ELSEVIER

Automation in Construction 12 (2003) 447–461

AUTOMATION IN CONSTRUCTION

www.elsevier.com/locate/autcon

Automatic schedule integration for highway projects

Ren-Jye Dzeng*, Wei-Chih Wang

Department of Civil Engineering, National Chiao Tung University, 1001 Ta-Hsueh Road, Hsin-Chu 300, Taiwan

Abstract

The construction of a highway/expressway, which involves a complex combination of roads, bridges, and tunnels, is generally separated into several projects. Various contractors thus execute different projects and often apply differing scheduling practices. Since all projects involved in highway construction must be completed for the highway to be useful, the management of the various projects should preferably be integrated. To assist project controllers in schedule integration, this study proposes algorithms based on standardized codes and network modules. A computer system was also designed to help contractors use these modules for scheduling, and ultimately to let project controllers combine these schedules electronically. A questionnaire survey and industry feedback revealed the potential benefits of using the proposed algorithms for generating and integrating schedules, respectively. Contractors' computation capabilities must be improved before the proposed scheduling algorithms can be fully implemented.

Keywords: Infrastructure management; Construction scheduling; Schedule integration; Standardization; Modularization

1. Introduction

The construction of a highway/expressway (both terms are interchangeable herein), which includes roads, bridges, and tunnels, is generally perceived to be a linear or repetitive project [1–3]. Such a project is frequently divided into several smaller projects based on factors such as location, the relation between project size and contractor capabilities, balance between soil excavation and filling, and budget and time constraints. Each project is awarded separately to an individual contractor, and thus the expressway is completed by several contractors simultaneously working on very similar work at different geographic locations. However, overall control of the construction of the expressway is still required, because the expressway can only operate once all projects are completed, and because a single project controller will eventually manage the expressway.

For the project controller it is better to manage the project schedules in an integrated fashion, namely by using a master schedule. Unfortunately, current Taiwanese practice is for each contractor to employ his own scheduling practice with different activity names, levels of detail and scheduling software packages. Integrated scheduling data is currently time-consuming for the project controller to gather since it must be gathered from each contractor individually. Computerized integration of the individual schedule files can only generate a "large mess" master schedule that is difficult to interpret. Also, these integrated

* Corresponding author. Tel.: +886-35733529; fax: +886-35716257.

E-mail addresses: rjdzeng@faculty.nctu.edu.tw (R.-J. Dzeng), weichih@mail.nctu.edu.tw (W.-C. Wang).

0926-5805/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0926-5805(03)00017-7

data are likely to inaccurately represent the overall project status because the individual data for each project are not uniformly defined. Furthermore, since the manipulated master schedule indicates only one level of the milestone schedule, the project controller is unable to precisely examine other schedule levels for other scheduling purposes. Restated, current practices make it time-consuming to collect information to facilitate overall expressway construction schedule management, and mean that the information gathered is often inaccurate. A well-integrated construction schedule for a highway is essential both to meeting the publicly announced project completion date, and facilitating government budgeting (namely by accurately predicting future cash flows).

Among current scheduling techniques (e.g. bar chart, line of balance, resource allocation and leveling, network analysis, and simulation) [4], several linear scheduling models have been designed to improve the popular critical path method (CPM) network models that may be inappropriate for construction projects with a linear or repetitive nature (such as highways, tunnels, and high-rise buildings) [1–3,5]. Unfortunately, commentators have considered these linear scheduling models to be graphical techniques that are less easily adaptable to computerization than CPM network models [2,5]. Many artificial intelligence planners, such as BUILDER [6], CONSCHED [7] and HISCHED [8], have been created for schedule generation, and have mostly been applied to multistory building and plant construction. Echeverry [9] attempted to identify and formalize key factors for generating construction schedules for mid-rise building projects. CasePlan is a planning technique that stores project schedules with multiple indexes, based on similar cases that can be used as references in creating a new schedule [10]. Overall, few investigations have addressed the problems of schedule integration for highway projects.

To coordinate the schedule of an expressway project, uniform activity standards (such as coding and work breakdown structure) and appropriate algorithms must first be developed to generate all project schedules. This work presents the extended results over 3 years of implementing a standardization and network modularization approach to facilitate the generation and integration of expressway project construction schedules. The following section describes current highway scheduling practice in Taiwan, and is followed by an illustration of the mappings of highway construction to module-based schedules. Next, module development is presented, after which the schedule generation and integration algorithms are illustrated. Then, industrial questionnaires and expert feedback are used to verify the potential benefits of the proposed algorithms. Finally, experiences learned from conducting this work are discussed.

2. Project scheduling practice in TANEEB

In Taiwan, the Taiwan Area National Expressway Engineering Bureau (TANEEB), an infrastructure public construction agency, is mainly responsible for the management of newly developed national expressways. TANEEB executed expressway projects worth approximately $US16,940 million dollars in the 2001 fiscal year. Numerous general contractors, ranging in number from 17 to 68, were involved in each major project. Most projects involve the construction of roads and bridges, with or without tunnels. Generally, influences on the determination of the number of projects involved in expressway construction include:

- Distributed geographic locations (such as counties). Each county in Taiwan is a municipal district with its own construction regulations. Consequently, it may be preferable to split a project that crosses two counties into two smaller projects, each of which only needs to follow the regulations enforced by one county.
- Scale of project size. The practical and financial capabilities of prospective contractors must be considered. Very few contractors are able to construct an entire expressway.
- Balance between excavation and soil filling. Excavated soils may be dumped into another area that requires filling to avoid the environmental problems. Projects with a scope that is adequate meet such a balance are preferred.
- Available governmental budget. Budgetary limitations may force certain aspects of a project to be set aside for future completion.
- Time constraints. Dividing the project into multiple smaller projects help to meet the completion date

since the various smaller projects can be executed concurrently.

Final decisions are made after trading off the impact of these factors. Also, despite the similar work applied, respectively, in each project, the contractors break down work differently, name activities differently, and include different levels of detail in their schedules. No unified set of construction activity names and codes exists. Contractors of TANEEB projects are required to submit schedules that are presented as a CPM network and in electronic form. CPM is the most widespread scheduling method for construction projects in Taiwan. However, because of the lack of competence with CPM scheduling software, submitted schedules are often filled with errors and do not always reflect actual plans. For example, many contractors do not include associated pay items under each activity, but the project controller typically requires the inclusion of such items so that earned value can be calculated based on actual work progress. Thus, extensive written or verbal verification is often required before a schedule is finally approved.

Because all projects must be completed before an expressway becomes usable, it is better to manage the projects in an integrated way. However, current scheduling practice, which lacks a consistent system of naming and coding activities among all contractors, not only leads to poor communication among all parties involved in a project, but also impedes automated schedule integration. Consequently, to achieve schedule integration, TANEEB project controllers must contact each contractor individually to gather progress information on various construction milestones. This data collection process is rather time-consuming because milestone activities are not defined consistently among different schedules. For example, a milestone activity is often an inherent part

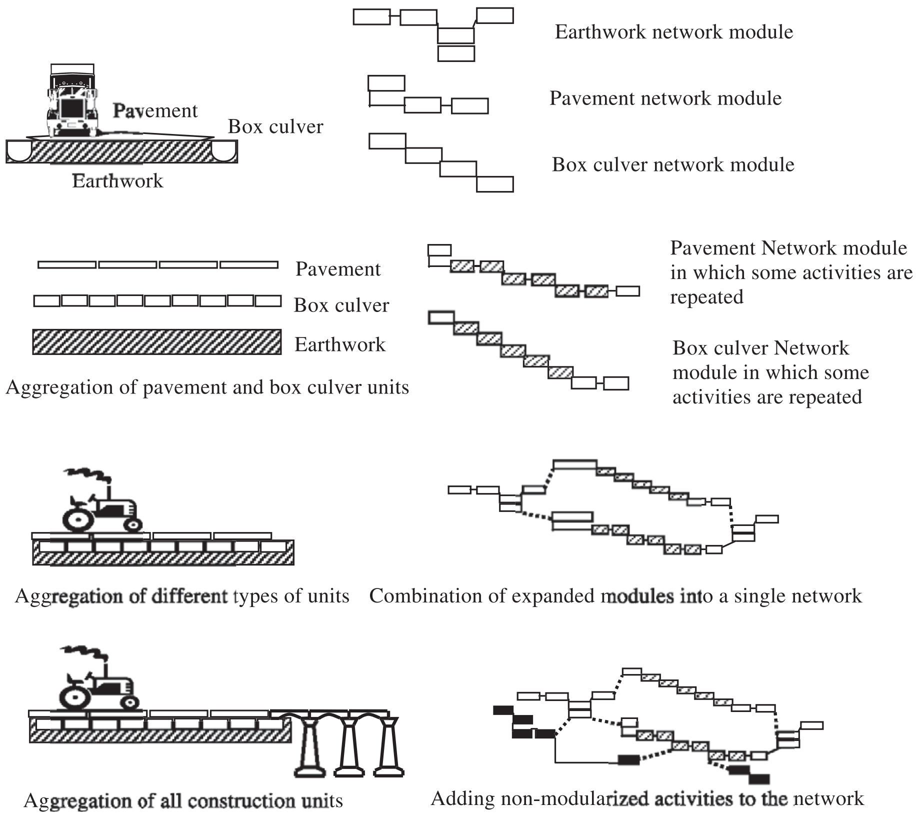


Fig. 1. Mapping of road construction to network modules.

Table 1
Data hierarchy in a module

Data objects and attributes	Data type: Essential	Data type: Supporting	Description
Module			
code	■		Identifying the module
name	■		Describing the module
section-code		■	Identifying the code, name, and direction of the associated
section-name		■	construction unit of the module
lane-direction		■	
recurring-times		■	(explained in text)
Activities			
code	■		Representing the class of activity under the proposed WBS
name	■		Standard name for the activity
type	■		i.e., normal, repetitive, cyclic, or merging
duration	■		Typical duration
counter		■	Uniquely identifying each activity in the same class to allow commercial scheduling tools to read the schedule
cycle-times		■	(explained in text)
duration-reference		■	Including formulas, factors, or relevant information for estimating duration
Sub-Activities			(attributes omitted)
Sub-Links			(attributes omitted)
Links			
id	■		For computer's internal use
predecessor-id	■		Identifying the activity at the left-hand side of the link
successor-id	■		Identifying the activity at the right-hand side of the link
type	■		i.e., start–start, start–finish, finish–start, or finish–finish
lead-time	■		e.g., required sediment duration following a backfill activity
Pay-Items			
code	■		Uniquely identifying the class of pay item
name	■		Describing the pay item
contract-no	■		Associating a pay item to a contract
unit	■		Measuring the quantity of the pay item, e.g., tons
quantity	■		Amount of the pay item

of an activity for one schedule and yet has a different activity name for another schedule. After conducting this data collection process for each project, the controller then enters the collected data into an "integrated" schedule (called a master schedule). To minimize data entry requirements, the master schedule only includes milestone data. This integration practice requires considerable experience-based human interpretation of collected data, and since the definitions of milestones vary among projects and are not always clear, the data provided by the contractor is generally only an approximation. Consequently, the master schedule based on these rough data tends to be inaccurate; it cannot represent the progress of individual activities, nor can it be abstracted into a summary schedule.

3. Mapping to module-based schedules

Our research has found that activity standardization combined with a module-based approach could achieve efficient schedule integration [11]. Activity standardization involves standardizing names and codes for construction activities and pay items (i.e., payments to contractors). These standardized names and codes can then provide a foundation for establishing network modules as a basis for the schedule network of a project. Module-based schedules that use the same names and codes for several projects can then be combined into a single schedule to represent overall progress on expressway construction.

Fig. 1 displays the use of evolutionary mappings of construction units to network modules for developing the project schedule for a road project. In this figure, each piece of project work can be broken down into a series of construction units. That is, a road involves earthwork, pavement, and box culver units. (The examples for bridge and tunnel projects can be found in Dzeng [11].) Each kind of construction unit is associated with at least one network module that describes how the unit can be constructed. Meanwhile, by duplicating or expanding certain internal activities, each network module can also describe how multiple units of the same kind are constructed. Schedules for projects involving multiple types of units can be established by combining the activities from different expanded modules. Creating a complete schedule generally requires adding certain non-modularized activities, such as mobilization, and utilities reallocation specific to individual projects.

4. Development of network modules

The following sections describe the establishment of network modules for highway projects at TANEEB.

4.1. Content of module

Table 1 presents the content of a module in a hierarchical fashion. Each module has attributes such as code, name and section-code. Each one contains data objects such as activities, links and pay items. An activity has attributes such as name and duration and includes sub-activities and sub-links. These attributes are essential or supporting data. Essential data are

Table 2
Standardized data for advance shoring method module of bridge construction

Activity			Major pay items			Sub-activities
Code	Name	Duration reference	Code	Name	Unit	
DB60	Preparation	Depending on the scale of the work				Design, purchase, submittal, site work, materials move-in, access, labor move-in
DB61	Wagon assembly	Ranging from 30 to 75 days				Assembly of Large-Scaled Hanging System Forms (LHSF), installation of LHSF
DB62	Box girder cast in place	Each cycle taking about 14 days except for the first cycle, which takes longer	01118.1000	Pre-stressed Concrete (Advancing Shoring Method), 350 kg/cm^2	m^3	Box girder/T girder cast in place diaphragm and Lead Rubber Bearing (LRB)
DB63	Approach slab	Ranging from 12 to 21 days	00310.1000	Backfill	m^3	Back-wall filling
			01102.0050	Concrete, 240 kg/cm^2	m^3	Utilities
			01102.0540	Forms	m^2	Formwork Assembly
			01401.1010	Deformed Bars, fy = 4200 kg/cm^3	ton	Reinforcement erecting, concrete placing
DB64	Barrier railing	Ranging from 50 to 100 m/day	01505.0000	Guard rail	m	Barrier railing
DB65	Asphalt concrete pavement	Ranging from 500 to 600 m^2/day	01002.1000	Dense graded asphalt concrete	m^3	Asphalt concrete pavement, concrete pavement
			01002.2000	Open graded asphalt concrete	m^3	
DB66	Expansion joint	Finger type: ranging from 16 to 30 m for each 15 days; modular type: 3 m/day; angle type: 2 m/day	01108.0000	Bridge expansion joint	m	Saw cutting, expansion joint assembling, nonshrink concrete placing, curing, rubber material filling
DB67	Traffic signage	Depending on the length of the work	01501.0000	Signs	units	Traffic signage
			01502.0000	Markings	m^2	
			01503.0000	Pavement markers	units	
			01504.0000	Delineator	units	
			01506.0000	Fencing	m	
			01507.0000	Glare screen	units	

those required to represent the substantial content of a network schedule, and they may or may not be standardized. Examples of essential data include the code, name, and duration for an activity; the id, predecessor-id, and successor-id for a link; and the code, name, unit, and quantity for a pay item. Section 6 depicts issues of standardization. Supporting data are those used to facilitate the automated generation of a schedule. Examples include data that describe the location of the construction unit associated with the module; such data include section-code, section-name and lane-direction. Table 1 presents the types of data (essential or supporting), describing each data object and attribute.

Table 2 shows an example of standardized data for the advanced shoring method module of bridge construction. The inclusion of major pay items under each activity in the table encourages contractors to complete the entries about the pay items simply by adding situation-based items. The included sub-activities describe the activity at a level of detail favored by contractors, more detailed than that required by project controllers. Standard codes are included in the activity so as to avoid human subjectivity following encoding.

Table 3 lists activity codes in an extended standard format. The codes include 12 digits, the first nine of which have designated meanings, and the final three of which are for use by contractors. The code is followed by a parenthetical description that provides explanations or examples. The code is arranged by considering activities from large to small and from general to specific. An example activity code, "DDNB62004", is given at the bottom of Table 3. Notably, the activity code in Table 2 is only in the basic standard format, while that in Table 3 is in the extended standard format, which is project-specific.

4.2. Types of activities

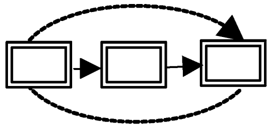
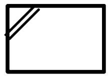
Activities in a module can be normal, repetitive, cyclic or merging. Table 4 lists definitions and legends associated with these different types of activities. For example, the activity "box girder segment" is repetitive. When the balanced cantilever method is adopted, the box girder segments are erected and extended one by one. Accordingly, the schedule includes repetitive box girder segment activities. In Fig. 2, activities "excavation", "bottom slab construction", and "side wall and top construction" performed in constructing a road are cyclic, and together form a cycle, as indicated by a circular dashed arrow. That is, the box culvert involves the execution of "preparation", several cycles of "excavation", "bottom slab construction", and "side wall and top construction", followed by "wing wall construction" and "backfilling". The activity "backfilling" in Fig. 2 is a

Table 3
Extended standard codes of activity

Phase (1)	Section (2)	Direction (3)	Project work (4)	Module (5)	Activity class (6)	Activity counter (7, 8, 9)	Remark (10, 11, 12)
A (Plan) B (Design) C (Land acquisition) D (Construction)	0–9; A–z	X (Null) N (North) S (South) E (East) W (West)	A (Road) B (Bridge) C (Tunnel)	0–9; A–z	0–9; A–z	001–999	optionally used by contractors
Example for an activity code							
D	D	N	B	6	2	004	
a construction activity	located in "Dashu County Overpass 170–175 km"	north direction	for a bridge project	of the 6th module, "advance shoring method"	of the 2nd activity class, "box girder cast in place"	the 4th activity of this class	

Columns (1), (4), (5), and (6) are standard or basic codes. Columns (7), (8), and (9) are determined according to the input sequence of activity. Columns (2) and (3) must supply values to identify the section names and direction of work on the expressway.

Table 4
Definitions of activity types

Activity types	Definition	Legend
Normal	The work that is performed as a single continuous process when the module is used.	
Repetitive	The work that is performed discretely, either section-by-section or unit-by-unit. The number of repetitions is specified by the value of the *recurring times* variable of the module.	
Cyclic	The work that is discretely (section by section or unit by unit) performed along with other *cyclic* activities as a cycle. The number of cycles is defined by the *recurring times* attribute.	
Merging	The work required by several modules but typically performed as a whole and represented as a single activity.	

merging activity. Therefore, even if the box culvert module is applied many times, the contractor may perform most the activities therein separately and independently, while treating backfilling as a single continuous activity. Dzeng [11] provided typical examples of different types of activities. The main benefit of distinguishing various types of activities in a module is to support the automated duplication and expansion of modules when generating a new schedule.

4.3. Duplication and expansion of modules

Establishing a schedule generally requires the duplication and/or expansion of modules. Duplication involves using a module repeatedly. Meanwhile, expansion describes the recurrence or repetition of some module activities for a certain number of times, as specified by the *recurring times* attribute. Figs. 3–6 describe *normal*, *repetitive*, *cyclic*, and *merging* activities under either duplicating or expanding situations. In the figures, "R" represents a repetitive activity, "C" a *cyclic* activity, "M" a *merging* activity, and the other letters *normal* activities.

Fig. 3 illustrates a situation in which a module involving a *repetitive* activity is used twice but does not recur. All activities, including the *repetitive* activity, are duplicated once. Fig. 4 shows a situation in which a module with a *repetitive* activity is used once and recurs n times. The *repetitive* activity is performed n times sequentially. Meanwhile, Fig. 5 displays a situation in which a module with a group of *cyclic* activities (C1, C2, and C3) is used once and recurs n times. The group cycles n times sequentially and its activity relationships remain unchanged. Finally, Fig. 6 presents a situation in which a module with a *merging* activity is used n times but does not recur. All activities except for M are performed n times, and

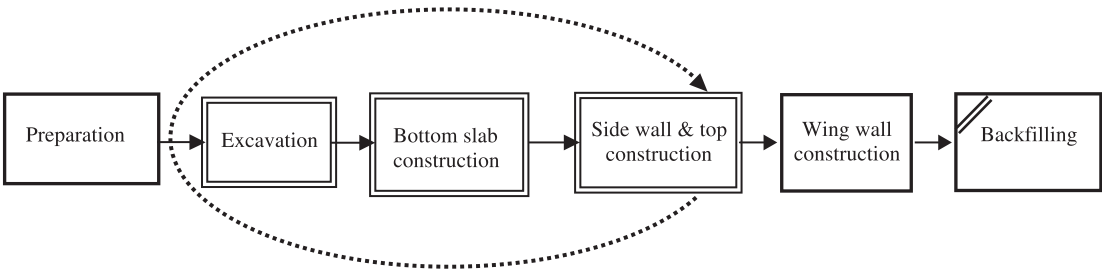


Fig. 2. The box culvert module for road construction.

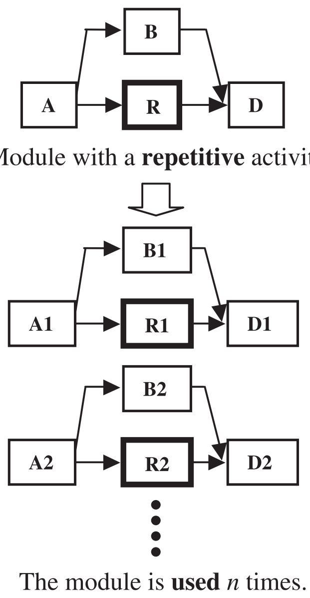


Fig. 3. Duplicating a module with normal and repetitive activities.

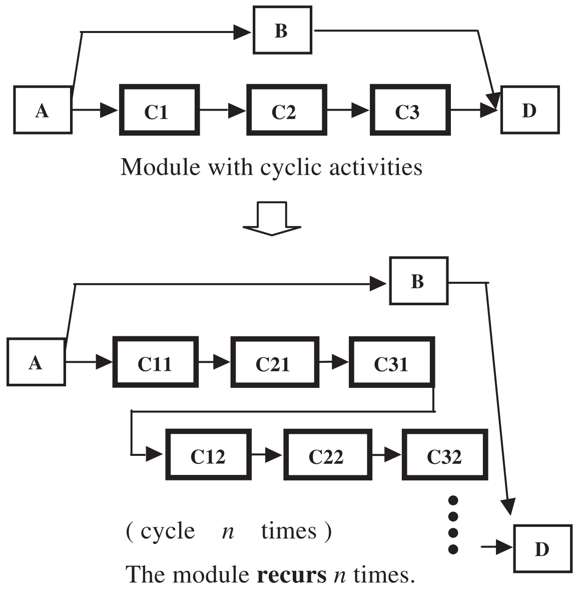


Fig. 5. Expanding a module with cyclic activities.

the precedence relationships with activity M persist after the activity duplication.

4.4. Work breakdown structure

Current practice for TANEEB projects does not involve a unified work breakdown structure (WBS). However, it is difficult for users to efficiently select appropriate modules if the modules are not properly organized. Thus this work designs a new WBS by breaking the expressway construction into components, and then organizing the modules according to these components (see Table 5). That is, the first layer of WBS denotes the type of construction (including road, bridge, and tunnel). Within each type of construction, the proposed WBS makes the second layer

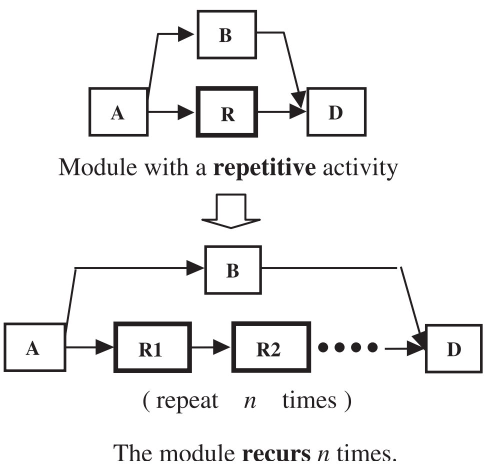


Fig. 4. Expanding a module with a repetitive activity.

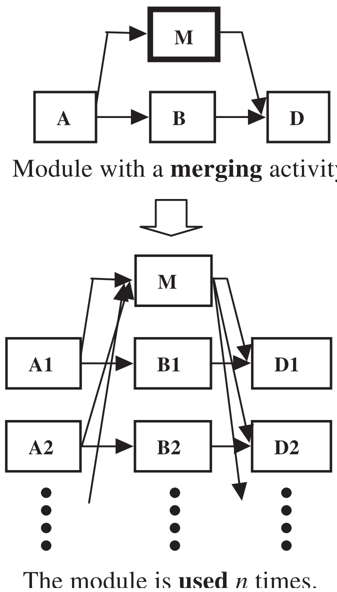


Fig. 6. Duplicating a module with a merging activity.

Table 5
Summary of developed modules by proposed work breakdown structure

Construction type	Module		No. of activities	No. of sub-activities	No. of major pay items
Road	Earthwork		5	22	12
	Pavement	Asphalt concrete	5	11	14
		Cement concrete	5	11	11
	Box culvert		6	25	17
Bridge	Superstructure	Pre-cast I-Beam (PCI) method	8	27	14
		Advance shoring method	7	25	15
		Incremental launching method	8	37	20
		Steel box girder method	10	30	22
		In situ shoring method	7	26	14
		Span-by-span erection method	7	24	15
		Balanced cantilever method	10	58	21
	Abutment	Spill-through abutment	5	35	18
		Cantilever	5	27	14
		Footing-foundation abutment	5	35	16
	Pier	Full casing pile	4	36	10
		Reverse circulation pile	4	35	9
		Caisson foundation	3	35	9
		Drilled-shaft foundation	3	31	9
		Pre-stressed concrete pile	4	47	9
	Excavation	New Austrian Tunneling Method (NATM)	10	41	70
		Tunnel Boring Method (TBM)	14	23	27
Tunnel	Portal construction		8	11	34
	Cross connection construction		6	11	19
	Shaft method		7	12	17

the module. For example, road construction comprises Earthwork, Asphalt Concrete Pavement, Cement Concrete Pavement, and Box Culvert modules. In each module, activities and sub-activities are provided in the third and fourth layers, respectively.

4.5. Constructed modules

Module development involved determining WBS, standard codes, and network representation (including the level of detail, activities and their relationships, and major associated pay items). The initial network modules were constructed based on a literature review, and existing schedules that were gathered from selected contractors of TANEEB projects. Meanwhile, the modules were discussed, revised, and finalized through interviews with experienced schedulers and formal meetings with representatives of the owner, A/E, contractors, and scheduling software companies [11]. For flexibility, the modules developed here are not intended to include all activities involved in expressway construction, and only modules with frequent and repetitive activities that are relatively constant among projects are covered. Table 5 also summarizes the developed modules for TANEEB. Dzeng [11] provides details for each module.

4.6. Interlinks between modules

Embedded precedence links between standard activities are provided within each network module to increase module reuse efficiency. Although users may change the links as desired, test experience demonstrates that such changes are only needed occasionally (because of the similarity of work). A schedule for a project with different types of construction units can be established by connecting the activities of different expanded modules. Such connection links (namely, links between modules) are termed module interlinks (shown by the dashed link in Fig. 1). Notably, a complete schedule typically includes some non-modularized activities. This connecting process can easily be conducted using existing scheduling software.

5. Schedule generation

The proposed schedule generation algorithms were implemented using Microsoft Visual Basic for Applications and Access 2000. Fig. 7 presents the procedural steps involved in generating a schedule for an expressway project. These steps are divided into three parts, namely, Module Library Management System (MLMS), Modularized Schedule Builder System (MSBS), and Conversion to Commercial Schedule (CCS). The MLMS provides the system user with a graphical interface for establishing a library of network modules. The primary functions of MLMS include creating new modules, deleting existing modules, and editing existing modules. MSBS provides users with a graphical interface for selecting and editing modules that are built by MLMS, and then using them to generate a basic schedule. After a basic schedule is created by the MSBS, the CCS allows users to save the schedule data in formats readable by MicroSoft Project, OpenPlan, and Primavera Project Planner. Restated, a commercial schedule file is generated for manipulation at this stage.

6. Schedule integration

Standardization and modularization are crucial for efficient communication and data integration. Fig. 8

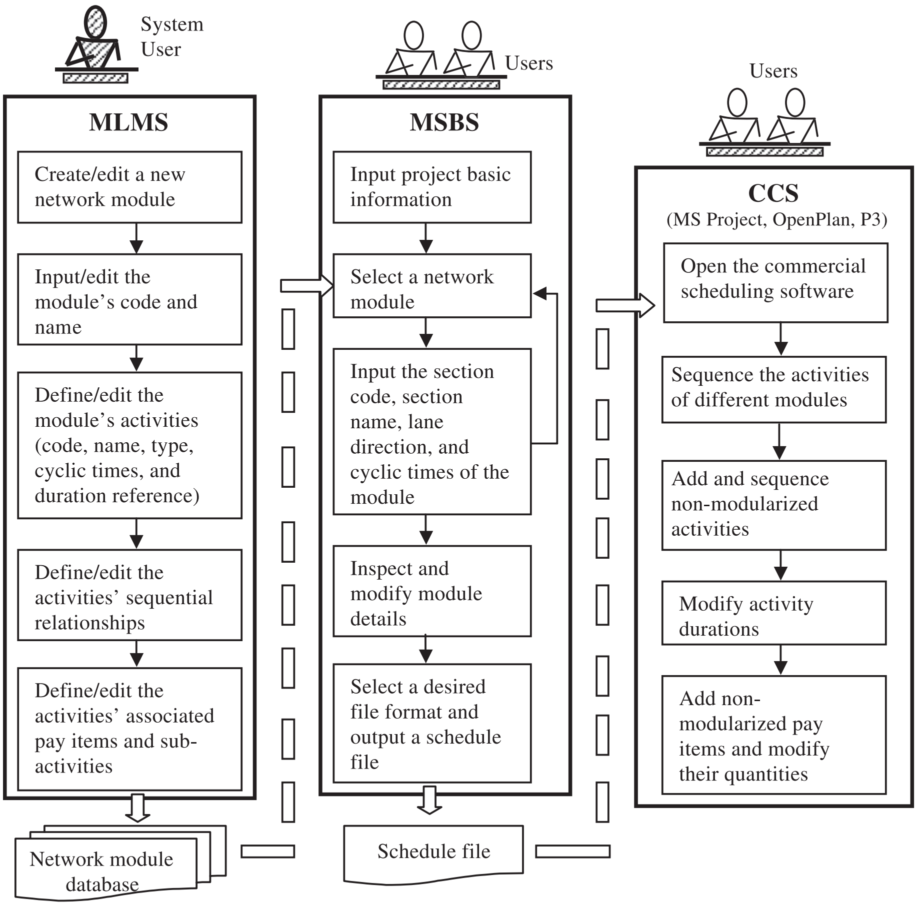


Fig. 7. Procedural steps for schedule generation.

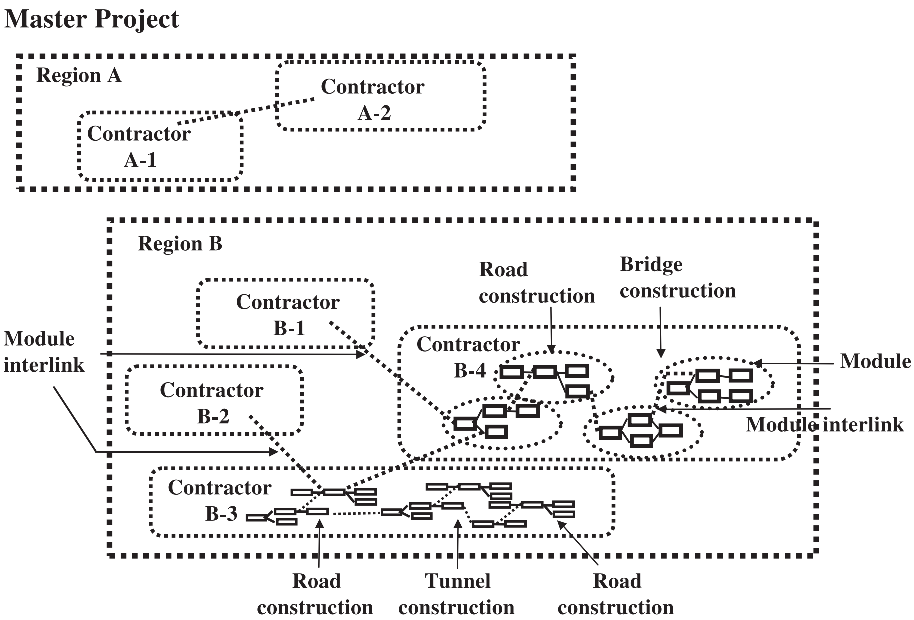


Fig. 8. Example of a master schedule integrated by six projects.

displays an example of a master schedule for an expressway construction project that spans two geographic regions (A and B). The large size of the contract is such that the contracts covering regions A and B are awarded to two (A-1 and A-2) and four (B-1, B-2, B-3, and A-4) contractors, respectively. Each contract may cover various types of construction work, including the building of roads, bridges and tunnels (as in B-3 and B-4). Each contractor must submit his schedule at the activity level of detail (level three in Table 5) required by the TANEEB project controller. However, the contractor requires a more detailed (sub-activity level in Table 5) schedule for his own management purposes. The reusable modules can help the contractor achieve both purposes. Each schedule is generated from selected modules (indicated by dashed ovals) and selected interlinks (shown by dashed straight lines) between the modules.

During schedule integration, the TANEEB controller electronically combines the individual schedules submitted by the six contractors into a master schedule. These individual schedules are connected by shared milestone activities. That is, the interlinks are used to connect these milestone activities across the various schedules. Typical milestone activities include completion of land requisition, notice to proceed, mobilization, completion of auxiliary buildings, completion of toll plaza, completion of bridge piers, completion of bridge columns and opening of highway to the public. These shared milestone activities are also called interface activities. Since each of these individual schedules is described at different levels of detail including activity codes and pay item codes, the integrated master schedule can be abstracted into a summary schedule or explicated in great detail, according to management objectives. Information on the distribution of pay items among activities (the payment schedule) can also be derived.

Although standardization is the key to schedule integration for project controllers, contractor flexibility should be provided if the proposed algorithms are to be practically useful. Restated, integration need not be absolute, and only some data must be standardized. Tables 6 and 7 summarize the various degrees of standardization of data objects and attributes within each module and across projects, respectively, as established by the proposed integration algorithms. In these tables, “Rigid” implies that the data object (or attribute) must be expressed in a particular standard form to meet the requirements of the project controllers. Meanwhile, “Flexible” represents that although a standard form is provided for the data

Table 6
Standardization degrees of data objects and attributes within each module

Level	Name	Code	Predecessor	Successor	Example
Module	Flexible	Flexible			"Earthwork" module with code "M001"
Module interlink			N/P	N/P	"Excavation" (of the earthwork module) precedes "Sub-base Aggregate" (of the asphalt concrete pavement module)
Activity	Flexible	Rigid			"Excavation" activity with code "DA01"
Activity link			Flexible	Flexible	"Preparation" (of the asphalt concrete pavement module) precedes "Sub-base Aggregate"
Pay item	Flexible	Rigid			"Concrete, 240 kg/cm^2" pay item with code "01102.0050"
Sub-activity	Flexible	Flexible			"Formwork assembly" sub-activity with code "S0215"
Sub-activity details	N/P	N/P			

N/P: not provided.

object (or attribute), compliance with this form is not required, and so contractors can customize those data objects (or attributes). Finally, "Not provided" indicates that no standard form of the data object (or attribute) exists because the project controllers do not require information about that data object (or attribute).

More specifically, in Table 6, a module includes the names and codes of sub-activities, but does not include details like resources because the controller does not require such a detailed schedule. A module defines the precedence links between activities, but contractors can adjust these links without affecting compliance with the system used by the controller. Pay item and activity codes require confirmation while their names do not, although communication is better when conformation is provided. Interlinks are not provided between the activities of different modules owing to their versatility. Both the names and codes of the modules are provided, but can be modified without influencing compliance with the system of the project controller. In Table 7, schedule data must be integrated horizontally across different construction types and projects. This integration is achieved by rigid compliance with the codes of activities and pay items. The modules supply the names of activities and pay items, as well as the precedence relationships between the activities, and all of these data attributes can be modified without affecting the schedule integration, although compliance with the system requirements helps horizontal communications.

Table 7
Standardization degrees of data attributes across projects

Level	Activity name	Activity code	Activity link	Pay item name	Pay item code
Project	Flexible	Rigid	Flexible	Flexible	Rigid
Construction type	Flexible	Rigid	Flexible	Flexible	Rigid

7. Industry feedback

Since the contractors of TANEEB projects are not currently required to use the proposed algorithms, it is impossible to validate this work of schedule generation and integration using an actual case study. A questionnaire was thus conducted to test the efficiency of the implementation of the module applications in creating new expressway project schedules. The questionnaire included 97 participants in a series of training courses, and collected and analyzed their comments regarding the proposed algorithms and computer system [11]. The participants mainly comprised TANEEB managers and engineers, A/E schedule reviewers, and the schedulers of contractors. The survey response rate was around 75.8% (72 out of 97). The questionnaire was aimed to determine the expected time saving and error reduction achieved by the use of each of the primary features of the system, including, (A) automatically creating activities with standard codes; (B) automatically creating activities with names to specify activity class, location, lane direction, and counter; (C) automatically repeating, cycling, and merging activities; (D) automatically defining activity relationships within each module; (E) providing data which can be used to estimate activity duration; (F) defining contractor sub-activities; (G) automatically creating associated standard codes, names, and units for major pay items for activities; and (H) using the NBA system over all. Fig. 9 displays the testing results. The three features that were expected to save the most time in schedule generation were: feature (C), with 41.4%; feature (B), with 39.2%; and feature (G), with 38%. These features focus on tasks that require significant data entry, duplication, and editing. The three features that were expected to achieve the highest error reductions in schedule generation were: feature (A), with 41%; feature (G), with 38.8%; and feature (B), with 36.8%.

The proposed schedule integration algorithms were demonstrated to two controllers managing schedule administration for TANEEB. The demonstration aimed to ask these experts to critically review the validity of the integration algorithms, their potential practicality, and further research for professional implementations. Overall reviews indicated that the novel algorithms were superior to the current practice at TANEEB in terms of efficiency (i.e., faster production of an integrated schedule), and accuracy (i.e., less errors when using automatically generated standardized data and clear distinction among different levels of schedule data). However, it was argued that most Taiwanese contractors had inadequate information technology (IT), meaning that the proposed scheduling algorithms will be impossible to implement on a full scale with current Taiwanese practice. Consequently, the computational capabilities of contractors will have to be enhanced before the algorithms can be usefully implemented.

8. Experience gained from this study

The following was learned during the development of network modules.

- Regarding activity coding issues, a consensus on the scheme (meaning the information that to be included in the code, and how the digits should represent this information) for standard codes was easily reached. Consensus on the level of detail to be used was more difficult to secure since those involved had different needs. The needs of parties (owner's controllers, A/E, and contractors) differed because of their differing management practices. For example, some contractors tend to prefer to allow those in charge of a project to handle the details, and thus would prefer a system with minimal detail (since rough detail suffices for management) to be included in the codes, while

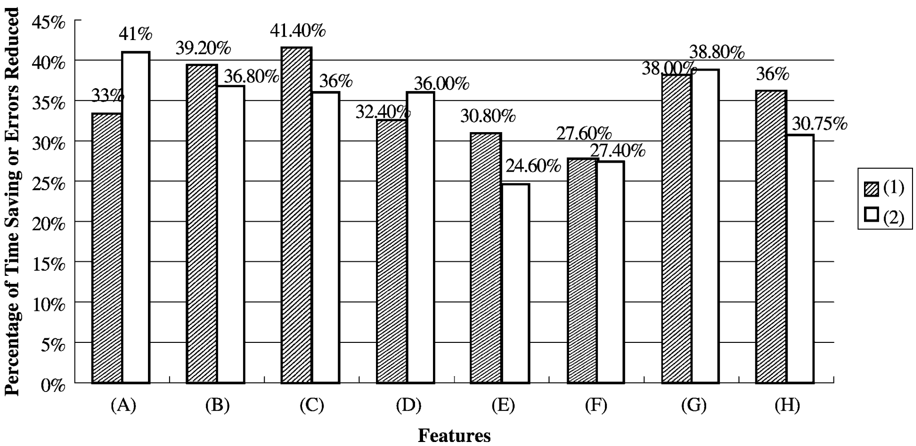


Fig. 9. Testing of schedule generation using questionnaires.

others take the opposite view. Accordingly, each module was developed to include activities and sub-activities to meet the need of both sides. Consensus on activities to be included in the modules was easily obtained once the desired level of detail in the modules was determined.

- Pay items to be included in the modules were identified without extensive discussion, not because a consensus was reached, but because it was agreed that a consensus was impossible. Consensus was impossible because the composition of pay items for a given activity varied among projects. The "expansion joint" activity that occurs in many projects provides one example. Since several methods can be used to construct the expansion joint, each of which involves different workers, equipment, and materials, the pay items associated with this activity can differ markedly. Accordingly, only commonly used pay items (such as those displayed in Table 2) were included under each activity, and contractors were expected to add situation-based pay items upon using the modules.
- During module establishment, typical interlinks among the modules were also predefined. These module interlinks were classified into three categories, namely: interlinks between the same kinds of modules for the same construction type, interlinks between different kinds of modules for the same construction type, and interlinks between different kinds of modules for different construction types. Unfortunately experience showed that users needed to frequently change these predefined interlinks. Consequently, this study concluded that typical interlinks do not exist.
- Another attempt was also made to encode "knowledge" about typical interlinks among modules. However, users needed to input considerable additional characteristic data (such as site geography and expressway length) to make a module that was intelligent enough to determine appropriate interlinks. The additional input effort required did not offset the benefits of time savings from predefined interlinks. Restated, it can be concluded that interlinks among modules tend to be "soft" links, unlike the "hard" links among activities within modules. For example, the same pair of modules could have different interlink settings for two projects with identical characteristics other than contract durations, because one contractor (with a shorter contract than the other contractor) may increase resource utilization to accelerate their rate of progress, altering activity sequences as a result. In conclusion, in expressway construction the links among modules are more diversified and dynamic than those within modules.
- During this investigation, it was felt that potential contractors might be unwilling to adapt the novel algorithms because of fears of unfamiliarity. Thus, a three-stage implementation of standardization (that is, modularization, soft standardization, and rigid standardization) was proposed to TANEEB to increase contractor acceptance in a step-by-step fashion. The modularization stage involves a set of modularized activity networks, and a software tool to help contractors use these modules for schedule generation [11]. The main goal at this stage is to motivate contractors to use these modules by saving time and effort in scheduling. The soft standardization stage encourages contractors to use standard activities, which allow the project controller to efficiently review the value earned by contractors through their work, and thus facilitate earlier payment. It is also suggested that the TANEEB add the capability to comply with standard codes and present schedules electronically as part of the criteria for evaluating bid proposals. The rigid standardization stage attempts to include the use of standard codes and electronic schedule representation in the contract provisions. Currently, the proposed algorithms are used in the second stage of TANEEB projects.

9. Conclusions

Scheduling management for expressway construction requires the integration of individual schedules of a mixture of road, bridge, and tunnel projects executed by several contractors. Since each contractor follows their own scheduling practice, schedule integration is a problem for project controllers, such as TANEEB in Taiwan. Many linear scheduling models developed for linear and repetitive projects ignore the integration problem discussed herein. This work presents the theoretical development and computer implementation of modular-based scheduling algorithms for supporting the integration of construction schedules for expressway projects.

The proposed modules allow contractors to create an initial schedule comprising standard coded activities with location-, lane-direction-, and counter-specific names by simply clicking on the desired modules. The classification of normal, repetitive, cyclic, and merging activities in a network module reflects the common nature of expressway construction and facilitates the duplication and expansion of the modules. The sub-activities of contractors and pay items with standard codes are also automatically created when activities are generated. The schedule data can also be read using popular scheduling tools. With standardized activity codes and pay items, project controllers computationally combine the schedules of different contractors into a precise single master schedule with little effort. To allow contractors a degree of flexibility, different degrees of standardization (see Tables 6 and 7) are suggested to make the proposed work practical. Overall, the proposed standardization facilitated by network modularization can help public agencies move toward the automation of schedule integration. A supplementary benefit of standardization for meeting integration purposes is that it can improve communication among the project controllers, A/Es, and contractors.

A questionnaire survey revealed the potential benefits of using the proposed algorithms, including both time savings and reduced schedule generation errors. Feedback on the integration algorithms by those involved in the industry was also favorable. Field validation is a task for subsequent research. An efficient method of upgrading the IT ability of contractors should be explored to ensure that end users can efficiently use the proposed computer system. From the perspective of public agencies, it would be useful to apply the proposed algorithms (designed for expressways projects) to other infrastructure projects (such as utility projects and railroad projects) that are linear or repetitive in nature and require integrated administration.

Acknowledgements

The authors would like to thank the reviewers of this paper for their careful evaluation and thoughtful comments. The authors are indebted to the TANEEB for financially supporting this research and Mr. T.M. Huang and Mr. C.M. Hsia of the management information division of TANEEB for their assistance in validating the scheduling integration. Professor H.P. Tserng (from the Taiwan University, Taiwan) is also commended for his thoughtful comments.

References

[1] D.W. Johnston, Linear scheduling method for highway construction, J. Constr. Div., ASCE 107 (2) (1981) 247–261.
[2] E.N. Chrzanowski, D.W. Johnston, Application of linear scheduling, J. Constr. Eng. Manag., ASCE 112 (4) (1986) 476–491.
[3] K. El-Rayes, Object-oriented model for repetitive construction scheduling, J. Constr. Eng. Manag., ASCE 127 (3) (2001) 199–205.
[4] J.J. Moder, C.R. Philips, E.W. Davis, Project Management with CPM, PERT and Precedence Diagramming, 3rd ed., Van Nostrand Reinhold, New York, 1983.
[5] D.J. Harmelink, J.E. Rowings, Linear scheduling model: development of controlling activity path, J. Constr. Eng. Manag., ASCE 124 (4) (1998) 263–268.
[6] J. Cherneff, R. Logcher, D. Sriram, Integrating CAD with construction-schedule generation, J. Comput. Civ. Eng., ASCE 5 (1) (1991) 64–84.
[7] O. Shaked, A. Warszawski, CONSCHED: expert system for scheduling of modular construction projects, J. Constr. Eng. Manag., ASCE 118 (3) (1992) 488–506.
[8] O. Shaked, A. Warszawski, Knowledge-based system for construction planning of high-rise buildings, J. Constr. Eng. Manag., ASCE 121 (2) (1995) 172–182.
[9] D. Echeverry, Factors for generating initial construction schedules, USACERL Technical Report P-91/54, Construction Engineering Research Laboratory, US Army Corps of Engineers 1991.
[10] R.J. Dzeng, I.D. Tommelein, Boiler erection scheduling using product models and case-based reasoning, J. Constr. Eng. Manag., ASCE 123 (3) (1997) 338–347.
[11] R.J. Dzeng, Development of activity network modules for expressway projects, Technical Report, Taiwan Area Expressway Engineering Bureau, Taiwan, (In Chinese) 2000.