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AUTOMATIC DATA PROCESSING SYSTEM FOR INTEGRATED COST AND SCHEDULE CONTROL OF EXCAVATION WORKS IN NATM TUNNELS

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Abstract. A type-based system is widely used for cost and schedule control in the NATM (New Austrian Tunnelling Method) tunnel. This study raises several limitations of the type-based system: a broad level of control, a distributed approach to cost and schedule data, ad hoc management, and difficulty in deriving meaningful data. Integrated cost and schedule control promises a myriad of benefits on both information flow and construction management. Nevertheless, the integrated approach still seems to be a long way from common use in the construction industry because it requires considerable overhead effort to acquire, track, and analyze the integrated data. The objective of this study is to propose a new method to automate the required processes for implementing cost and schedule integration. We propose an operational-level automatic data processing system for cost and schedule integration. The proposed system consists of a real-time location system for detecting equipment locations, a wireless mesh network for transmitting the location signals to a field office, and a prototype model for transforming the signals to cost and schedule data. Technical feasibility is analyzed through a pilot project. The study offers a new approach to facilitating sensor technologies for cost and schedule integration.

Keywords: data integration, NATM, RTLS, wireless mesh network, automation, information technology.

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Introduction

In the age of limitless competition, the construction industry has been increasingly challenged to improve work performance. Traditional methods such as organization or process changes seem to have reached their limits and their leverage seems to be insignificant. With the incredible rate of advancement in information technology, IT convergence for the construction industry has been in the spotlight as a new approach to lead the industry from its traditional labour-intensive status to become technology or knowledge intensive. While the IT convergence has been attractive to the industry, its influence has been imperceptible compared with other industries. IT convergence must not simply utilize some technology in projects, but must optimize core technologies in the construction environment considering work processes, field characteristics, business strategies, and so on.

Timely feedback on a project's status enables project managers to identify problems early and make appropriate adjustments that can keep a project on time and within budget. Cost and schedule control have been regarded as two major management factors for successful performance of construction projects. Because cost and schedule control are closely interrelated in terms of sharing data and management process (Jung, Woo 2004), an integrated approach also promises a myriad of benefits for information systems and management. While extensive research has attempted to provide a systematic method to integrate cost and schedule data, the integrated approach still seems to be a long way off in the construction industry. Different levels of detail between cost and schedule data structures generate many integrated Control Accounts (CAs), which require considerable overhead effort from field managers to acquire, track, and analyze data throughout the integrated data processing. The additional overhead has generated much resistance to adopting the integrated approach in the industry. As a result, despite much effort, integrated cost and schedule control has been considered as irritating work in construction fields. While previous effort to integrate cost and schedule data have mostly focused on building projects that consist of many elements, operations, and crews, it is not widely applied to a large construction project such as a tunnel, road, or bridge characterized by a relatively small number of information units, horizontally repetitive operations, and construction in open space.

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Motivated by these challenges, this study hypothesizes that an automatic data processing system (ADPS) applied to a large construction project should help facilitate the integrated approach by reducing the number of CAs and overhead effort in the data processing. The primary objective of this study is to propose a new method to automate the required processes for implementing cost and schedule integration. NATM tunnel projects focusing on excavation works is considered to verify the proposed method.

1. Cost and schedule integration

As construction projects become larger and more complex, a great amount of data is generated. Project participants must rapidly understand and leverage these data for efficient project management. Because cost and schedule control are the two major functions determining a project's success or failure, various document forms and software applications are used to acquire, track, and analyze cost and schedule data. These independent tools might be well customized to represent original data, but there are many redundancies in using different forms, structures, and perspectives (Rasdorf, Abudayyeh 1991). They require considerable overhead effort to acquire, analyze, and manipulate fundamentally the same data over and over again in the data processing.

Because cost and schedule information are closely interrelated, it would be ideal for both cost and schedule data to be represented by a single hierarchy and controlled by a single parameter. Unfortunately, the low-level items in a traditional bill of quantity (BOQ) representing cost data and the low-level items in a scheduling diagram are in two different levels of an information hierarchy and there is considerable mismatch (Perera, Imriyas 2004). The different levels of detail have been regarded as the main difficulty of cost and schedule integration (Hendrickson, Au 1989; Rasdorf, Abudayyeh 1991; Jung, Woo 2004; Fleming, Koppelman 2005). Many researchers have attempted to derive an appropriate integration model for the industry. Teicholz's CBS to WBS Mapping Model (Teicholz 1987), Hendrickson and Au's Work Element Model (Hendrickson, Au 1989), Kim's Design Object Model (Kim 1989), and Rasdorf and Abudayyeh's Work-packaging Model (Rasdorf, Abudayyeh 1991) are well known. These models have tried to find an integrated control point through distributing cost data into schedule data or vice versa (Cho 2009) to remove mismatches between cost and schedule data.

An integrated Control Account (CA) is derived from three information structures, Work Breakdown Structure (WBS), Cost Breakdown Structure (CBS), and Organization Breakdown Structure (OBS). Thus, the integrated CA is referred to a combination of zone and element from the WBS, corresponding operations from the CBS, and organizations from the OBS responsible for the operations. In other words, an integrated CA must encompass all relevant information units such as element, operation, location, and organization to resolve the mismatch. As a result, an integration model requires a large number of CAs, which form a complex data structure. Additional effort to generate CAs (Deng, Hung 1998) and the overhead costs to control field data (Rasdorf, Abudayyeh 1991; Deng, Hung 1998; Jung, Woo 2004) created resistance to wide adoption of the integrated approach. It is paradoxical that project managers resist the integration because of the additional work required, while the integration system was designed to reduce the managers' workload.

Rasdorf and Abudayyeh (1991) proposed an automatic data acquisition method using bar codes and a relational database management system to reduce the overhead effort of data acquisition and processing. Jung and Woo (2004) proposed a flexible WBS method to minimize the number of CAs. On one hand, these approaches improved the practicability of an integration system, but on the other hand, they were still limited to apply to all construction projects.

Representations of cost and schedule control items and their levels of detail vary according to both project characteristics including project size, type, cost, duration, technical complexity, management level, delivery system, contract type, and management policies (Jung, Woo 2004), and situational characteristics including development stage, delivery method, available resources and constraints, contractual relationship, construction method, developer's experience, perspective and knowledge, etc. Considering these characteristics, a single representative integration method might not be suitable for all construction projects.

While previous efforts towards integration have usually focused on building projects, they are rarely applied to large construction projects such as tunnels, roads, railroads, or bridges. These are characterized by relatively small numbers of elements and organizations, horizontally repetitive operations, and construction in open spaces. The different characteristics of these large construction projects might positively impact on the integration method. In the following sections, we propose a method to reduce the required number of integrated CAs and the overhead effort in data processing, focusing on excavation works in NATM tunnel projects.

2. Cost and schedule control in an NATM tunnel

2.1. Characteristics of NATM tunnels

The New Austrian Tunnelling Method (NATM), also commonly referred to as the Sequential Excavation Method (SEM) uses the inherent strength in the rock mass to support the roof during excavation. Because this self-supporting capability achieves economy, flexibility in uncovered ground conditions, and dynamic design variability, NATM is widely applied for underground structures. NATM tunnels are largely dependent upon round length, types of support, and ground conditions such as shear strength, deformation, and groundwater level. Excavation works accounting for more than fifty percent of the project budget and consuming roughly sixty percent of the total project duration are critical management points determining a project's success.

Excavation methods and supporting patterns are predefined using "types" in the planning phase. As ground conditions deteriorate, the type number increases, the number of supporting processes (such as rock bolts, steel plates, and forepoling) increases, and the length of excavation per cycle decreases from 3.5 metres to 1.0 metres. For example, Type-I is the lowest support type; it is applied in favourable ground conditions, allows full-face excavation, and usually advances by 3.5 se or more per cycle. On the other hand, Type-VI allows only partial excavation and advances by 1.0 metres or less. Type-VI tunnels are excavated in two stages independently. First, the top half of the tunnel (or heading) is excavated, and then the bottom half (or bench) is excavated, because prompt reinforcements are required to protect against unfavourable ground conditions. The standard types provide a common platform for project participants to communicate in the field. A tunnel project may have several drift patterns (e.g. Type-I, Type-II), and more than six types have been recommended to cope more flexibly with various ground conditions.

A standard type of excavation is implemented by cyclic operations such as boring, charging, blasting, mucking, reinforcing, and shotcreting operations. Each operation in the repetitive series must usually be completed before the subsequent operation can start (Department of Transportation 2009). Twelve-hour shifts and two cycles of excavation per day are typical in a portal. Thus, four shifts of excavation are performed in a two-portal tunnel. Because one set of equipment and crews is usually responsible for the four cycles, smooth operational transitions from one portal to the other might be quite important for efficient cost and schedule control.

2.2. Type-based cost and schedule control

Because of the limitations in investigating precise ground conditions, excavation plans in the design phase can change frequently during the project execution. Project management schedules are used widely to assess the change and to compare the current status with the plan. Figure 1 shows a project management schedule used for underground construction. The big table is divided into a plan table and an actual table. The plan table includes: (1) a station representing the excavation point; (2) a planning type denoting an excavation and support method; and (3) the total excavation length for the planning type. The actual table includes: (1) an actual start date for the corresponding station; (2) the implemented type; and (3) the total excavation length of the actual type.

Table 1 shows a type-based unit costing system that is used in a real tunnel project. These type-based unit costs are derived from the company's own historical database. In the type-based system, cost and schedule control is implemented by comparison between planned and actual type for a given construction period. For example, Type-VI and Type-V were designated for the first 28 metres of excavation in the plan in Figure 1. However, only Type-VI was actually performed because of unfavourable ground conditions. On April 4, a project manager calculates the change's negative impact: the tunnel is 3.2 metres behind schedule and KRW 47 203 200 over budget. Because both cost and schedule control are implemented based on types, it can be regarded as a type-based cost and schedule control system; in short, a type system in the paper.

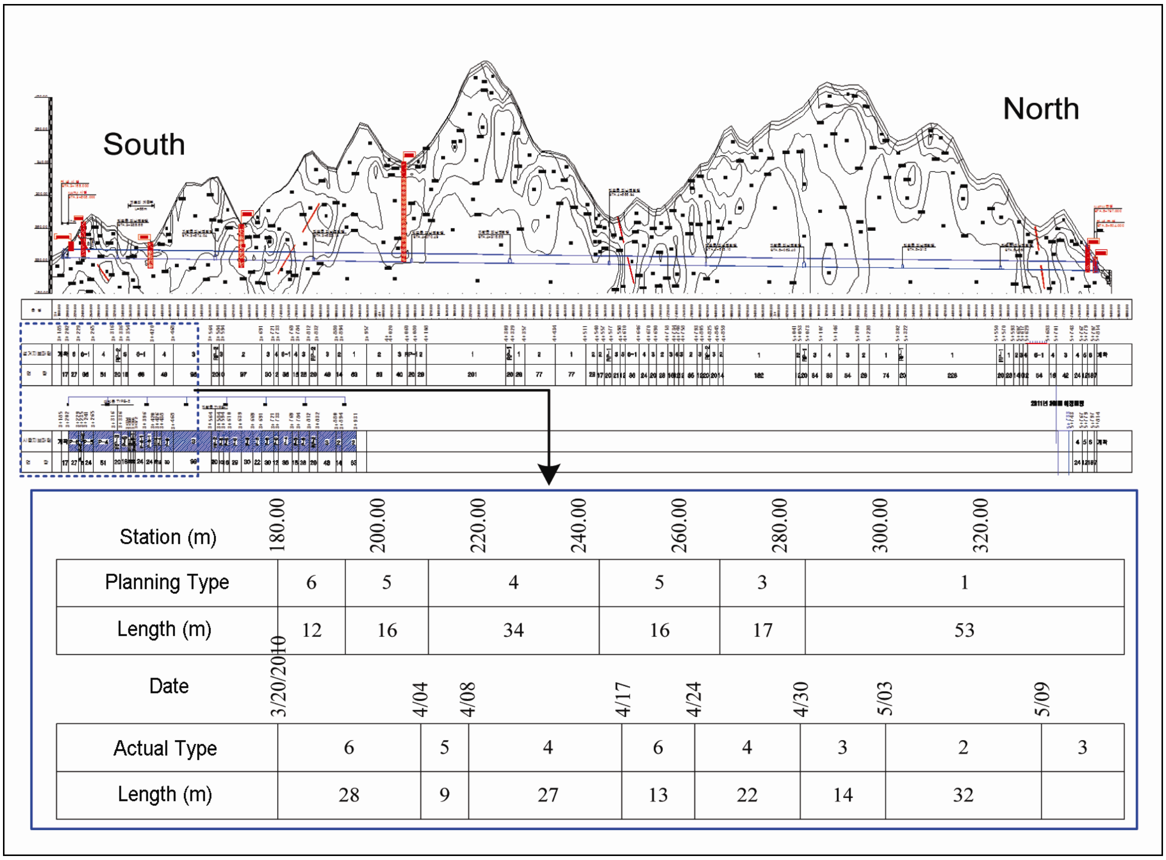

Fig. 1. An example project management schedule for a tunnel project

Table 1. Type-based unit costs used in Samtan 1 Tunnel

Standard type	Excavation length per cycle (m)	Unit cost per cycle (wons)
TYPE-I	3.5	9,607,500
TYPE-II	3	8,547,000
TYPE-III	2	7,342,000
TYPE-IV	1.5	7,726,500
TYPE-V	1.2	8,734,800
TYPE-VI	1	11,685,000
TYPE-VI-1	1	11,677,000

2.3. Limitations of the type-based control system

The type system consists of several cost items listed in BOQ. A cost item can be divided into several operations according to equipment requirements. Table 2 describes the cost items used in the BOQ and their required operations for the Type-IV top cycle. The type system can be delineated into cost item levels composed of a bundle of operations.

Table 2. Cost items and operations of Type-IV top cycle

Cost Item in BOQ	Operation	Equipment (ea.)	Time (min)
NA1613 Excavation	Survey & mark	Charging car (1)	20
	Drill	Drilling jumbo (1)	80
	Charge & blast	Charging car (1)	60
	Ventilate		30
NA1920 Muck disposal	Scale	Backhoe (1) Charging car (1)	20
	Load & haul	Backhoe (1) Dump truck (5)	90
	Clean	Backhoe (1) Loader(1)	70
NG2111 Steel ribs	Install steel ribs	Charging car (1)	50
NE1102 Shotcrete	Cast lining	Shotcrete machine (1) Ready-mix truck (1)	80
	Clean	Loader (1) Dump truck (1)	30
NG1154 Rock bolt	Drill	Drilling jumbo (1)	20
	Install rock bolts	Charging car (1)	60
Total			610

Three limitations of the type-based control system were identified in our study. First, the type system does not allow project managers to track individual performances in particular periods of time. Cost control relies on the level of detail used in the BOQ and schedule control relies on the productivity rate of an operation performed by a crew. Meanwhile, the type system's data are at a too broad level because all operational performances are lumped together. This broad level is rarely appropriate for bills of quantity and detailed schedule control. Accordingly, instead of ad hoc management from the type system, a more detailed level of control system is required for a more systematic project control.

Second, the type system does not support smooth transitions between operations. As previously mentioned, excavation works are implemented by a series of independent operations, each of which must be completed before the next can start (Department of Transportation 2009).

Usually, one set of equipment and crew implements a two-portal tunnel. At the operational level, a charging car is used several times at both tunnel faces to survey and mark, charge, scale, install steel ribs, and install rockbolts. To complete two cycles within 12 hours, the one set of equipment and crew must frequently move from one portal to the other considering the operational sequence, resources availability, and work space. Because the following factors influence the operational planning, smooth transitions are generally quite complex:

1) *Two portals*: e.g. Southbound and Northbound Tunnel;
2) *Eleven types*: Type-I, II, III, IV-Top, IV-Bottom, V-Top, V-Bottom, VI-Top, VI-Bottom, VI-1-Top, and VI-1-Bottom;
3) *Thirteen operations*: surveying and marking, explosive drilling, charging and blasting, ventilating, scaling, loading and hauling, muck cleaning, steel rib installing, cast lining, floor cleaning, rockbolt drilling, rockbolt installing, and forepoling;
4) *Different quantities* according to the applicable type;
5) *Inconsistent and ever-changing work conditions*: the distance from a tunnel face to a muck pile or a batch plant, access road conditions, equipment efficiency and productivity rate according to excavation progress, equipment failure, relationships with subcontractors, complaints from neighbouring residents, etc.

In the type system, the assembly of operations is unable to represent operational levels of detail, so ad hoc decision-making relying on a project manager's experience, knowledge, and intuition prevails in practice. Thus, a more detailed control system enabling project managers to track current work status should be designed to support the smooth transitions.

Third, the type system seems to be convenient to control a project, but it requires considerable effort to derive meaningful data, e.g. feedback on a subcontractor's performance, productivity rate, equipment efficiency, and effective cycle times of crews. An efficient control system enables project managers to understand who is going to do what, and how, where, why, and when they are going to do it. Unfortunately, supporting data in the type system are distributed in various documents and software applications with different forms, structures, and points of view. Although the type system might be quite adequate to support a broad level of control, additional effort is required to manipulate data for deriving meaningful feedback on project performance. Eventually, the type system triggers inaccuracy, inefficiency, and inconsistency in information flow and interrupts systematic project management.

So far, we have reviewed several limitations of the current approach to cost and schedule control. Excavation works are described by several predefined supporting types and employ sequential operations at multiple places at the same time. While various field characteristics should be understood by planners and reflected by constructors in the project execution phase, the type system does not allow project managers to handle the characteristics. These limitations fundamentally originate from the too broad level of cost and schedule control. Thus, an operational-level cost and schedule control system should be considered as a solution to overcome the limitations.

3. Information technologies required for integrated cost and schedule control

An NATM tunnel is excavated by repetitive cyclic operations, as described in Table 2. Every operation is performed at the tunnel face and by a set of equipment. Thus, we hypothesize that the operations and their related data can be identified by detecting which equipment is at the tunnel face. For example, a project manager can figure out that a shotcreting operation is in progress if an information system shows that a shotcrete machine and a ready-mix concrete truck are located at the tunnel face. The running time of a piece of equipment can provide the start and end times of the operation: shotcreting.

Based on an analysis of the characteristics of excavation works, we propose an automatic data processing system (ADPS) that identifies the locations of equipment in tunnels. To accomplish this, the following systems are required: 1) a real-time location system to detect an equipment location; 2) a network system to deliver the location signals from the tunnel face to a field office; and 3) an information transformation system to convert the location signals to cost and schedule data. Based on extensive reviews of currently available technologies, this study adopts both a real-time location system (RTLS) using a time of arrival (TOA) method to identify the location of equipment in tunnels and a Wi-Fi wireless mesh network to deliver signals to a field office.

3.1. Real-time location identification system

Location identification technologies include the global positioning system (GPS) using satellites, location-based systems (LBSs) using a mobile base station, and RTLSs using an indoor network (Kim 2011). Because GPS and LBS are not available inside tunnels, an RTLS was adopted in our proposed system for identifying equipment locations within the tunnel, while a GPS receiver was used for locations outside the tunnel. RTLS technology is used to monitor the locations of assets, materials, and people in real time using location tags and readers (Sadeghpour 2006). The RTLS transmits real-time location data using readers from tags such as passive, semi-passive, or active radio-frequency identification (RFID) tags. The real-time location data showing the routes of tag movement are transmitted to a network system.

An active tag system was adopted for tracking locations of equipment in a variety of situations, particularly those appropriate to a tunnel's long, linear structure. According to measurement methods, location identification technologies can be divided by angle of arrival (AOA), time of arrival (TOA), time difference of arrival (TDOA), and received signal strength indication (RSSI). Among these, TOA was adopted for the proposed system because it allows relatively precise measurement values in a wide range of areas. Figure 2 illustrates a cell-based topology to utilize the TOA algorithm inside a tunnel. The *x*- and *y*-axis values representing the equipment location are calculated by the times of arrival of radio-frequency (RF) signals in a cell composed of four anchor nodes and one mobile node.

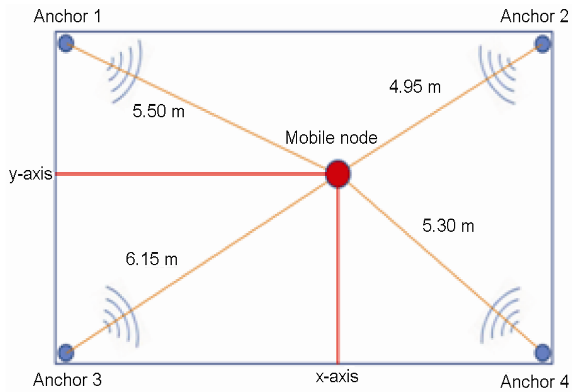

Fig. 2. Location identification measurement using TOA algorithm inside tunnel (Kim 2011)

3.2. Wireless mesh network system

A network system is necessary to transmit the location signals from the RTLS to a field office. Tunnels are usually remote from towns and pass under mountains, where installation of all means of communication, including telephone and the Internet, is quite difficult. As a result, communication problems are typical in tunnel projects and communication is intentionally minimized. However, systematic project control relies greatly on efficient communication among project participants. A wireless network system was adopted to transmit location signals, considering that tunnel projects include large, extensive construction fields and an unfavourable work environment involving blasting, rockslides, and underground water.

Examples of network technologies include wireless local area networks, Bluetooth, ZigBee, and Ultra WideBand. Specifications appropriate to tunnel projects include: a topology appropriate for a long, narrow, linear structure; durability against blasting operations; transmission distances as long as possible; low installation cost; and ability to transmit signals in real time. A wireless mesh network (WMN) was adopted as the best solution to match the specifications. A WMN is a network system made up of routers, nodes, and gateways organized in a mesh topology connecting all the terminals and relaying signals to users. Advantages of WMNs include an ability to switch routes, allowing failures in nodes, relatively low cost, and easy installation. Figure 3 illustrates the overall system architecture of a wireless mesh network installed in a tunnel project.

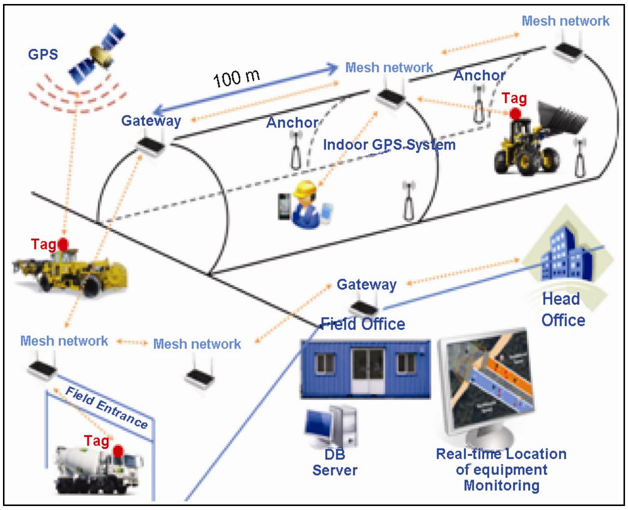

Fig. 3. Wireless mesh network system installed in a tunnel project

4. Methods to control cost and schedule data from real-time location of equipment

4.1. Operation-based information unit

To overcome limitations of the type system, an operation-based information system was designed to measure cost and schedule data. Figure 4 illustrates an example of an operational-level schedule, presenting one cycle of excavation works for a two-portal tunnel. The schedule shows that Type-I for the southbound tunnel and Type-IV-Top for the northbound tunnel were implemented as of 30 April 2010.

The dotted line in Figure 4 indicates that the load and haul operation in the southbound tunnel and the survey and mark operation in the northbound tunnel were in progress at noon. Based on the southbound tunnel schedule, project managers coordinate the northbound tunnel schedule to eliminate a bottleneck in operations. Thus, the operation-based schedule not only allows project managers to avoid operational conflicts, but also shows the actual feasibility of daily scheduling. A smoother transition might be possible depending on how the project manager plans the operational sequences and utilizes float time (for example, the prepare operation in Fig. 4). In addition, the operation-based control system shows the productivity of an operation and the efficiency of equipment usage, the fundamental data of short-term project planning.

Table 3 describes the unit costs of one cycle of Type-IV-Top. This unit cost is based on the cyclic quantities of Type-IV-Top and it can be utilized to account for cost data in the project budget. For example, when the "shotcrete clean" operation is completed (Table 2), the one-cycle unit cost (NE1102; KRW 1 492.963) of the shotcrete operation is added to the project budget. The one-cycle unit cost makes cost control possible at the operational level, because the respective types are performed by identical cyclic operations.

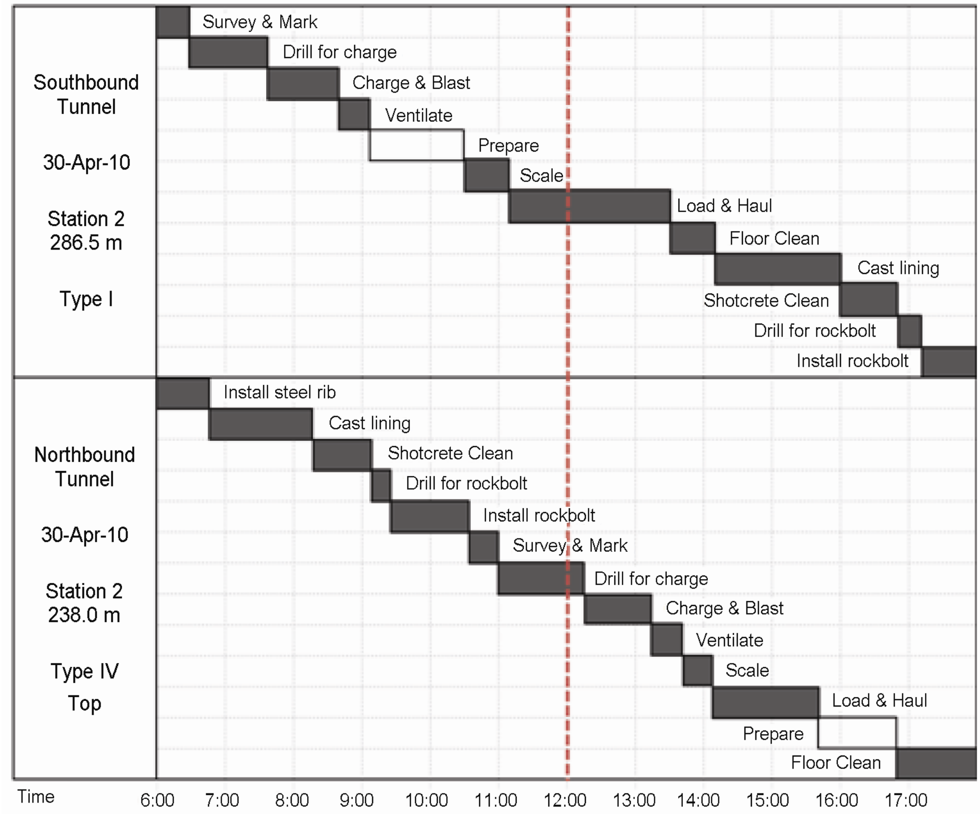

Fig. 4. An example of an operation-level schedule for concurrent Type-I and Type-IV-top operations

Table 3. One-cycle unit cost of Type-IV-Top

Code	Operatio	Unit	Cycle quantity	Unit cost (Won)			Total cost (wons)
				Materials	Labour	Equip.	
NA1613	Excavation	m^3	99.47	5,747	878	6,239	1,279,582
NA1920	Muck disposal	m^3	105.94	1,328	649	1,051	320,786
NX1304	Labour	Times	1.00		1,027,557		1,027,557
NG1154	Rock bolt (L = 4.0 m)	ea.	9.50	21,396	129	29,700	486,638
NG2111	Steel rib (50*20*30)	NR	2.33	393,580	369,186	20,739	1,825,567
NE 1102	Shotcrete	m^3	7.87	133,703	17,404	38,596	1,492,963

4.2. Conditions for cost and schedule integration

Integrated cost and schedule control can be defined as an effort to combine both kinds of information in a single controllable account. As previously mentioned, an integrated cost and schedule control system requires a great number of integrated CAs, including spatial, elemental, operational, and organizational information units. A single integrated item for a building project frequently includes physical and functional properties and sometime requires structural, architectural, and electrical properties with various levels of detail. A building project typically generates more than several thousand integrated CAs. Deng and Hung (1998) mentioned that a large number of CAs requires an increase in the labour force and heavy overhead costs. Consequently, the large number of control items and a complex data structure are the main obstacles to wide adoption of the integrated approach. Although the integrated approach provides easy access to cost and schedule control for project managers, considerable effort may still be required to acquire, track, and analyze operational data

On the other hand, an integrated CA for excavation works requires a single linear space represented as a station, no specific element, and several cost items consisting of a bundle of operations. A small number of CAs an integrated approach might be easily accomplished. Existence of eleven types and on average twelve operations means that the integrated approach to excavation works would require 132 CAs, which must be a relatively small number compared with a building project.

In addition, the integration supports smooth transitions and meaningful analysis during project execution because an integrated CA is based on the operation level. In summary, the characteristics of tunnel excavations make operational-level cost and schedule integration to be possible with a relatively small number of integrated CAs.

However, despite a small number of CAs, data acquisition, transaction, and analysis in the fields might be far from realistic, when considering the large construction field, unfavourable access, long distances from a field office to jobsites, and limited administrative staff. In this respect, we propose an Automatic Data Processing System (ADPS).

4.3. Algorithms to convert location signals to operational-level cost and schedule data

In Section 3, we described a real-time location identification system to track equipment near a tunnel face and a wireless mesh network to transmit location signals from the tunnel to a field office. The location signals of equipment are converted into operational-level cost and schedule data in the proposed system. The following algorithms are part of the proposed model:

1) A series of repetitive operations, each of which must be completed before the subsequent operation can start;
2) Respective operations are implemented by a specific set of equipment at the tunnel face;
3) The running time of an item of equipment can provide the start and end time of an operation;
4) A cost item used in BOQ can be represented by a bundle of operations;
5) A type cost can be represented by the sum of one cycle of unit costs.

Figure 5 illustrates a prototype model for the ADPS that we are proposing. The RTLS detects the locations of a shotcrete machine and ready-mix concrete truck at the southbound tunnel face (Station 818 m) and the WMN transmits the signals from the RTLS to the field office. The prototype model automatically realizes that the cast-lining operation is now in progress and the installing steel rib operation has just been completed from the signals that show a charging car is moving back (Fig. 5-A). Then, the one-cycle unit cost of the installing steel rib operation (KRW 1 825 567) described in Table 3 is included in the BOQ in the prototype model (Fig. 5-B). Next, the accumulated unit costs comprise the Type-IV-Top cycle cost (Fig. 5-C) and finally, the type-based cost is included in the project budget (Fig. 5-D). The proposed system thus enables project managers to access four levels of detail including the operation, bills of quantity, type, and project budget level; to accomplish integrated cost and schedule control; and to automate all required processes including data acquisition, tracking, and analysis.

5. Pilot project

The practicability of the proposed ADPS for integrated cost and schedule control was tested using a pilot project. The Samtan 1 tunnel is the longest tunnel (2 645 metres in the Samchuk direction and 2 619 metres in the Jeachen direction) in the Samchuk–Jeachen road construction in South Korea. The NATM tunnelling method and seven standard types were employed in the project. Total duration was 48 months for the two-portal tunnels with two-lane roads. Figure 6 illustrates the prototypical longitudinal profile of the Samchuk–Jeachen road construction and shows overall project deliverables of the pilot project.

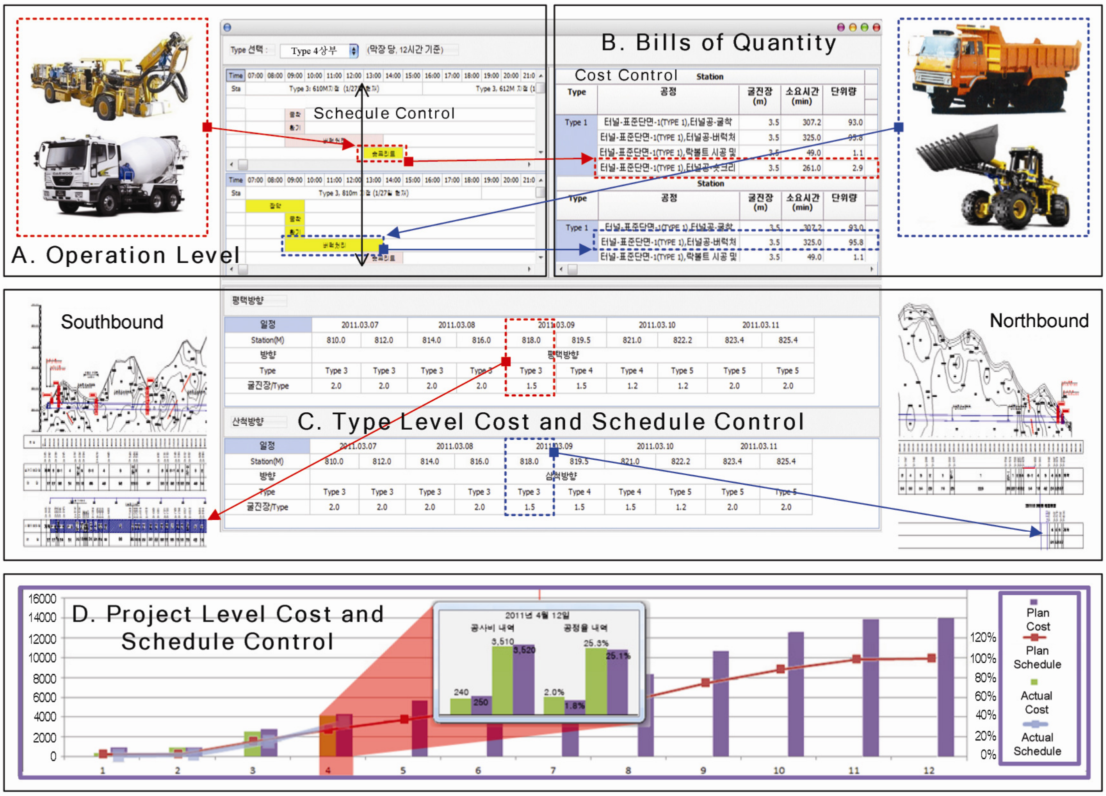

Fig. 5. A prototype model of the ADPS for integrated cost and schedule control

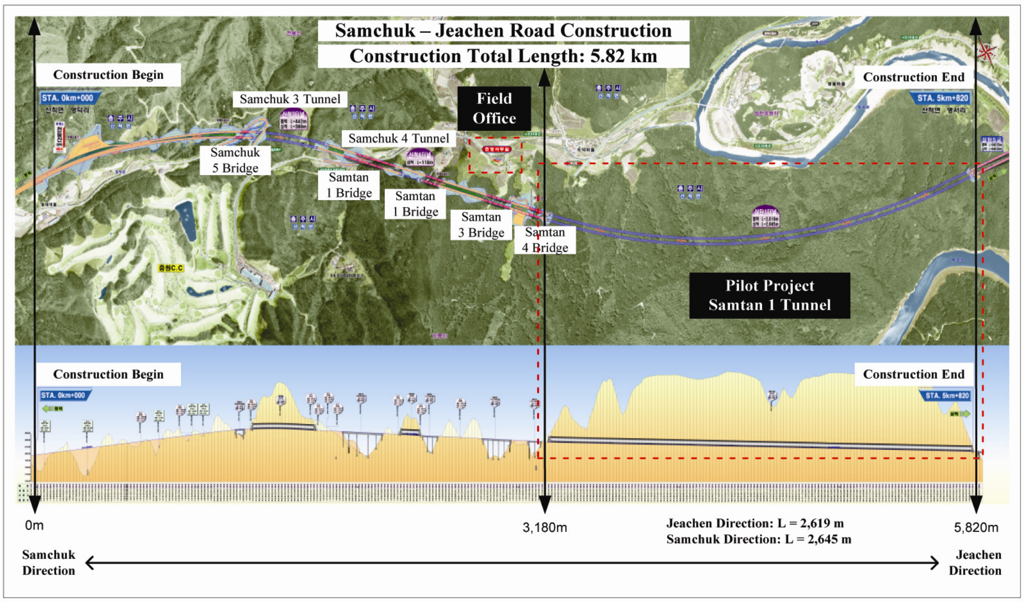

Fig. 6. Prototypical longitudinal profile of Samchuk–Jeachen Road construction

5.1. System application to tunnel fields

Figure 7 illustrates the overall system application in the pilot project. The RTLS consisted of location anchors (Fig. 7-B) installed inside the tunnel and a location tag installed in a sport utility vehicle (Fig. 7-C). Six anchors were installed at 9 metre width and 30 metre, 50 metre, and 70 metre lengths respectively, as shown in Figure 7, to minimize location errors according to longitudinal changes. The vehicle substituting for construction equipment moved within the rectangular fixed areas (section) and its movement was measured by a total station to check for errors in the RTLS. Anchor nodes were designed to transmit real-time location data 30 times per minute. Figures 7-E and 7-F illustrate the WMN installed inside and outside the tunnel at 100 metre intervals. Table 4 describes system specifications applied in the pilot project.

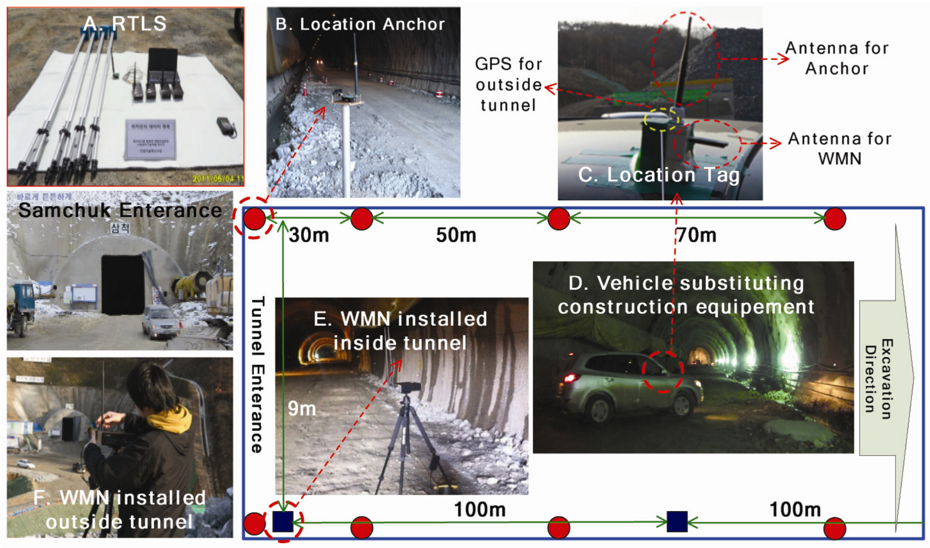

Fig. 7. Overall system application to the pilot project

Table 4. System specifications applied in the pilot project

Applied System	RTLS	Location Anchor	GPS	WMN
Model	GNC-TAG-V1	GNC-An-V1	UIGGUB02-ROO1	RouterStation Pro
Major Specifications	2.45 GHz RF Wireless LAN Embedded Linux Cortex A8 (1 GHz) Main CPU	2.45 GHz RF (ISM Band) Atmega 128L RS-232C JTAG	–160 dBM Sensitivity –160 dBM Tracking System NMEA Protocol	SuperRange 2 Network Interface Card AR7100 Network Processing Unit 100–500 m Coverage

5.2. Test results

Several rounds of testing are summarized in the following material. First, signals from the anchors in every section were detected to identify equipment locations precisely, and their errors were minimum 45 centimetres, maximum 315 centimetres, and average 150 centimetres when compared with measurements by a total station. The range of errors must be low enough to identify equipment locations in the tunnel and to regard a set of equipment at the tunnel face as an operation. Second, the range of errors is slightly impacted by longitudinal changes. A later test in a section of more than 100 metres and a test using an extended Kalman filter to reduce errors were considered to improve technical and economic feasibility.

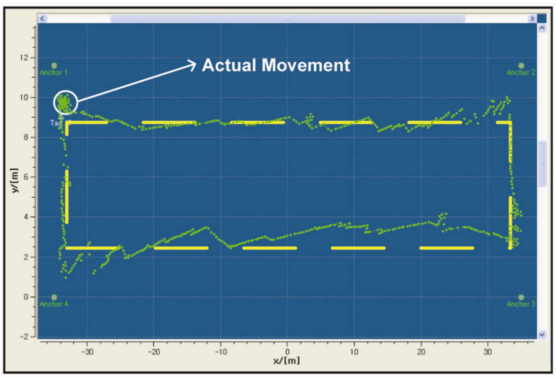

Fig. 8. Vehicle movements in the 70 metre section

Figure 8 shows the pilot test results in the 70 metre section. The dotted line indicates the planned movements and the staggered line shows the actual movements of the vehicle location tag in the narrow-width tunnel and at the unfavourable ground conditions.

Conclusions

The purpose of cost and schedule control can be defined as the optimization of the resources required by tunnel projects: large amounts of material, labour, and equipment for long periods. Thus, cost and schedule control must be realistic and must reflect all the restrictions that are imposed on the project (Department of Transportation 2009). Based on the analysis of characteristics of NATM tunnel excavation works, this study raises several limitations of the type system: the level of control is too broad; cost and schedule data are too distributed; management is ad hoc; and it is difficult to derive a meaningful database. The type system relies on a project manager's experience, knowledge, and intuition, rather than quantitative analysis of field data. This study emphasizes the necessity of operational-level cost and schedule integration and control. While an integrated approach might contribute greatly to the overall enhancement of project management (Jung, Gibson 1999), it requires considerable overhead effort to acquire, track, and analyze data in the project execution phase. Based on the motivation that the overhead effort has been the main cause of resistance to adopting the integrated approach, we have proposed an ADPS for cost and schedule integration.

The proposed system is composed of an RTLS, a WMN, and a prototype model for integrated cost and schedule control. The RTLS has location tags installed in construction equipment and location anchors calculating the relative position of a tag within a section. From the signals transmitted by the WMN, the prototype model identifies equipment locations in tunnels and converts the location signals into integrated cost and schedule data through the inherent algorithms. Based on the operational level of an integrated Control Account (CA) having cost and schedule values, the prototype model provides various levels of integrated control, i.e. operation, BOQ, type, and project budget level.

Effect of IT convergence using sensor technologies has been limited in the construction industry. This study introduces novel uses of sensor technologies to facilitate cost and schedule control. The proposed system can reduce the considerable overhead effort of implementing cost and schedule integration through automating data processes and reducing the required number of integrated CAs. The integrated approach using sensor technologies thus offers project managers easy access to operational-level cost and schedule control, smooth transitions, productivity analysis, and improved equipment efficiency. In addition, the operational-level database allows efficient construction planning and management considering field characteristics. Technical and economic feasibility studies to install RTLSs and WMNs in construction sites, extension of the application range to whole tunnel projects, and quantitative measurements of advantages of the proposed system remain future study areas. We expect that the algorithms proposed by the study will become a capstone to an approach to more systematic construction management.

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