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Ontology for estimating excavation duration for smart construction of hard rock tunnel projects under resource constraint

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Abstract: Although stochastic programming and feedback control approaches could efficiently mitigate the overdue risks caused by inherent uncertainties in ground conditions, the lack of formal representations of planners' rationales for resource allocation still prevents planners from applying these approaches due to the inability to consider comprehensive resource allocation policies for hard rock tunnel projects. To overcome the limitations, the authors developed an ontology that represents the project duration estimation rationales, considering the impacts of ground conditions, excavation methods, project states, resources (i.e., given equipment fleet), and resource allocation policies (RAPs). This ontology consists of 5 main classes with 22 subclasses. It enables planners to explicitly and comprehensively represent the necessary information to rapidly and consistently estimate the excavation durations during construction. 10 rule sets (i.e., policies) are considered and categorized into two types: non-progress-related and progress-related policies. In order to provide simplified information about the remaining durations of phases for progress-related policies, the ontology also represents encoding principles. The estimation of excavation schedules is carried out based on a hypothetical example considering two types of policies. The estimation results reveal the feasibility, potential for flexibility, and comprehensiveness of the developed ontology. Further research to improve the duration estimation methodology is warranted.

Key words: hard rock tunnel, scheduling, resource constraints, resource allocation policy, smart construction

1. INTRODUCTION

Tunnel construction planners (CPs) often encounter cost overruns, schedule delays, and associated risks due to the inherent uncertainties in ground conditions [1]. Moreover, the adaption of stochastic programming and feedback control approaches can help planners mitigate the risks caused by uncertainties and reduce construction costs as well as excavation durations [2].

CPs often find a locally optimal schedule with shortest project duration based on previous experience. If the scheduling problems are combined with the uncertainties in ground conditions, the optimal schedule selection becomes more difficult and time-consuming. Although some existing approaches focus on the estimation of excavation durations for hard rock tunnel construction projects, they do not consider the impact of resource limitations (i.e., limited equipment) during different project states [3][4]. In other words, planners cannot currently use stochastic programming and feedback control approaches because of the lack of formal method for CPs to rapidly generate and estimate optimal excavation schedules (i.e., activity allocation rules) with minimum durations under resource constraints considering uncertainties in ground conditions.

Before developing a formal method, a formal representation ought to be presented first. The proposed rationales should explicitly and comprehensively represent necessary information for planners, including schedules, ground conditions, excavation methods, project states, resources, resource allocation policies (RAPs), etc.

The research team explores how to comprehensively represent the formal rationales for estimating excavation durations of resource-constrained hard rock tunnel projects in construction. This paper first reviews previous studies to identify the research gap. After that, an ontology for formally representing estimation rationales for the excavation duration of resource-constrained hard rock tunnel projects will then be proposed, followed by an example to explain the application of the ontology.

2. POINTS OF DEPARTURE

The rationales for estimating excavation durations of resource-constrained hard rock tunnel projects in construction should formally represent the information about ground conditions, excavation methods, project states, resources, and RAPs. Some formal rationales for duration estimation of hard rock tunnel projects proposed in existing studies are briefly reviewed in this section to discuss their advantages and limitations.

The Industry Foundation Classes (IFC), which provides the standard and open BIM specification, has been widely applied for the digital information repository in many domains like design, construction, and facility management [5]. ifcOWL provides a Web Ontology Language (OWL) representation of the Industry Foundation Classes (IFC) schema. It represents and standardizes process information (e.g., data time) and product information (e.g., material, topology, geometry) necessary for tunnel construction. However, only one value of the slot for the description of material properties can exist, which leads to limitations on the representation of multiple possible ground condition compositions [4]. Similarly, several Kriging methods have limitations on the representations of uncertainties in ground conditions, even though they allow engineers to clarify the spatial correlations among different ground conditions in multiple blocks of tunnels [24]. Decision Aids for Tunneling (DAT), a computer-based tool, could estimate the tunnel construction duration and cost, considering the uncertainties in ground conditions and spatial relationships among blocks with different probabilistic geologic properties. However, only First Come First Served (FCFS) is involved in the current DAT study as the policy for resource allocation without considering other RAPs [3].

Aalami et al. [6] proposed a generalized construction method model on the basis of a tuple of <Component>, <Action>, <Resources>, <Sequencing constraint>, <Elaboration> (i.e., CARSE). Liu et al. [7] have specialized the CARSE tuple based on their objectives, in which the proposed models enable planners to explicitly represent the rationales about the operation of excavation methods in the excavation method level of detail. However, the uncertainties in ground conditions and RAPs have not been comprehensively considered in the models. Kim et al. [4] extended the CARSE tuple and developed an ontology called the dynamic excavation method model (DEMM) to represent cost and duration estimation rationales for hard rock tunnel excavation. Although the uncertainties in ground conditions and excavation methods have been included in this study, the influence of resource constraints and the way to allocate limited resources are still not considered.

The e-COGNOS approach [8] proposed an ontology as a platform for heterogeneous knowledge management from different sources during construction, although it was not tailored for hard rock tunnel projects. In other words, the characteristics of hard rock tunnel excavation cannot be represented in this ontology like multiple possible ground condition compositions, uncertainties etc. The RAPs are also not considered in this ontology.

Therefore, the existing studies that formally represent the product (e.g., ground conditions of tunnels, the topology of tunnels) or the process (e.g., construction method models) information still have limitations in estimating excavation durations for resource-constrained hard rock tunnel projects and covering all required information (e.g., ground conditions, excavation methods, project states, resources, RAPs).

3. ONTOLOGY FOR ESTIMATING EXCAVATION DURATIONS FOR HARD ROCK TUNNELS USING GIVEN EQUIPMENT FLEET

In this section, an ontology is proposed to answer the research question (i.e., how to comprehensively represent the formal rationales for estimating excavation durations of resource-constrained hard rock tunnel projects in construction). This ontology is developed based on the methodology recommended by Noy and McGuinness [9]. The authors formalized the required information for solving the scheduling problem and estimating durations for hard rock tunnels using the given equipment fleet in a comprehensive and structured way.

In order to provide more detailed information for scheduling, the developed ontology represents excavation methods at the excavation activity level of detail. The authors identified the required classes and properties (i.e., slots). As shown in Figure 1, this ontology consists of five main classes: ground condition and excavation method (GC and EM), project state, resource, policy, and schedule. They will be further stated after the explanations of some terminologies by a hypothetical example.

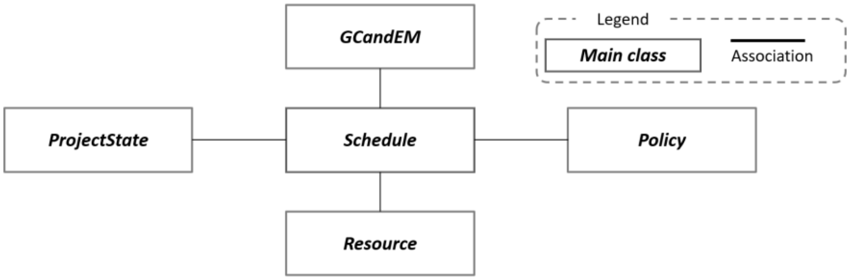

Figure 1. Main classes of the developed ontology for estimation project durations for hard rock tunnel projects using the given equipment fleets

3.1. Case example

A hypothetical example is presented to illustrate some terminologies involved in the rationales. Figure 2 shows the possible “State N” of a parallel tunnel project with two sections during excavation. The grey color represents excavated sections while the other colors represent unexcavated sections. Section 1, whose total length is 8400m, consists of two kinds of ground conditions: the good ground condition in blue (i.e., G1; 4800m long) and fair ground condition in yellow (i.e., G2; 3600m long). Section 2, whose total length is 6000m, contains two kinds of ground conditions: fair ground condition (i.e., G2; 3600m) and poor ground condition in red (i.e., G3; 2400m). Figure 2 shows the ID, start station, and excavation direction of each phase of “State N.” Phase 1 (P1) starts from STA(1, 20), where STA(X, Y) denotes location Y from section X, where

Y is calculated by dividing the distance between this location and the excavation's starting location of the section to which the current phase belongs (i.e., STA(X,0)) by 100m. Phase 2 (P2) starts from STA(1,104), Phase 3 (P3) starts from STA(2, 35), and Phase 4 (P4) starts from STA(2, 95).

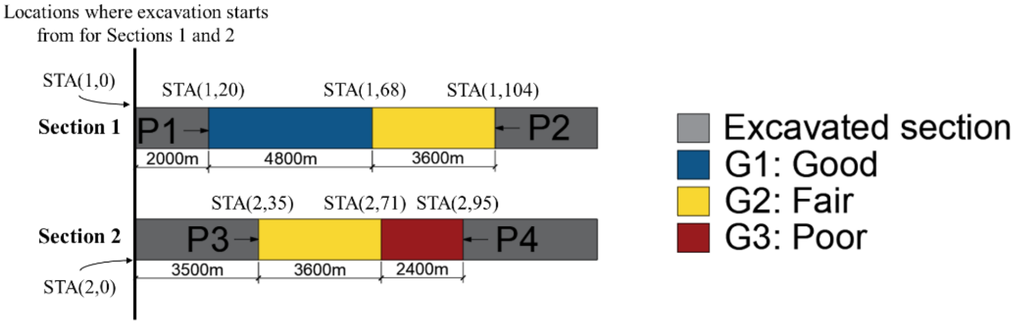

Figure 2. State N of a two-section tunnel excavation project

3.2. Ground condition and excavation method

The "GCandEM" main class formally represents all considered ground conditions, possible scenarios of ground conditions from all phases, and all involved excavation methods. The "GCandEM" main class includes two subclasses: "GroundCondition" and "ExcavationMethod". The subclasses and their properties are shown in Figure 3.

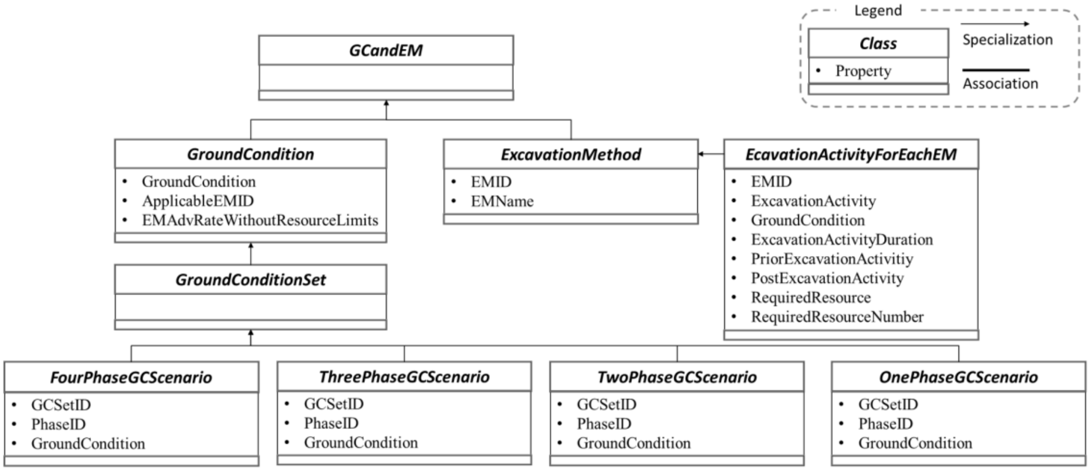

Figure 3. Subclasses and properties of "GCandEM" main class

The "GroundCondition" class represents all considered ground conditions as well as the applicable excavation methods (e.g., drilling and blasting method, tunnel boring machine method) for them. The advance rates without considering resource constraints would also be represented after ground conditions and excavation methods are known. The "GroundCondition" class has one subclass—namely, "GroundConditionSet" —which is the mother set of all probable ground condition scenarios. It is further divided into four subclasses according to the total number of phases (up to four): "FourPhaseGCScenario," "ThreePhaseGCScenario," "TwoPhaseGCScenario," and "OnePhaseGCScenario." The ground condition of each phase should be clearly illustrated in these scenarios. The "ExcavationMethod" class represents all excavation method alternatives. It has one subclass, the "ExcavationActivityForEachEM" class, which describes the information of all excavation activities for each excavation method. The information about name, duration under the specific excavation method and ground condition, sequential constraints (i.e., prior and post activities), and required resources will be given for each excavation activity in this class.

3.3. Project state

The "ProjectState" main class formally represents the excavation progresses at specific times (e.g., the time when the project starts, the time when the ground condition scenario changes). The representation of excavation progress includes the current time, ground condition scenario of all phases, and the number of sections still under excavation. The "ProjectState" can be further described in two ways: section-based representation and phase-based representation. First, the section-based representation describes the excavation progress for the whole project by the "GCInEachSection" class. The "GCInEachSection" records the ground condition compositions with the exact start and end locations of each ground condition for all sections. Second, the phase-based representation collects the ground condition information from all phases by the "StateForEachPhase," which is necessary for the successful development and invocation of the scheduling algorithms. The selection of excavation methods for phases is based on the current ground condition scenario, and the information of excavation activities can then be obtained for the scheduling algorithms. The "StateForEachPhase" records three kinds of information of each phase: (1) which section it belongs to, (2) current ground condition, and (3) length of the current ground condition.

3.4. Resource

The "Resource" main class formally represents the given equipment fleet with the information about the name and the total number of each type of resource. The subclasses and their properties are shown in Figure 4.

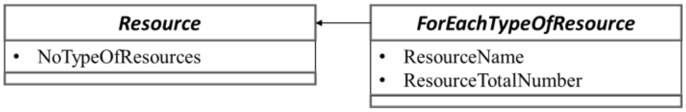

Figure 4. Subclasses and properties of "Resource" main class

3.5. Policy

To assess comprehensive resource allocation policies, the research team identified 10 policies based on literature reviews and interviews (Table 1) and formalized the information required to assess the policies in the "Policy" class. The subclasses and their properties are shown in Figure 5. The first nine policies are popular policies proposed in previous studies [10][11][12]. The 10th policy is "Binary Policy," which is recommended from the interview with experts. It introduces the concept of a resource buffer to the activities from relatively critical phases to assign higher priorities to relatively critical phases for the resource allocation and obtain shorter total project durations. Here, the resource buffer is a time buffer with a user-defined size. Policies 1 through 5 are non-progress-related policies while policies 6 through 10 are progress-related policies. For non-progress-related policies, the advance rates of all phases obtained from scheduling algorithms are not influenced regardless of the remaining durations of phases. The remaining duration of the phase refers to the time period required for each phase to complete the excavation of the section to which it belongs, without considering resource constraints, when the excavation of all phases is carried out simultaneously. In contrast, for progress-related policies, the remaining durations of phases have impacts on the advance rates of all phases obtained from scheduling algorithms.

Table 1. 10 policies considered in the developed ontology

Non-progress-related RAPs	Progress-related RAPs
1. First Come First Served (FCFS)	6. Shortest Activity from Shortest Project (SASP)
2. Shortest Operation First (SOF)	7. Longest Activity from Longest Project (LALP)
3. Maximum Operation First (MOF)	8. Minimum Slack (MINSLK)
4. Minimum Total Work Content (MINTWK)	9. Maximum Slack (MAXSLK)
5. Maximum Total Work Content (MAXTWK)	10. BINARY POLICY

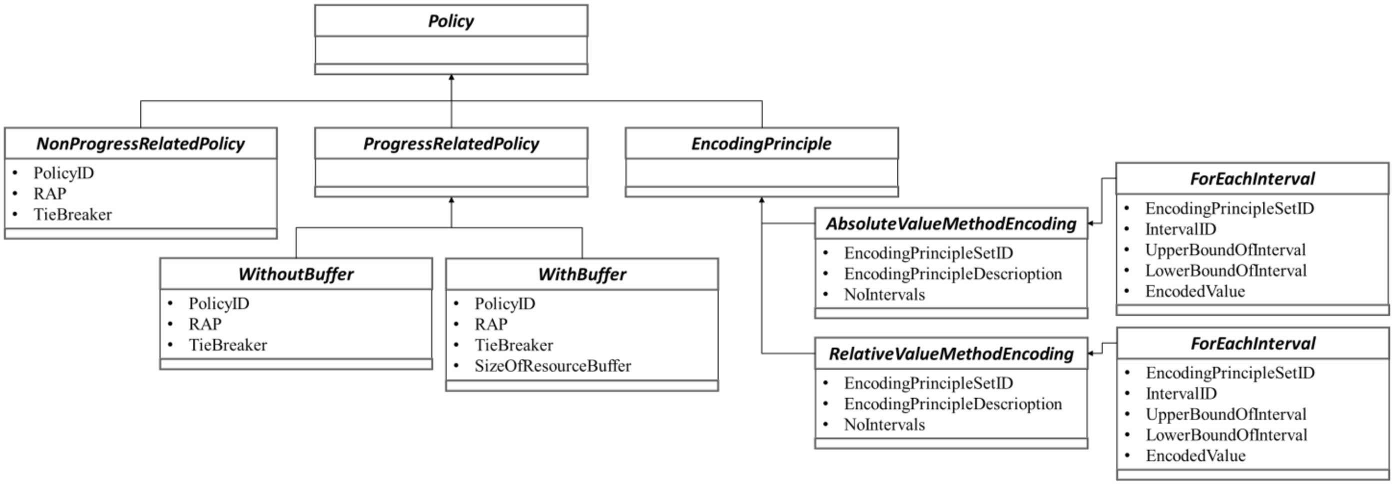

Figure 5. Subclasses and properties of "Policy" main class

The remaining durations of phases are essential input information for the scheduling algorithms of progress-related policies. However, it is inefficient to input the absolute values of remaining durations again and again, which will lead to an apparent increase in computation amount. Encoding the remaining durations of phases is strongly suggested for the computer-efficient development of scheduling algorithms. Planners can design their own encoding principles based on their own requirements and tolerances about errors. Two methods can be used to design encoding principles: the absolute value method and the relative value method. For both methods, planners are expected to design the number of intervals and both the upper and lower bounds of each interval. The upper and lower bounds of intervals can be determined by the sizes of floats (for the absolute value method) or the ratios of floats to the maximum remaining duration among all phases (for the relative value method).

3.6. Schedule

The "Schedule" main class formally and comprehensively represents the required input and output information for the project duration estimation by using scheduling algorithms. The "Schedule" class itself represents the time-related information combined with the corresponding project state (i.e., excavation progress) and has one subclass, the "ScheduleEvaluation" class, which records policy-related information for scheduling, including RAP applied and encoding principle applied (if the selected policy is progress-related). In addition to the time-related and policy-related information, the scheduling algorithm still requires the excavation activity information, which is determined by the excavation methods for all phases. Therefore, the "EMForEachPhase" subclass is created to store the excavation method information for the "ScheduleEvaluation" class.

4. DISCUSSION

The research team applied the ontology for the case study shown in Figure 2 to estimate excavation durations for different RAPs. The CPs are required to provide information included in the ontology and obtain the durations estimated for different excavation plans shown in the ontology. It is assumed that the project will start from State N, as shown in Figure 2, and the same excavation method, “EM1” (i.e., drilling and blasting), will be selected for all phases. In this example, three activities are considered for each cycle (i.e., A1→A2→A3). Three kinds of resources are involved in the example (i.e., R1, R2, and R3), for which the total numbers are all 2. The project state descriptions are same as those illustrated in Figure 2. The further required information for instances is listed in Table 2.

Based on the ontology proposed, the excavation durations for two different kinds of policies (one non-progress-related policy and one progress-related policy) have been estimated for the case study. The approximate scheduling results under FCFS and MINSLK are shown in Table 3. It can be observed that the excavation duration of schedule 2 (i.e., around 5651hrs) is shorter than that of schedule 1 (i.e., around 6002hrs). It shows that for this hypothetical example, adopting MINSLK policy can lead to shorter project duration than FCFS policy, which is the only conventional policy used for resource allocation in existing DAT studies.

Table 2. Policies selected for scheduling by planners

Progress-related?	RAP ID	RAP	Tie-breaker
N	1	FCFS	Random
Y	8	MINSLK	FCFS

Table 3. Schedule information under FCFS and MINSLK obtained by planners

Schedule ID	Current project state ID	Start time (h)	End time (h)	Policy ID
1	N (N=0)	0	6002	1
2	N (N=0)	0	5651	8

The successful estimation of the two excavation plans with two different RAPs reveals that the ontology proposed in this study can formally represent the required information for scheduling problems for hard rock tunnels using the given equipment fleet. In addition to the two mentioned policies, planners can flexibly apply this ontology for all considered policies under different possible states. There are still some limitations of this research. The resource applicability is not considered in this research. All types of resources are assumed to be applicable for all phases. However, some resources can only be used for some specific phases in the actual project. In addition, the validation of this ontology is carried out on a hypothetical example with 2 sections without considering the excavation of shaft. Moreover, the ontology is expected to be applied into an actual project in the future.

5. CONCLUSION

The stochastic programming and feedback control approaches, which are beneficial for reducing risks caused by inherent uncertainties in ground conditions, are expected to be applied for hard rock tunnel projects when considering resource constraints. Currently, CPs cannot successfully adapt the approaches due to the lack of formal methods. Before the presentation of the formal method, this study proposed a formal representation to answer the research question (i.e., how to comprehensively represent the formal rationales for estimating excavation durations of resource-constrained hard rock tunnel projects in construction) and solve the practical problems for CPs. The ontology is expected to include the ground condition and excavation method, project state, resource, and policy classes. No existing rationales cover all of these classes for hard rock tunnel projects. Therefore, an ontology is proposed for planners to explicitly represent their rationales to estimate excavation durations for different RAPs for hard rock tunnel projects using the given equipment fleet. The developed ontology contains 5 main classes and 22 subclasses. It is applied to a case study using two different policies to compare the results, which demonstrated the feasibility and potential of the flexibility of the ontology. In the future, formal schedule estimation methodology could be proposed with more comprehensive and detailed considerations (e.g., resource applicability for specific phases, more complicated scenarios for different types of tunnels) based on the ontology developed by this paper.

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