the implementation of the new resource model are also presented. The final part of the paper demonstrates the new resource model with the application to a road tunnel project, which includes a comparative analysis among different approaches for resource scheduling and planning.

2. Resource modeling for tunneling

2.1. Introductory comments on resource modeling

A resource model for tunneling needs to be designed to represent and implement some fundamental concepts (Halabe, 1995):

- The model needs to represent various types, quantities and properties of resources that may affect the sequence of activities.
- The model needs to control construction processes considering types, quantities and properties of resources.
- The model needs to represent resource flow by associating resource availability, resource production, and consumption with the tunneling activities.
- The model needs to represent the characteristics of the resource flow, which include storing, queuing, sharing and competing of resources.
- The model needs to track the resources used and produced to identify the critical resources and activities.

2.2. Current resource model of DAT

The main features and algorithms used for the resource model of the DAT that existed up to now (called current resource model in the following) are based on developments by Halabe (Halabe, 1995) and Marzer (Marzer, 2002). In addition to having the main features and fundamental concepts required for resource modeling listed above, the current resource model of the DAT has the following capabilities:

- Resource dependency on ground conditions and location can be recognized.
- Performance of different process alternatives with regard to production and utilization of resources as well as operational efficiency can be considered by the model.
- Predefined heuristic rules are used for resource allocation (e.g., first-come-first-serve).
- Calendars are used to keep track of real calendar dates, and specify days-off, delays and different working schedules of the activities.

Nevertheless, the current resource model of the DAT has the limitations pointed out earlier (Section 1).

2.3. Resource modeling in other construction simulation tools

Several other construction-oriented simulation tools and their resource modeling have been reviewed and compared with the current resource modeling in the DAT (Min, 2008). These other construction simulation tools include CYCLONE which models a process as a series of work cycles with a network of graphical symbols (Halpin and Woodhead 1976); INSIGHT (Paulson 1978), and RESQUE (Chang 1986), which are two significant further developments of CYCLONE; COOPS (Liu 1991), and CIPROS (Odeh 1992); which are two conceptual and functional extensions of RESQUE; STROBOSCOPE which is a general-purpose simulation programming language used for the simulation of processes common to construction engineering (Martinez 1996); RBM (Shi and AbouRizk 1997) and LBS (Oloufa et al. 1997); and Symphony.NET (Hajjar and AbouRizk 2002).

Compared to the current resource model of the DAT, some limitations in addressing resource handling and management identified in the other simulation tools or programming languages are as follows:

- The uncertainty in geology is not considered and hence all construction processes have to be performed for fixed geologic conditions.
- The uncertainty in the amount of resources consumed and produced from the activities is not considered in most other simulation tools except for STROBOSCOPE.
- Many of these simulation tools can handle only a small portion of a project instead of the project as a whole except for STROBOSCOPE and Symphony.NET. Therefore, they can be used for very specific tasks or operations, only, and for a project with a short duration.
- Many of these simulation tools cannot handle projects on a real-time basis since they can only model a particular process of a project instead of the overall project.
- Many of these simulation tools cannot model the construction processes at the necessary level of detail required by process planning, and cannot easily model the multiple resource requirements and dynamic complexity of construction processes except for STROBOSCOPE.
- Many of these simulation tools cannot recognize and represent resource dependency on ground conditions and location.
- Many of these simulation tools cannot handle different types of delays occurring in the construction processes, such as delays due to maintenance/inspection, equipment breakdown or holidays, and delays caused by ground conditions and/or locations of the tunnels.

- The users may have to learn the corresponding simulation languages (e.g., STROBOSCOPE).

There are also other recently developed simulation tools for resource modeling, which are commercially available such as CPM-based scheduling application (e.g., Primavera, Microsoft Project). However, CPM becomes convoluted if the schedule is resource-constrained (Fondahl 1991) and these tools also have similar or the same limitations addressed above. Most importantly, these tools employ priority-based heuristics for resolving resource allocation (Christodoulou et al. 2010), but do not provide optimal resource planning and functionalities to analyze the optimum resource supply (Primavera 2005; Harris 2013; Siu et al.2014) as will be discussed in Section 5.

There is also significant research performed on modeling of resource leveling and allocation, and resource optimization. Zahraie and Tavakolan (2009) proposed a stochastic multi-objective optimization model using non-dominated sorting genetic algorithm and discrete fuzzy sets, and Jun and El-Rayes (2011) also proposed a multi-objective optimization model using a genetic algorithm module to minimize undesirable resource fluctuations and maximize resource utilization efficiency. Koulinas and Anagnostopoulos (2012) proposed a resource allocation and leveling approach using a hyperheuristic algorithm. Bettermir and Sonmez (2014) developed a hybrid strategy based on genetic algorithms and simulated annealing for resource-constrained project scheduling. However, all these recently developed approaches also have similar or the same limitations or problems discussed above. In particular, all of them were not developed for modeling of tunnel construction, i.e., specific characteristics of tunneling activities and associated resource flows cannot be modeled. All these recently performed studies are based on existing approaches (i.e., mathematical approaches, heuristic methods, and genetic algorithms) as will be discussed in Section 4.

3. Requirements for a new resource model of the DAT

Allocating resources to an activity is an important decision because it may affect part of or even the entire process**.** Also, the quantities of resources are usually limited. Therefore, resource scheduling and planning strategies in the model are crucial to the success of projects. These strategies should be designed in a way that the model can effectively distribute resources between various, possibly competing, activities and examine the interaction between committed resources and activities to eliminate avoidable delays and idling in the work flow. Most importantly, the model should be able to allocate resources optimally to the tunneling activities in terms of cost, time and resource usage.

In dealing with resource competition between the activities, the current resource model of the DAT uses predefined heuristic rules for prioritizing activities (first-come-first-serve). These heuristic rules have advantages in terms of their simplicity and efficiency. However, this default resource allocation plan is problematic since it may ignore the overall criticality of the activities, and thus cannot guarantee an optimal tunneling plan, which can allocate resources optimally in terms of construction time and cost. Priority of resource allocation should be given to the more critical activities in order to produce the optimal resource allocation. However, it would be very difficult to find whether the activities are critical or non-critical beforehand because construction sequences and resource allocation plans can change dynamically. Therefore, the new resource model should be able to run simulations considering all the possible resource allocation alternatives, and the one which can produce the shortest construction time and the smallest construction cost needs to be selected.

For resource scheduling and planning, it is also important to consider special characteristics of the tunnel construction process such as the type of excavation methods, distance requirements between the top heading and bench in heading and bench operation (or multiple drifting), cyclic operation, and preempting activities (e.g., blasting). This is so because tunneling plans (i.e., the construction sequence and resource allocation plan) can vary significantly depending on these characteristics. Hence, consideration of special characteristics of the tunnel construction process is another major requirement for the new resource model of the DAT.

4. Existing approaches for resource scheduling and planning

There are various existing approaches for resource optimization, which have been developed and implemented in various models. Some of these existing approaches**,** which have been widely used in practice such as mathematical approaches, heuristic methods, and genetic algorithms will be briefly introduced in the following sections.

4.1. Mathematical approaches

Mathematical approaches have been formulated to optimally solve the problem of resource allocation, including integer programming (IP), branch-and-bound and dynamic programming and implicit enumeration approaches (Lee and Gatton 1994; Sung and Lim

1996; Demeulemeester and Herroelen 1997). However, the mathematical approaches may not be applicable to solve the problem of resource allocation for large and complex projects such as tunnels since it is very difficult to consider and represent all dynamic changes in construction sequences and resource allocation, as well as the interaction/interrelation between the tunneling activities, in the mathematical formulations of the objective functions and constraints.

Furthermore, no model using mathematical approaches has taken into account the special characteristics and practical aspects of the tunnel construction process (e.g., type of excavation methods, cyclic operation, distance between the headings or drifts, and the preempting activities).

4.2. Approaches with heuristic methods

Heuristic methods have been widely used in practice because of their simplicity and efficiency in application. A single rule or a hierarchy of rules is used to decide on the order of resource allocation among competing activities (Morse and Whitehouse 1988). Accordingly, the resource is given to the top-ranked activity and the others are delayed. These rules have been shown to perform well for a variety of problems. In fact, heuristic rules are able to rationalize the scheduling process and make it manageable for practical size projects as mentioned by Talbot and Patterson (1979). However, there are no hard guidelines that help in selecting the best heuristic rule to use for a given project (Hegazy 1999). Furthermore, the most critical limitation of heuristic rules is that they cannot guarantee optimum overall solutions.

4.3. Approaches using genetic algorithms

Genetic algorithms work by emulating the natural evolution and “survival of the fittest” mechanism in living organisms such as inheritance, mutation, selection, and crossover (also called recombination). Genetic algorithms can be easily implemented in a computer simulation, and have already been applied successfully to numerous areas in civil engineering and construction.

The genetic algorithms (GAs) overcome the problem with the combinatorial explosion, which is the major drawback of the mathematical approaches, and they also provide the optimal or near-optimal overall solutions to the problem, which cannot be guaranteed by the heuristic methods. However, there are also several limitations to the application of the GAs because they do not consider the technical/structural precedence of the activities, dynamic degree of the resource requirements, and special characteristics of the tunnel construction process. In addition, a large amount of computing time may be required considering the very large number of resources and associated tunneling activities, and repetitive activation of activities.

It is thus apparent that the existing approaches may not work well for resource scheduling and planning of tunnel construction. A new approach for resource scheduling and planning is required, and this is described in the following section.

5. New approach for resource scheduling and planning in tunnel construction

Resource scheduling and planning in tunnel construction are formulated in tunneling plans, which are used to determine the sequence of the tunneling activities and resource allocation during construction. The structuring of resource modeling into tunnel plans and –phases represents the "new approach". The principles of this approach are discussed in this section while the associated, detailed modeling is described in Section 6.

Tunneling plans can be divided into two categories depending on the type of excavation method; full-face excavation and multiple-face excavation (e.g., heading and bench, and multiple-drift) as shown on Fig. 1. This is so because the precedence logic to model tunneling projects controls the performance of tunneling activities considering start time, end time, and processing time of each activity, the interrelation among activities, and especially resource allocation. This precedence logic is different depending on the type of excavation method. In particular, tunneling plans for heading and bench operation can vary by 1. the distance between the heading and bench; 2. resource availability; and 3. different ways to treat the preempting activities.

The principles of the new resource model of the DAT will now be described in detail.

5.1. Type of excavation methods (full-face excavation vs. heading and bench)

Resource handling in tunnel construction differs depending on the type of excavation methods (e.g., full face, heading and bench or multiple drifting). The precedence logic of the activities in one cycle for the full-face excavation is mostly determined by technical/structural precedence (The term "cycle" or "round" in tunnel construction represents a physical length of tunnel excavation, which consists of a series of repetitive tunneling activities). This usually means that a new activity can only start after all preceding activities are completed, and resources are allocated to the activities on a first-come-first-served basis in the same cycle. Therefore, for full-face excavation, there are no tunneling activities occurring in parallel, which compete for or share the same resources in the same cycle. As a consequence, characteristics of the construction process and resource allocation in the full-face excavation can be represented using the current resource model of the DAT with no modification (see Section 2.2).

In heading and bench excavation, three different phases are distinguished depending on the distance between the two headings (see Section 5.2 and Fig. 3). The precedence logic of the tunneling activities and the resource allocation plan for a heading and bench operation (or multiple drift operation) can be very complicated compared to those for full-face excavation. This is so because tunneling plans must be developed in a way to satisfy not only technical/structural precedence of tunneling activities, design details and resource/space availability, but also other aspects such as min-max distance between headings, the preempting activities (e.g., blasting), as well as resource availability. Fig. 1 shows all possible tunneling plans for the full face, and heading and bench operation; the latter will be described in detail, below.

[Fig. 1. Tunneling plans for full face and heading and bench operation]

5.2 Three different phases for heading and bench operation

The minimum and maximum distances between headings or drifts are a critical factor in planning the resource allocation and the construction sequences for a heading and bench operation. The distance requirements between headings are physical constraints in tunneling and are typically defined by considering ground conditions and the construction process. In the longitudinal sense, “headings” follow each other at a certain distance. The leading heading cannot be less or more than a certain distance ahead of the following heading (“*distance x*” in Fig. 2).

[Fig. 2. Distance requirement in heading and bench operation]

Fig. 3 illustrates the heading and bench operation, which can be divided into three different phases depending on the distance between the two headings: Phases I, II and III. Schematic views of tunneling activities along the tunnel length in different phases are presented in Fig. 3. In Phase I, only the heading is excavated. This is usually the starting phase of a heading and benching operation. In Phase 2, the top heading and bench advance together but at different locations of the tunnel due to the distance requirements between the two headings. In Phase III, only the bench is excavated; this is usually the final phase in a heading and benching operation.

Phase I: At the beginning of the heading and bench operation, only the top heading advances (shaded area) till it reaches the “minimum distance” between the two headings (as shown at the top of Fig. 3). For this, all resources will be allocated to the activities performed in the top heading as long as the distance between the top heading and bench is shorter than the “minimum distance” between the two headings. Therefore, the construction sequence in this phase is simply determined by the precedence logic of the activities in the top heading. In Phase I, there is thus no competition for resources between the two headings because construction happens only in one heading as in full-face excavation.

Phase II: In this phase, the top heading and bench advance together but at different locations of the tunnel due to the distance requirements between the two headings (i.e., the required distance between the two headings is kept between the minimum and the maximum, and the two headings advance more or less simultaneously, but in different locations/segments of the tunnel. There will be dynamic changes in resource allocation depending not only on the required distance between the two headings but also on the differences of the advance rates and of the activity durations between the two headings. Phase II can be further subdivided into two tunneling plans, namely "Phase II-A" (Section 5.2.1) and "Phase II-B" (Section 5.2.2) depending on resource availability, as will be discussed in Section 5.2.1.

Phase III: When construction in the top heading is completed, all the resources will be allocated to the activities performed in the bench. Analogous to construction in Phase I, the construction sequence and the resource allocation in Phase III are the same as those for full-face excavation.

[Fig. 3. Three different phases in the heading and bench operation]

5.2.1. Phase II-A

This represents the case, in which all the resources required for the activities are available in both headings. Therefore, there is no competition for resources between headings. However, Phase II-A can be further divided into two tunneling plans, namely "Plan A" and "Plan B" depending on how to treat the preempting activities in practice. Preempting activities (e.g., blasting) are activities in one heading that prevent other activities to be carried out in the other heading.

Fig. 4 shows a schematic view of Plan A and Plan B related to tunnel length (top) and to time (middle and bottom). The bottom two figures show an enlarged view of two cycles in the heading and bench showing a different way to treat the preempting activities; i.e, "Blast-H" (Blast in Head) and "Blast-B" (Blast in Bench).

Plan A: In Plan A of Phase II-A, when a preempting activity is performed in one of the two headings, no activity can be performed during that time in the other heading; the activity has to remain idle until the preempting activity in the other heading is completed. Fig. 4 (a) illustrates an example of Plan A in Phase II-A (note that Phase II-A begins after the top heading proceeds 3 cycles (i.e., Cycles 1(H), 2(H) and 3(H)) to produce the minimum distance between the two headings). As shown in the time related view of Cycle 4 (H) and Cycle 1 (B), no other tunneling activities are performed while the preempting activities (e.g., "Blast-H" and "Blast-B") are performed in the other heading.

Plan B: In Plan B of Phase II-A, preempting activities in both headings are performed at the same time. For this, one of the two preempting activities in one heading may need to be delayed in order to synchronize the starting times of the preempting activities in the two headings (see Fig. 4). In this example, the starting time of the preempting activity in the top heading (i.e., "Blast-H" in Cycle 4 (H)) is delayed until the "Load-B" in the bench is completed so that the preempting activities in both headings (i.e., “Blast-H” in Cycle 4 (H) and “Blast-B” in Cycle 1 (B)) can start at the same time.

[Fig. 4. Schematic view of Plan A and Plan B in Phase II-A]

5.2.2. Phase II-B

This represents the case, in which resources for the activities are available in only one of the headings. Therefore, the tunneling activities in both headings may not be performed simultaneously due to limited resources even if the distance requirement between the two headings is satisfied. With regard to resource constraints in Phase II-B, it is particularly important to consider 1. the prioritization of the activities between the two headings and 2. the criticality of the activities for the tunneling plans.

Due to limited resources in Phase II-B, activities in both headings compete for the same resources when the activities in both headings require the same type of resources at the same time. The prioritization of the activities will guarantee the optimal resource allocation leading to the shortest construction time and the smallest construction cost.

When considering resource allocation with limited resources, it is very important to consider the overall criticality of the activities. The optimal dynamic resource allocation plan requires that non-critical activities be held back deliberately and not be allowed to start so that resources will be available to perform more critical activities.

6. Model implementation

In this section, the implementation of the resource scheduling and planning in the new resource model will be discussed in detail.

6.1. Plan A of Phase II-A

In Plan A, during the operation of the preempting activities in one heading, no tunneling activities can be performed in the other heading. For this, the new resource model has been developed such that an activity performed in one heading can control the activities in the other heading. This can be done by adding new starting conditions of the activity. As shown in Fig. 5, an activity in the DAT consists of three components (i.e., start node, activity arc, and end node), and can be in any of five different statuses, namely “Not activated (NA)”, “Waiting for resource (WFR)”, “Running (RUN)”, “Waiting for space (WFS)”, and “Finished (FIN)”.

[Fig. 5. Components, status and duration of an activity in the DAT]

The status of an activity changes depending on the resources involved. The status changes from NA to WFR when the activities preceding the activity in the activity network are finished. If resources are available, the status changes directly to RUN. At that time, the resources needed by the activity must be known. The time when the status changes from WFR to RUN is referred as the “starting time”. At that time, the duration of the activity must be known. The time when the status changes from RUN to WFS is referred as the “stopping time”. If space for the produced resources is available, the status changes directly to FIN. Otherwise the activity waits until space is available. The time when the status changes from WFS to FIN is the “finishing time” of the activity.

In Plan A, an activity in one heading must check the resource availability as just explained and have the information on the status and type (i.e., preempting or normal activities) of another activity performed in the other heading before its start. This follows the process described in Section 5.2.1.

6.2. Plan B of Phase II-A

In Plan B of Phase II-A, the preempting activities in both headings are performed simultaneously given that all resources required for these activities are available in both headings.

6.2.1. Tunneling plans considering interrelation of the preempting activities between the two headings

The number of cycles of each heading in Phase II-A is different given that the cycle lengths of each heading are generally different. Thus, the number of the preempting activities in each heading is different as well. Therefore, in Plan B, the model should be able to decide, which preempting activity in the top heading starts with which preempting activity in the bench. If there are n number of the preempting activities in the top heading and k number of the preempting activities in the bench, the number of possible combinations of the two preempting activities of each heading, which are performed simultaneously, can be obtained from the following equation:

$$ {}_{n}C_{k} = \binom{n}{k} = \frac{n!}{k!(n-k)!} \tag{1} $$

where,

${}_{n}C_{k}$: the number of ways of picking k unordered outcomes from n possibilities

For example, if the top heading has three cycles, Cycles 4 (H), 5 (H), and 6(H), and the bench has two cycles, Cycles 1(B) and 2(B) in Phase II-A as shown in Fig. 6, there are three possible combinations of the preempting activities of each heading starting at the same time (i.e., ${}_{3}C_{2} = 3$).

[Fig. 6. Possible combinations of the preempting activities in each heading for Plan B]

6.2.2. "Cycle set"

Among the possible tunneling plans (i.e., possible combinations of the preempting activities) in Phase II-A, an optimal tunneling plan can be obtained by selecting the one that satisfies the distance requirement between the two headings and produces the shortest construction time and the smallest construction cost.

In order to simplify the process to find the optimal tunneling plan among many possible tunneling plans, the concept of "cycle set" is introduced. The entire tunnel section in Phase II-A can be divided into a number of "cycle sets", which are tunnel sub-sections with the same length. Since the length of each tunnel sub-section (i.e., cycle set) is the same, the number of cycles, and thus the number of preempting activities in each cycle set are the same for each heading. Therefore, a "cycle set" is a collection of the same number of the cycles for each heading. This can narrow down the number of the possible tunneling plans to be checked before selection of the optimal one since the number of cycles and thus, the number of preempting activities in a checking process can be reduced. Also, this can eliminate the combinations that are not practically possible due to the distance requirement between the headings.

It is important to note that time and cost can only be optimized if the construction sequence and activity interaction between the two headings satisfy the requirements for the distance and preempting activities. For instance, if the progress in the bench is faster in the bench than in the heading the bench activities will have to wait till the heading has reached a location satisfying the distance requirement. The time to complete a cycle set in each heading does not have to be same, and in fact, they are typically different.

It should be also noted that without using cycle sets, the simulation results would be the same, but the cycle sets can eliminate unnecessary computational time and resources by eliminating tunneling plans within a cycle set that do not satisfy the requirements for the distance between the two headings or for the preempting activities. Tunneling activities are a series of repeated activities for each heading and they are constrained by minimum/maximum distance between the headings. Each cycle set repeats the same series of cycles (i.e., a number of possible tunneling plans in one cycle set is the same as in another cycle set). All this allows one to use cycle sets unless the minimum distance between the headings is smaller than the length of the cycle set, which is very unlikely and unrealistic in tunneling.

In the example shown in Fig. 7, the top heading consists of 9 cycles and the bench consists of 6 cycles in Phase II-A. Therefore, the number of the possible tunneling plans (i.e., the possible combinations of the two preempting activities starting at the same time in each heading) is ${}_9C_6$ (= 84) (see Section 6.2.1). However, if the tunnel section in Phase II-A is divided into three sub-sections of the same length (i.e., "cycle sets"), each of the three "cycle sets" has 3 cycles in the top heading, and 2 cycles in the bench. Therefore, the number of the possible tunneling plans is 3 (= ${}_3C_2$) for each cycle set, and 9 (= 3 possible tunneling plans x 3 cycle sets) for the entire tunnel section in Phase II-A.

[Fig. 7. Reduction in number of the possible tunneling plans in "Plan B" using "Cycle Sets"]

The length of each "cycle set" can be determined by the least common multiple of the cycle lengths of each heading, which is the simplest way to divide the entire tunnel section in Phase II-A into a number of "cycle sets". For example, if the cycle lengths of the top heading and bench are 4 m and 6 m, respectively, the length of a "cycle set" is 12 m as shown in the example of Fig. 8, and consequently the entire tunnel section in Phase II-A can be divided in to three "cycle sets".

[Fig. 8. Example of determination of "Cycle Sets"]

With this approach, tunnel construction for the entire tunnel section in Phase II-A can be represented by a number of "cycle sets", each of which consists of the same number of the cycles for each heading.

6.2.3. Multiple simulations in every "cycle set"

Another development in the new resource model for Plan B is that it runs multiple simulations in every “cycle set”. Before running simulations at the beginning of every “cycle set” in Phase II-A, the model generates a number of tunneling plans reflecting the possible combinations of the preempting activities between the two headings as discussed in Section 6.2.1. During multiple simulations within a “cycle set”, the tunneling plan(s) that cannot maintain a certain distance between the two headings will be eliminated; the plan that satisfies the distance requirement, and produces the shortest construction time and the smallest construction cost to complete the length of the “cycle set” will be selected at the end of each “cycle set” (The DAT first choose the tunneling plan resulting in the shortest construction time, and if there are more than two plans with the shortest construction time, the DAT select the one with the smallest construction cost).

Each “cycle set” may have a different optimal tunneling plan due to the differences in the advance rates and durations of the activities between the two headings, and the “minimum and maximum distances” between the two headings. This can be handled by the new resource model. In essence, it represents the dynamic changes in the construction sequences and resource allocation, and also provides the optimal tunneling plan during construction.

One should note that the concept of “the optimal tunneling plan” in the context of this paper means the “locally optimized” solution (among many possible tunneling plans) under the given specific conditions e.g., given geologic conditions, given the performance of the construction method and given the amount of resources selected from their probabilistic distributions for a specific “cycle set” during a specific simulation.

6.3. Phase II-B

As discussed in Section 5.2.2, in Phase II-B, resources required for the activities are available only in one heading due to resources limitations. Because of this, activities in both headings may compete for the same resources if the activities in both headings require the same type of resources at the same time. Hence, the following developments are implemented for Phase II-B:

6.3.1. Resource allocation plans

With regard to resource allocation plans for Phase II-B, there are two major limitations of the current DAT: 1. the heuristic rules used for prioritizing the activities cannot guarantee the optimal resource allocation; 2. the default allocation plan used (i.e., the first-come-first-served basis) may ignore the overall criticality of the activities. These two problems are closely related since the priority of resource allocation should be given to the more critical activities in order to produce the shortest construction time and the smallest construction cost. However, it would be very difficult to find whether the activities are critical or non-critical beforehand because construction sequences and resource allocation plans can change dynamically. Therefore, the new resource model needs to run simulations considering all the possible resource allocation alternatives, and the one that can satisfy the distance requirement between the two headings, and produces the shortest construction time and the smallest construction cost will be selected as the optimal tunneling plan.

If there are m number of cycles in the top heading and n number of cycles in the bench in Phase II-B, the number of all the possible resource allocation alternatives that specify all the possible ways to set the priority of the resource allocation between the two headings is:

$$_{m+n}C_n = \binom{m+n}{n} = \frac{(m+n)!}{m!n!} \quad (2)$$

where,

$_{m+n}C_n$: the number of ways of picking n unordered outcomes from $m+n$ elements

For example, if there are 3 cycles in the top heading (Cycles 4 (H), 5 (H) and 6 (H)) and 2 cycles in the bench (Cycles 1 (B) and 2 (B)), the number of all possible ways to specify the priority of the resource allocation between the two headings is 10 (= $_{3+2}C_2$), as shown in Fig. 9. One should note that the sequences of the cycles in the same heading should remain in the order of occurrence (e.g., Cycle 5 (H) cannot precede Cycle 4 (H)).

The example in Fig. 9 shows that the resources are allocated between the two headings in the order of Cycle 1 (B), Cycle 2 (B), Cycle 4 (H), Cycle 5 (H) and Cycle 6 (H) if the "Tunneling Plan 1" is selected. According to this resource allocation plan, all the resources are allocated to the activities in Cycle 1 (B) first. Within the same cycle, the resources are allocated to the activities in the order of occurrence of the activities (e.g., in the order of "Drill", "Load", "Blast", "Muck", "Rock Bolts" and "Shotcrete" in the bench). The resources used for or produced from Cycle 1 (B) can be allocated to the following Cycle 2 (B) only if no other activities in Cycle 1 (B) require these resources.

6.3.2. "Cycle set"

Recall that among all the possible resource allocation plans, the one which can satisfy the distance requirement between the two headings, and produces the minimum construction time and cost to complete the project will be selected as the optimal tunneling plan. In order to simplify the process to find the optimal tunneling plan, the entire section in Phase II-B can again be divided into a number of "cycle sets" (see Section 6.2.2 for the definition of a "cycle set").

In the example shown in Fig. 10, the entire section in Phase II-B is divided into three "cycle sets"; each "cycle set" has 3 cycles in the top heading and 2 cycles in the bench. Therefore, the number of possible resource allocation plans is 10 (= ${}_{3+2}C_2$) within each "cycle set", and 30 (= 10 possible plans x 3 "cycle sets") for the entire section in Phase II-B instead of 5005 (= ${}_{9+6}C_6$) without defining the "cycle sets". As shown in this example, the number of possible resource allocation plans can be significantly reduced by using "cycle sets".

[Fig. 10. Reduction in number of the possible tunneling plans in Phase II-B using "Cycle Sets"]

6.3.3. Multiple simulations in every "cycle set"

It is necessary to run multiple simulations in every "cycle set" since there are a number of possible tunneling plans in each "cycle set" in Phase II-B. After running multiple simulations for all possible resource allocation plans, the one which satisfies the distance requirement and produces the shortest construction time and the smallest construction cost to complete the length of the “cycle set” will be selected as an optimal tunneling plan at the end of every “cycle set”.

6.3.4. Preempting activities

The preempting activities in Phase II-B are treated in the same way as used for Plan A of Phase II-A. Therefore, the preempting activities in Phase II-B can be considered by adding new starting conditions and by differentiating the preempting activities from the normal activities. For this, an activity in one heading should check the status (e.g., active or idle) and type (e.g., preempting activities or normal activities) of another activity in the other heading before its start (See Section 6.1 for more details).

6.4. Idle Costs

Another development of the new resource model is to estimate the idle costs of the activities. Idle costs of the activities are incurred every time the activities are delayed, and therefore, these costs need to be considered together with the idle times of the activities. Since the idle costs vary depending on the idle time of the activities, the idle costs of the activities can be defined as a function of the idle time of an activity and idle cost of the activity per unit time. In the new resource model, the cost equation for the idle cost of the “*Activity*” is defined as follows:

$$idle\_cost\_activity = idle\_time() \times idle\_cost\_unit\_time \qquad (3)$$

where,

idle_cost_activity: idle cost of the “*Activity*”, ($)

idle_time( ): idle time of the “*Activity*” (day)

idle_cost_unit_time: idle cost of the “*Activity*” per unit time ($/day)

7. Application of the New Resource Model

The application of the new resource model of the DAT will be shown with simulation results such as total construction time and - cost distribution for the different tunneling plans.

7.1. Project overview and preparation for the DAT simulations

The tunnel used in this study is a road tunnel in Korea consisting of two parallel tunnels, (Fig. 11) which was completed in 2009 (Min et al. 2008). The total length of “tunnel A” is 1910m, and “tunnel B” is 1900m long. Five cross passages are located between the two parallel tunnels that have the same cross-section. The geologic profile is shown in Fig. 12. The rock classification and overburden are the main geologic parameters considered for this tunnel. The NATM with drilling and blasting was applied and several different tunnel support patterns were used. The tunnel cross section is 13m wide and 9.6m high, while the maximum overburden is about 300m.

[Fig. 11. Tunnel layout]

[Fig. 12. Geologic map and profile of the tunnel]

Since this tunnel was excavated by a combination of full-face and heading and benching, it is well suited for application of the new DAT resource model.

To demonstrate the new resource model, only a limited section of the tunnel (i.e., “H&B” section in “Tunnel B” in Fig. 11), where heading and benching operations were performed, was considered since this is the aspect in which the new resource model differs from the current DAT. The results from DAT simulations performed in this study reflect uncertainty only in the construction process (e.g., costs per unit length and advance rates) because the geologic conditions were all known at the time of performing this simulation.

Note that even with the fixed geologic conditions, there are still uncertainties reflected in the model related to construction-related parameters such as resource availability, duration of activities, cost of activities and criticality of activities. It is thus possible to examine the construction sequences of the tunneling activities between the two headings and how the resources are allocated optimally for the specific construction method. It should also be noted that consideration of geologic uncertainties is one of the major features of the DAT, which can easily be modeled in the DAT by defining geologic parameters such as lengths and sequences of areas, zones, ground parameters (e.g., rock type) and their states (e.g., schist, gneiss and granite), probabilistically. In fact, the uncertainties in geology were considered in the previous phases of this study performed for the same project (Min et al. 2008). The reason for not including geologic uncertainties in the example presented here is to provide a clear picture on the effect of construction process uncertainties.

The tunneling activities are specified by activity networks in the DAT. Each heading consists of a series of the tunneling activities (e.g., drilling, loading, blasting, mucking, installing rock bolts, and shotcreting) as shown in Fig. 13. This shows an example of DAT’s graphical interface and how the tunnel activity network is defined as input in the DAT.

[Fig. 13. Activity network in the DAT]

Three different sets of DAT simulations with "Plan A of Phase II-A", "Plan B of "Phase II-A" and "Phase II-B" have been performed. In “Plan A of Phase II-A”, a preempting activity can be performed in one of the two headings while no activity can be performed in the other one. In Plan B of Phase II-A, preempting activities are performed in both headings at the same time. In Phase II-B, resources for the activities are available in only one heading and activities are prioritized such that resources can be allocated to activities in either the top heading or the bench (see Section 6 for more details).

7.2. Simulation results and comparative analyses

Fig. 14 shows the results of 500 simulations for three different sets of DAT simulations using the new resource model for "Plan A of Phase II-A", "Plan B of "Phase II-A" and "Phase II-B", respectively, in form of scattergrams. A table at the bottom of Fig. 14

provides the statistical results of total construction time and cost in terms of the minimum, mean, maximum, standard deviation and coefficient of variation.

The time-cost scattergrams show that both total construction time and cost for "Plan B of Phase II-A" are smaller than those for "Plan A of Phase II-A". This can be explained by the fact that delays due to the preempting activities occur only in the bench for "Plan B of Phase II-A" while delays due to the preempting activities occur both in the top heading and bench for "Plan A of Phase II-A".

Total construction costs for "Phase II-B" are greater than the others, and total construction time for “Phase II-B” is similar to “Plan A of Phase II-A” and greater than “Plan B of Phase II-A”. This is so because there are more delays with “Phase II-B” due to limited resources (i.e., resources are available only in one heading) and the preempting activities (i.e., when a preempting activity is performed, no activity can be performed in the other heading).

Fig. 14. Comparison of the time-cost scattergrams ("Plan A of Phase II-A", "Plan B of Phase II-A", "Phase II-B" are compared using the new resource model DAT)

The time-cost scattergram in Fig. 15 shows the results of the DAT simulation using the new resource model with "Plan B of Phase II-A" and the actual construction time and cost to complete the given road tunnel. “Plan B of “Phase II-A” was compared because it was reported that the preempting activities in both headings were performed at the same time, and all resources were available for both headings.

Fig. 14 demonstrates differences among three different tunneling plans implemented in the new resource model of the DAT while Fig. 15 illustrates comparisons between the output from the new resource model and the actual construction time and cost of the example project.

[Fig. 15. Actual total construction time & cost vs. results of DAT simulation with the new resource model]

One might infer from this comparative analysis in Fig. 15 that with the information provided the construction process employed during actual construction was not optimal and construction cost could have been reduced (about by 2.5~4%) if the optimal construction process and sequence simulated in the new resource model with "Plan B of Phase II-A" had been used during actual construction (Please note that the simulation with the new resource module for this tunnel project was performed after the project was completed).

7.3. Model Verification and Validation

The verification of new simulation model was conducted by confirming how correctly the model with the proposed tunneling plans (i.e., “Plan A and Plan B of Phase II-A” and “Phase II-B”) was implemented. For this, a number of simple sets of simulation runs were performed for the “H&B” section of “Tunnel B” (see Fig. 11), and outputs from the model simulations were compared with the results calculated using MS Excel spreadsheets and hand calculations. With this, the model outputs for reasonableness under variation in settings (e.g., different tunneling plans and different of resource availability) were verified. The model was also tested with variations in input parameters (e.g., amount of resources, minimum and maximum distances, cycle lengths, and etc.) and verified by confirming the consistency between simulation outputs and the outputs calculated with Excel. Table 1 shows the results of this model verification. For comparison purposes, all input parameters were defined deterministically (using the mean values of all variables), hence the output from the resource model should agree with those from the Excel simulation/hand calculations if the new model works and is verified as designed and implemented. As shown in Table 1, the verification tests were performed for all three different tunneling plans, and the results both from the new resource model and the Excel simulation/hand calculations are exactly the same.

The DAT has an interactive debugger with which errors can be easily detected and fixed. During verification, the model was checked and tested with this interactive debugger to find and fix errors in the implementation of the model.

Validation is the process of determining whether the proposed model is an accurate representation of the actual ("real world") system being analyzed. The validation process of the new model was conducted by ensuring that the results obtained from simulation runs of the model are within an acceptable range of the results obtained under the "real world" system (McCahill et al. 1993). As discussed in Section 7, the new resource model was applied to the actual road tunnel project (Fig. 15). The new resource model was validated by confirming that the results from the model simulating the real tunnel system were within the range provided from the real project data. For example, the new resource model was able to reproduce and represent distribution/allocation of resources and the sequence of activities reported from the actual tunnel activity cycle. The new resource model was able to take into account the actual field data (e.g., restrictions and delays due to the minimum and maximum distance requirements and performance of preempting activities), and generate the outputs reflecting these field data.

Details on the verification and validation process can be found in the thesis underlying this paper (Min 2008).

8. Conclusions

Resource scheduling and planning are required to determine the sequence of activities and resource allocation during construction. This is a particularly complex problem in tunneling where restrictions of space (geometry), type of construction operation and geologic and construction uncertainties affect cost, time, and used and produced resources. A new resource model has been developed as a part of the Decision Aids for Tunneling (DAT). The DAT are a method and associated computer code with which the tunnel process and the effect of a variety of uncertainties can be simulated to produce distributions of cost, time and resources. The new model can handle dynamic changes in construction sequencing and resource allocation. It does so by systematically representing the tunnel construction process in the form of characteristic phases and related tunneling plans. These tunneling plans are optimized to produce the smallest cost and time and optimal resource allocation.

The new resource model has been applied to a real tunnel project. The actual construction time and cost were compared with those obtained from the DAT simulation with the new resource model. This comparison shows that construction cost could have been reduced somewhat if the optimal tunneling plan produced with the new resource model had been used.

Optimization of the construction process considering time, cost and resources is particularly complicated in tunneling where activities and resource availability have to be appropriately sequenced and interference has to be avoided. The paper addresses this fundamental problem with the development of different schematic tunneling plans that consider the relevant activities and optimizes them with regard to overall cost and time, also considering uncertainties. It is equally important to make the theoretical development practically useable. This is done through implementation of the resource optimization in the DAT and, very importantly, by demonstrating the practical use with an application to a real tunnel case.

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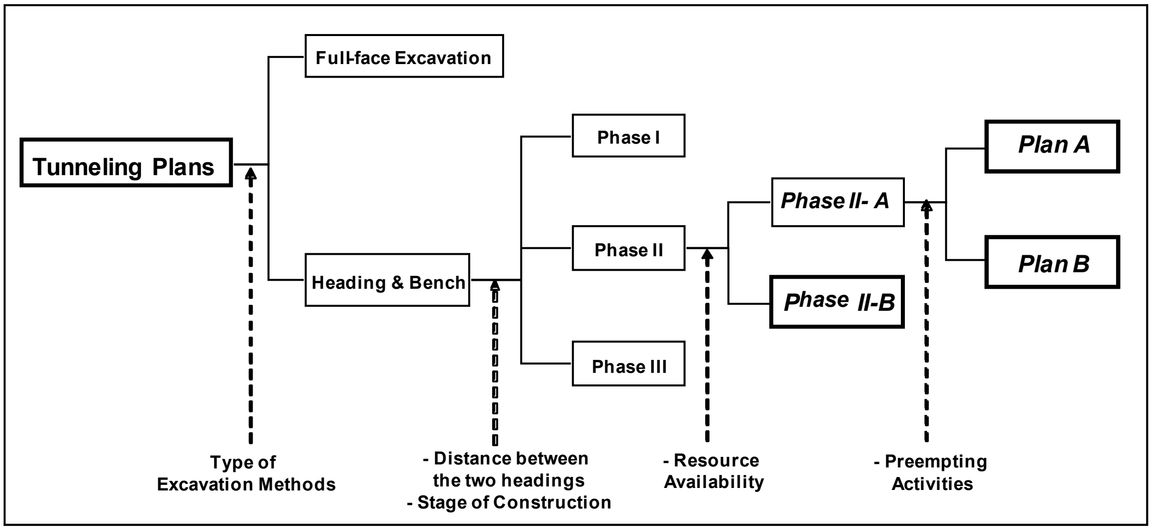

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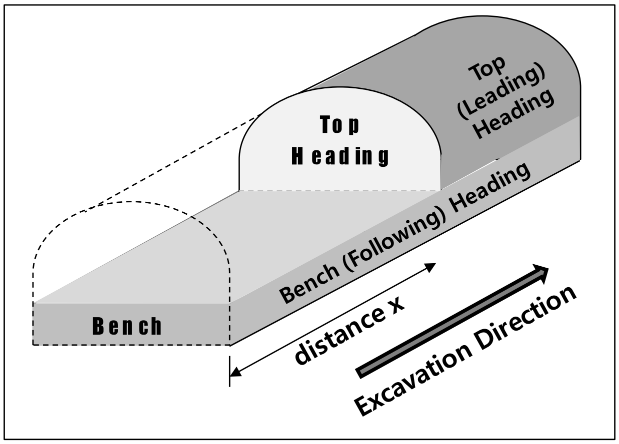

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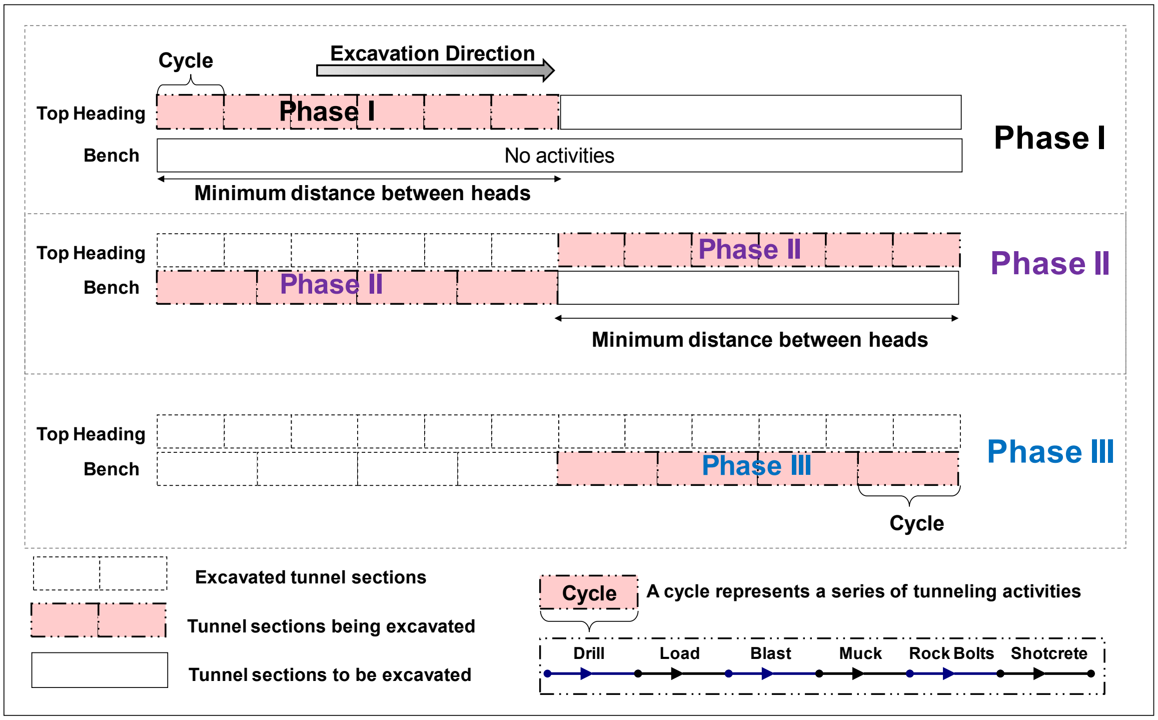

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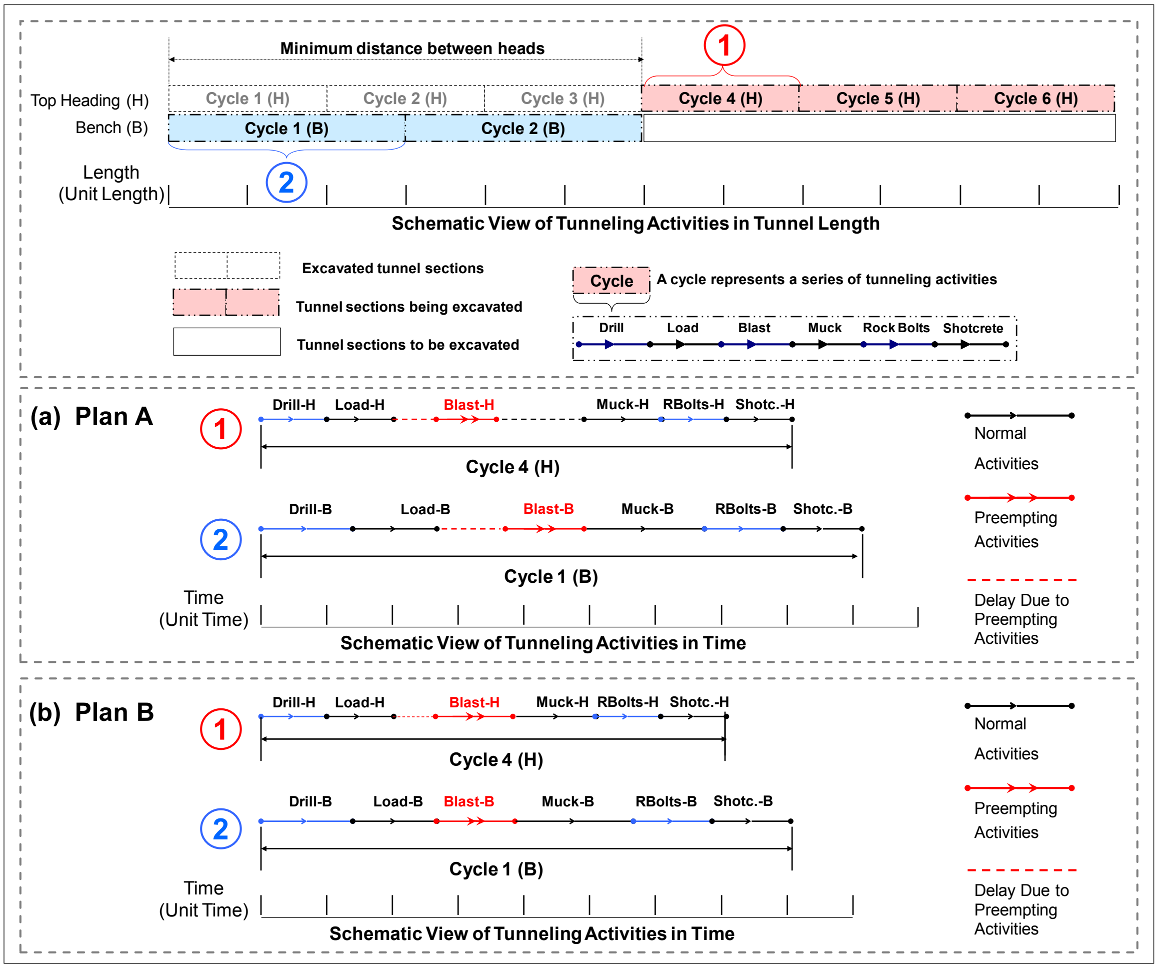

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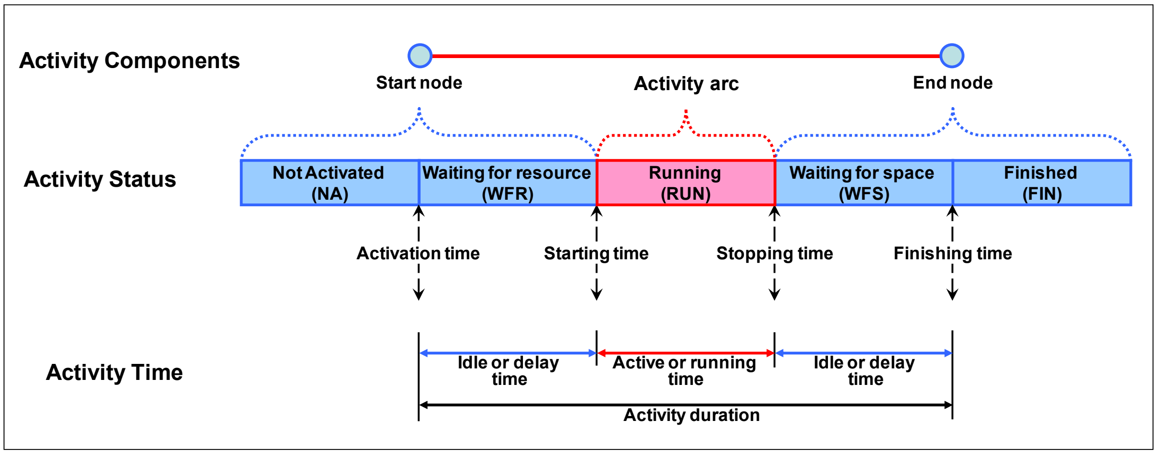

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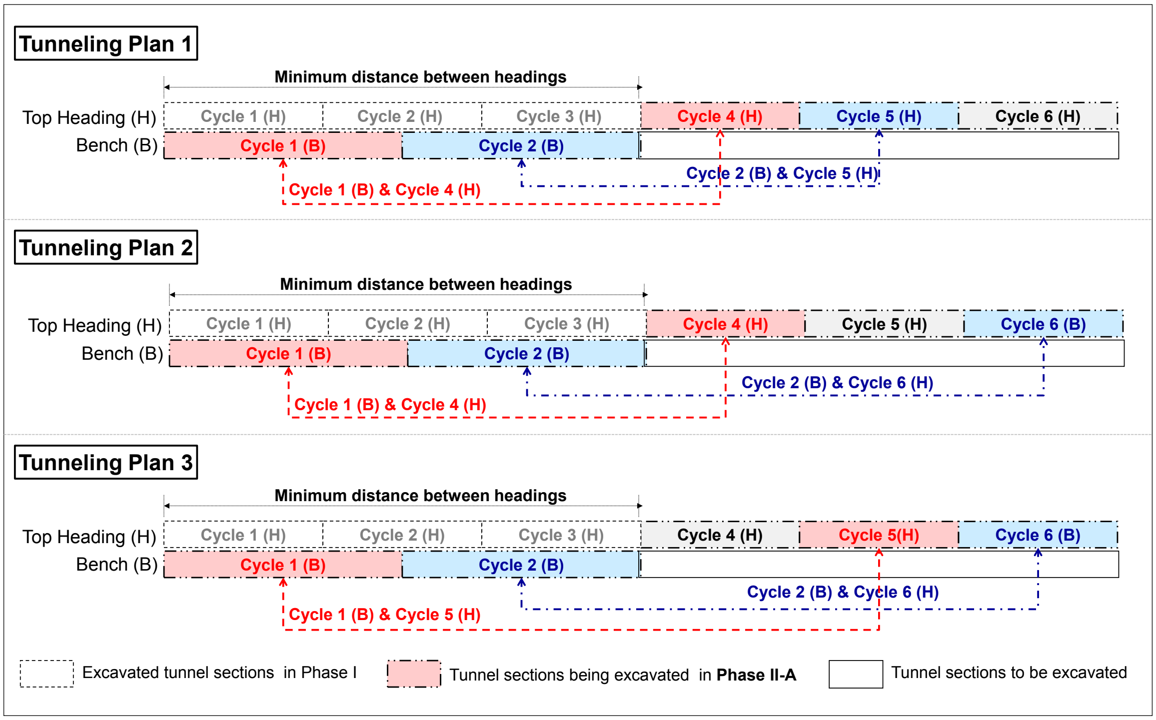

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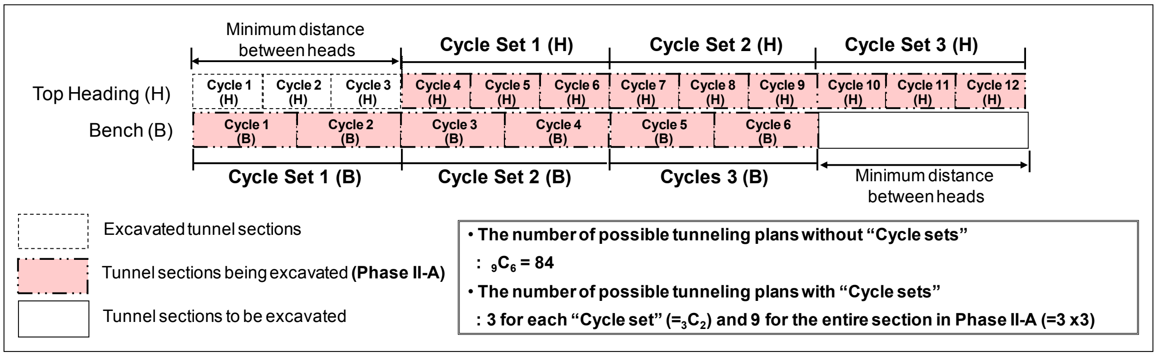

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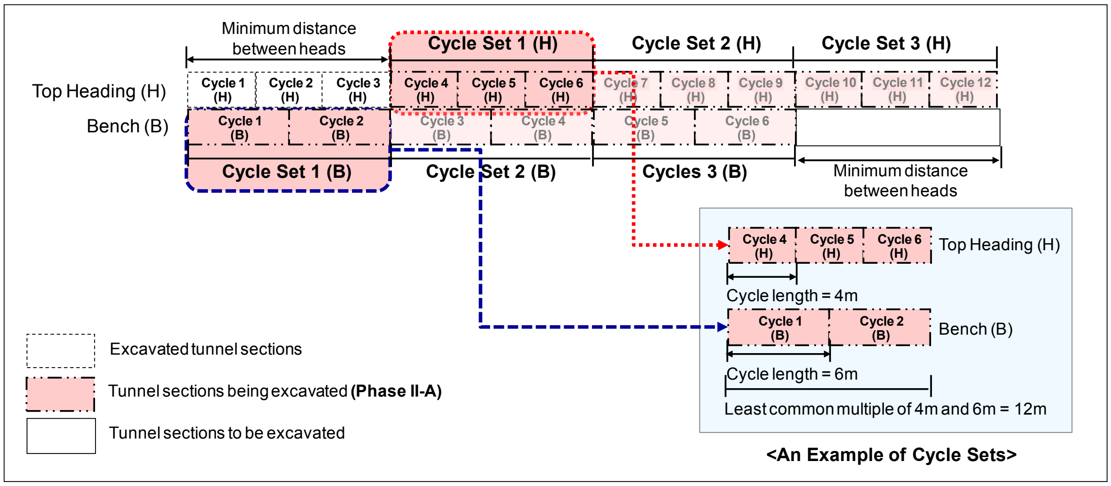

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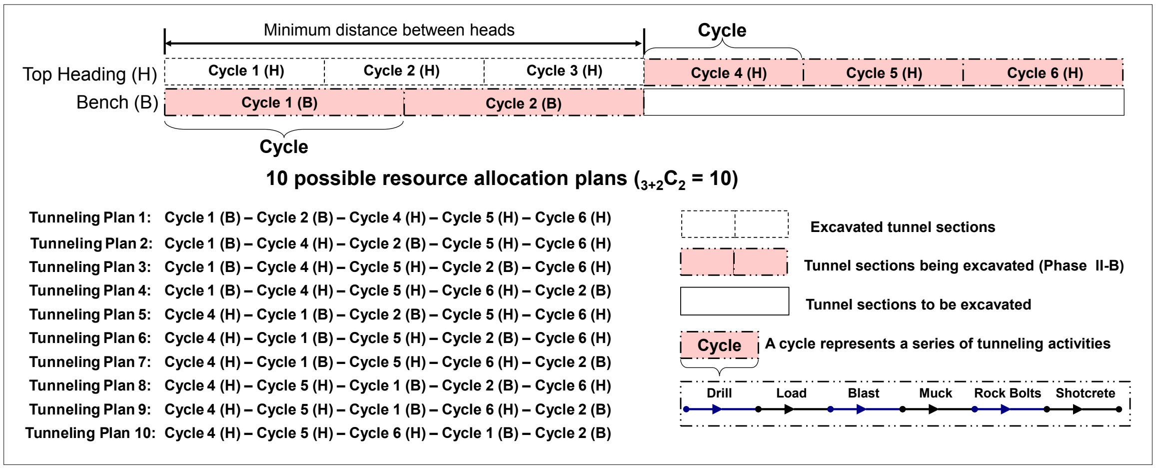

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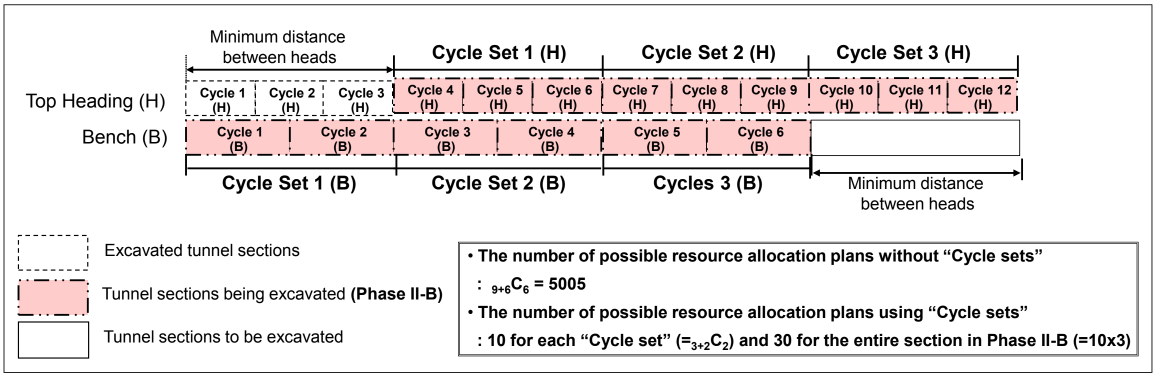

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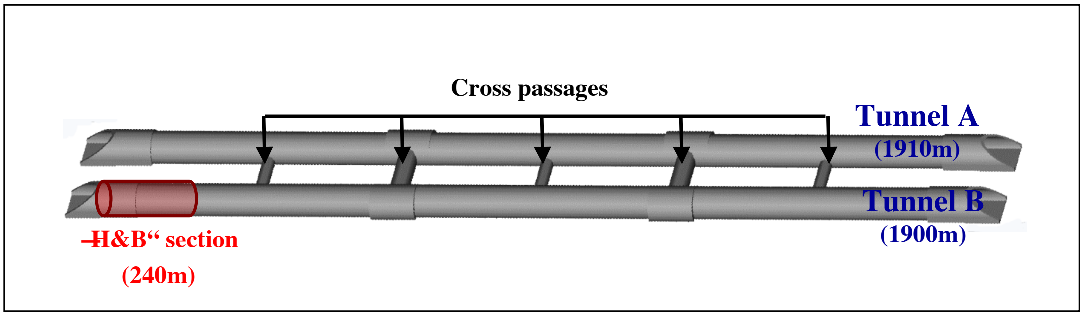

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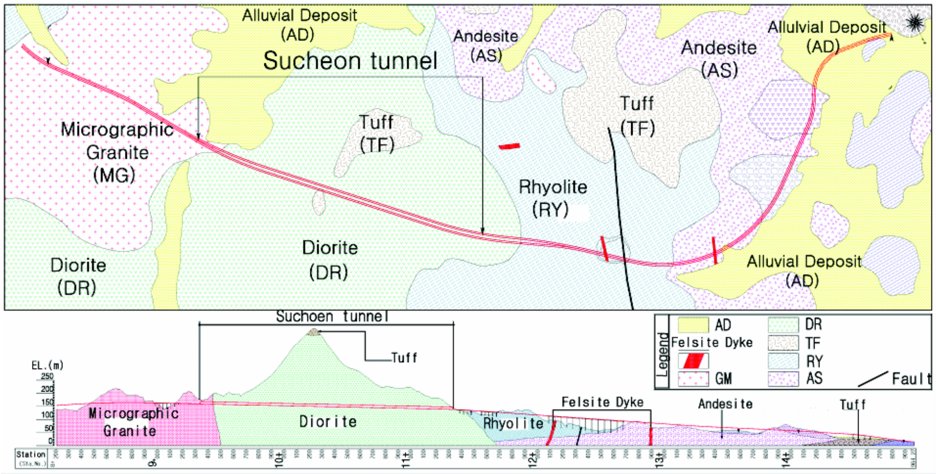
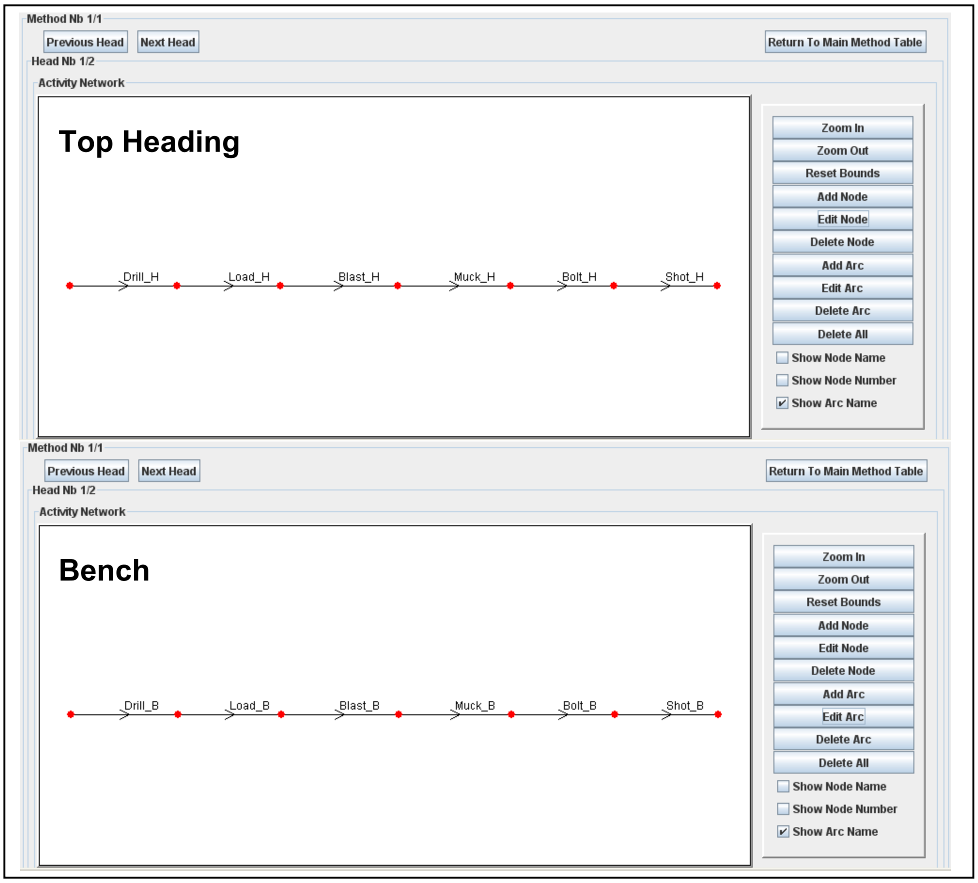


Fig. 12 Geologic map and profile of the tunnel



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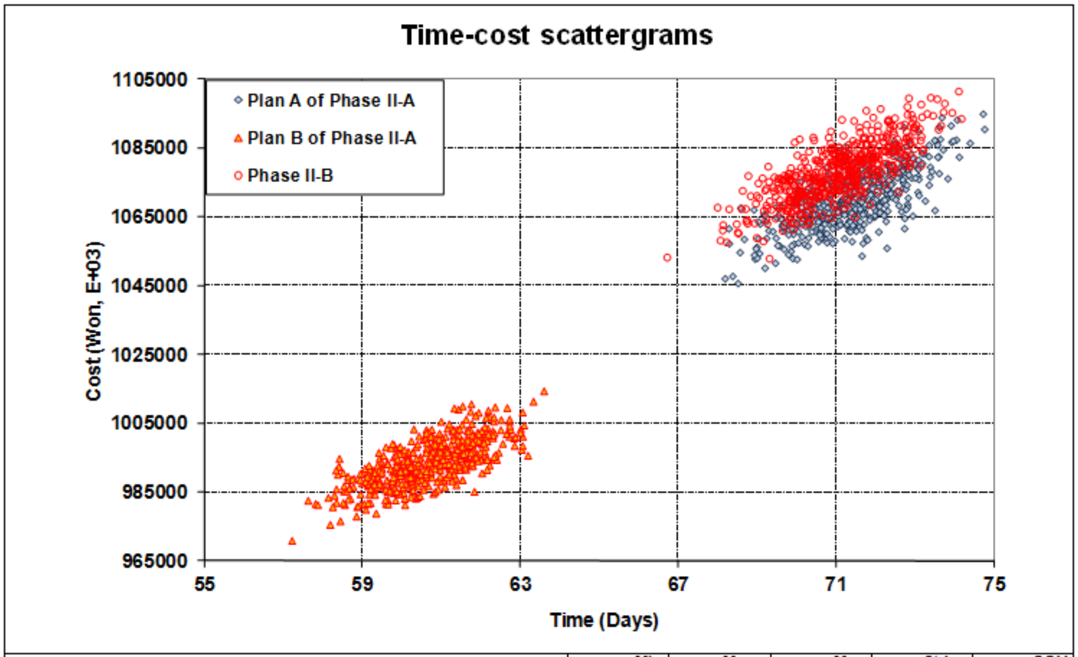
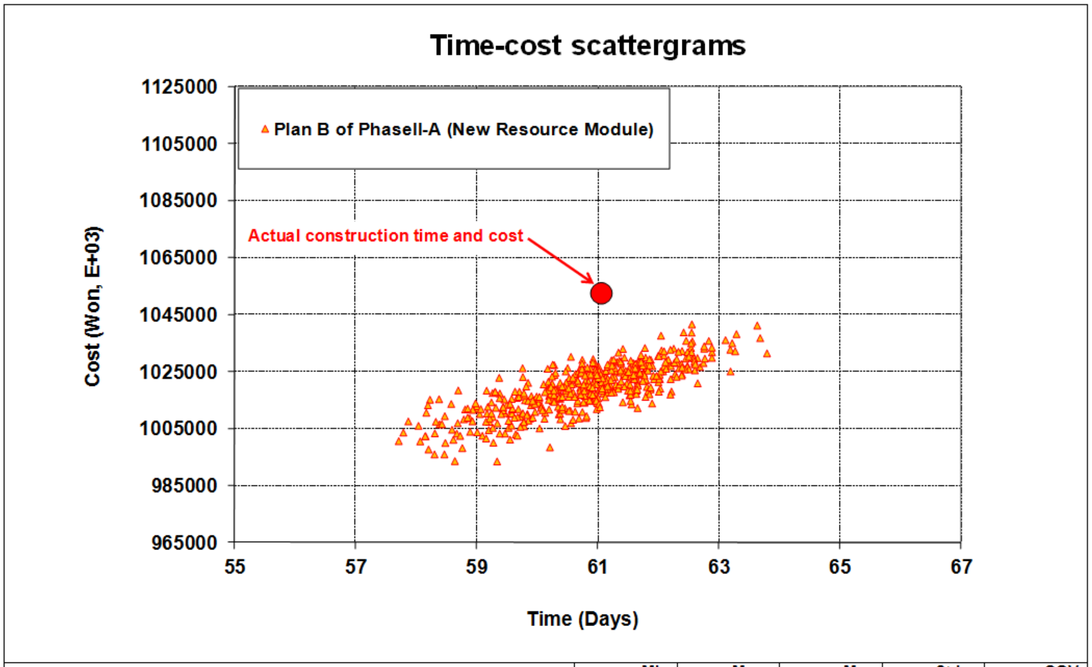


		Min	Mean	Max	Stdev	COV
Plan A of Phase II-A	Time	68.19	71.38	74.76	1.18	1.65
	Cost	1045678.39	1070084.52	1094923.88	8298.57	0.78
Plan B of Phase II-A	Time	57.23	60.69	63.61	1.14	1.88
	Cost	970796.39	993645.80	1014311.81	6662.85	0.67
Phase II-B	Time	66.73	71.05	74.18	1.19	1.68
	Cost	1052763.74	1077928.51	1101336.58	8352.61	0.77

Fig. 14. Comparison of the time-cost scattergrams ("Plan A of Phase II-A", "Plan B of Phase II-A", "Phase II-B" are compared using the new resource model DAT)



		Min	Mean	Max	Stdev	COV
Plan B of Phase II-A (New Resource Module)	Time	57.70	60.78	63.79	1.17	1.93
	Cost	993570.10	1019249.38	1052400.00	8587.72	0.84

Fig. 15. Actual total construction time & cost vs. results of DAT simulation with the new resource model

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Table 1. Verification of the New Resource Model

		Activity Cost (kWon)	Idle Cost (kWon)	TOTAL Cost (kWon)	Idle Time (days)	TOTAL duration (days)
Phase II-A - Plan A	Excel Simulation	987,600	822,092	1,809,692	18.80	71.20
	New Resource Model in DAT	987,600	822,092	1,809,692	18.80	71.20
Phase II-A - Plan B	Excel Simulation	987,600	62,220	1,049,820	5.45	60.58
	New Resource Model in DAT	987,600	62,220	1,049,820	5.45	60.58
Phase II-B	Excel Simulation	987,600	926,686	1,914,286	34.39	74.32
	New Resource Model in DAT	987,600	926,686	1,914,286	34.39	74.32