Study of Factors Influencing the Efficient Management and Downtime Consequences of Highway Construction Equipment in Thailand

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Abstract: Downtime resulting from machine breakdown invariably has a considerable impact on the performance of construction projects and companies as a whole, especially to contractors with heavy investment in equipment. Attempts to investigate the causes and consequences of downtime are rarely found. The aim of this paper is to characterize and quantify factors that influence downtime consequences (consequential problems resulting from downtime) of highway construction equipment based on the structural equation modeling (SEM) approach. A questionnaire survey was conducted to collect data on equipment management practices and downtime consequences among highway contractors in Thailand. The SEM model proposed is of value for both researchers and practitioners to facilitate a better understanding of the relationships among acquisition condition, operational practice, maintenance quality, disposal practice, and downtime consequence of heavy equipment. The model also helps contractors to manage equipment more efficiently by concentrating on several practices that can convey the greatest benefit in minimizing downtime consequences at each particular stage of a machine's life cycle, rather than considering all practices simultaneously where the benefits gained are perhaps not proportional to the effort.

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Introduction

In Thailand, the construction industry has experienced a large increase in capital investment not only from the domestic budget, but also from foreign financial sources, especially for basic infrastructure projects, over the past few decades. A high volume of work and the pressure to finish projects within specified requirements (for example, budget, time, quality, and safety) force contractors, especially highway contractors, to employ a variety of heavy machinery to complete most of their contracts. As a consequence, construction equipment is one essential factor in improving the ability of contractors to perform their work more productively and efficiently (Day and Benjamin 1991).

Since equipment is of paramount importance, contractors need to build their capability to manage equipment; otherwise problems may occur. Problems faced by contractors throughout a machine's life cycle include, for instance, huge capital investment in the acquisition phase which invariably causes a major financial burden to the company (Stewart 2002). One may not be able to compete for certain contracts without a substantial cash reserve and/or financial support in acquiring a fleet of equipment. It has been found that the average percentage of major equipment cost is as high as 36% of the overall construction project cost (Yeo and Ning 2006). In the operational phase, such problems include lack of training (Cabahug and Edwards 2002), which may consequently cause equipment breakdown and accident (Edwards and Holt 2002). Education for operators is frequently perceived as costly and, in some cases, even unnecessary (Cabahug and Edwards 2002). In the maintenance phase, as equipment ages and enters the wear-out stage with increasing failure rate, forecasting becomes difficult. Maintenance managers are often faced with resorting to a large amount of inventories, overplanning, and inflated budgets (Mathew 2004). The tangible and intangible costs of downtime resulting from failed equipment are frequently found among contractors, as well as dependent parties (Vorster and De La Garza 1990; Elazouni and Basha 1996). In the disposal phase, determining the appropriate equipment service life and the timing for replacement of machinery can be problematic since these decisions are governed by a number of factors such as equipment efficiency, obsolescence, and depreciation (Vorster 2005).

Among the above problems, downtime resulting from a breakdown of equipment which causes additional costs and affects project schedule significantly is one of the most important areas for research on equipment management. Downtime was defined as the time during which the machine cannot perform its specified function, consisting of administrative time, supply delays, as well as repair and maintenance time (Komatsu Ltd. 1986). A number of studies have been conducted regarding machine downtime in various aspects such as downtime classification (Pathmanathan

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1980; Vorster and De La Garza 1990), quantification (Vorster and De La Garza 1990; Tsimberdinis and Murphree 1994; Nepal 2001; Nepal and Park 2004), and prediction (Edwards et al. 2002). However, attempts to investigate the causes and consequences of downtime are rarely seen, especially in the context of developing countries where contractors encounter a number of equipment problems (Nepal and Park 2004). Company practices and policies for equipment management are some of the most influential factors affecting downtime (Elazouni and Basha 1996; Nepal and Park 2004). Nevertheless, despite their significance, few efforts have been made to assess the impact of these less tangible factors (for example, equipment management practices), which can all invariably influence downtime (Edward et al. 2002). This research is therefore intended to characterize factors influencing downtime consequences in highway construction equipment based on the structural equation modeling (SEM) approach. Downtime consequence, as stated earlier, is defined in this study as the consequential problems resulting from machine downtime. By using the SEM methodology, various factors in equipment management practices capable of reducing downtime consequences could be described and quantified simultaneously in a holistic view throughout a machine's life cycle. Adoption of such effective practices on equipment management not only enhances production time and equipment reliability, but also maximizes company profit by minimizing various costs such as those from costly downtime and repair (Edwards et al. 1998).

Equipment Management Practices of Contractors

Research in the domain of equipment management practices of contractors has been the subject of various studies. Hinze and Ashton (1979) proposed equipment policies for utility contractors in the United States which were classified into seven areas (i.e., equipment acquisition, financing, depreciation, maintenance, obsolescence, equipment life, and disposal). Subsequently, Tavakoli et al. (1989) reviewed the work of Hinze and Ashton (1979) and of Garies (1979), and reclassified equipment management policies into four aspects (equipment financing, replacement analysis, equipment standardization, and miscellaneous). Schexnayder and Hancher (1981) further examined the current industry practices regarding equipment ownership such as record keeping, recognition of replacement-decision factors, replacement decision-making practices, and equipment retention periods. More recently, Dulaimi and Shan (2002) reported the procurement practices of heavy equipment related to bidding decisions of contractors in Singapore. A review of the aforementioned literature as well as expert opinions during a pilot test of the questionnaire rendered 73 variables on equipment management practices of highway contractors (see Table 1). These variables were categorized into four groups. The variables in each group are called observed variables, and are utilized in characterizing the following latent factors: acquisition condition, operational practice, maintenance quality, and disposal practice. Here, a latent factor was defined as a hypothetical or theoretical variable that cannot be observed directly; instead, it must be measured or characterized by a set of specified observed variables (Kline 1998).

Equipment Management Problems Resulting from Downtime

Problems of equipment management occurring as a consequence of downtime were reviewed from the literature. As a result, a total of six problems were found (see Table 2). These problems act as an observed variable to describe and characterize the downtime consequence latent factor.

Research Hypotheses Development

The causal relationships between equipment management practices and downtime consequence have been mentioned widely in the literature (Phair and Angelo 1998; Smith 2003). One such study revealed that maintenance could be modeled as a process of defect management, where a defect is defined as anything short of perfection (Phair and Angelo 1998). Equipment accumulates defects until it breaks down. The level of defects in the equipment determines the breakdown rate. Once breakdown occurs, a number of consequences would then be generated including costs of repair and maintenance. In general, equipment defects can arise from many sources such as initial condition of purchased equipment, workmanship quality, operational practices, machine failure, material, and spare parts quality. On the other hand, machine defects can also be reduced in several ways such as repair and maintenance, replacement of worn parts, and disposal of old equipment. All of the above are examples of defect generators and eliminators, which characterize the status of equipment management practices. The status of equipment management practices, in turn, influences downtime consequence. In this study, the status of equipment management practices was illustrated by the following latent factors: acquisition condition, operational practice, maintenance quality, and disposal practice. The theoretical grounds of each factor associated with downtime consequence are as follows.

First, acquisition condition which affects downtime consequence may include acquisition approaches (for example, rent, lease, and purchase). Renting and leasing of construction machines are considered as a key strategy to improve the status of equipment management practices (Smith 2003). For instance, once the equipment fails in the field, contractors would always obtain a substitute machine from a rental agency in 1 h without incurring a delay from the repair process. Thus, less downtime occurs. In addition, purchasing new rather than used equipment is another alternative to avoid downtime problems (Phair and Angelo 1998).

Second, good operational practice suggests an equipment operator is the best person in most circumstances to perform daily inspection for preventive maintenance in order to avoid downtime (Douglas 1975). Providing regular equipment safety and training programs ensures that defects are quickly identified by the equipment operator and all abusive behaviors are eliminated. This can also mitigate downtime problems (Stewart 1998).

Third, maintenance quality is often found to have a significant influence on downtime problems (Stewart 1999; Green 1999; Carter 2001; Schultz 2005). Maintenance quality could be achieved, for example, by adopting a preventive maintenance program and providing maintenance by dealers and operators. Such maintenance activities may include maintenance scheduling, machine cleaning, inspection, and spare parts management. Obviously, having quality in equipment maintenance not only improves the status of equipment management practices, but also alleviates downtime problems as well.

Finally, it is claimed that downtime consequences can be influenced by disposal practices. Disposal practices are characterized by the consideration of several factors: economic life, obsolescence, equipment efficiency, a company's financial status, downtime costs, investment costs, depreciation, and repair and

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Table 1. Equipment Management Practices of Highway Contractors

Acquisition condition (AC)	Operational practice (OP)
AC-01: Buy equipment outright by cash[c]	OP-01: Allow equipment operator to work in multiple machines[a,c]
AC-02: Buy equipment by financing[c]	OP-02: Provide training by in-house equipment department
AC-03: Acquire rental equipment[c]	OP-03: Provide training by equipment dealers
AC-04: Acquire leased equipment[c]	OP-04: Provide training by other external agencies
AC-05: Buy equipment in used condition[d]	OP-05: Consider poor operating procedures as a main cause of equipment accident[d]
AC-06: Buy equipment in new condition[d]	OP-06: Consider poor maintenance as a main cause of equipment accident
AC-07: Buy equipment based on personal judgments	
AC-08: Buy equipment based on current & future workloads	Maintenance Quality (MQ)
AC-09: Buy equipment based on internal rate of return on investment[b,c]	
AC-10: Buy equipment based on its life-cycle cost	MQ-01: Provide maintenance by equipment operators[a,c]
AC-11: Buy equipment based on financial status of the company	MQ-02: Provide maintenance by in-house equipment department[a,c]
AC-12: Buy equipment based on discount or special options from dealers	MQ-03: Provide maintenance by equipment dealers[a,b,c]
AC-13: Make decision on acquiring or disposing equipment by President/CEO[a–c]	MQ-04: Provide maintenance by other external mechanics[a,c]
AC-14: Make decision on acquiring or disposing equipment by board of directors[a–c]	MQ-05: Provide preventive maintenance programs to equipment[c]
AC-15: Make decision on acquiring or disposing equipment by equipment manager[a–c]	MQ-06: Seek for substituted equipment once it suddenly breaks down[f]
AC-16: Make decision on acquiring or disposing equipment by project manager[a,c]	MQ-07: Wait until the failed machine is completely repaired and ready for use[f]
AC-17: Buy equipment based on brand popularity and spare parts availability[a]	MQ-08: Transfer crews to other works once machine suddenly breaks down[f]
AC-18: Buy equipment based on functions and its usage	MQ-09: Accelerate speed of works once machine suddenly breaks down[f]
AC-19: Buy the same brand that is being used regularly[a]	MQ-10: Modify project activity and schedule once machine suddenly breaks down[f]
AC-20: Buy equipment from the familiar dealer	MQ-11: Consider poor operating procedures as a main cause of machine failure[e]
AC-21: Buy equipment based on price[a]	MQ-12: Consider poor maintenance as a main cause of machine failure during use[f]
AC-22: Buy new or used equipment based on budget availability	MQ-13: Consider the use of non-original parts as a main cause of machine failure[f]
AC-23: Buy used equipment because of cheaper price but still in good condition	
AC-24: Buy new equipment because of a need in functions and advanced technology	Disposal practices (DP)
AC-25: Buy equipment that composes of simple systems in used condition	
AC-26: Buy equipment that renders expensive repair costs once failure in new condition	DP-01: Dispose or replace equipment based on intuition and rules of thumb[b]
AC-27: Buy equipment that has low repair costs once failure in used condition	DP-02: Dispose or replace equipment based on economic analysis[a,b,c]
AC-28: Buy equipment that is important and frequently utilized in new condition	DP-03: Dispose or replace equipment when it becomes technologically obsolete[a]
AC-29: Buy equipment that is less important and infrequently utilized in used condition	DP-04: Dispose or replace equipment when it becomes inefficient[a]
AC-30: Use renting or leasing strategy for the infrequently utilized equipment[a]	DP-05: Dispose or replace equipment when the company financial status is good[a]
AC-31: Use renting or leasing strategy to avoid equipment obsolescence[a]	DP-06: Dispose or replace equipment before commencing a new job or project[a]
AC-32: Use renting or leasing strategy to avoid uncertainty of spare parts cost	DP-07: Dispose or replace equipment before major overhaul with high repair cost[a,c]
AC-33: Use renting or leasing strategy to avoid financial burden to the company	DP-08: Determine equipment economic life based on investment cost[a]
AC-34: Use renting or leasing strategy to test a newly launched machine[a]	DP-09: Determine equipment economic life based on downtime cost[a,c]

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Table 1. (*Continued.*)

Acquisition condition (AC)	Operational practice (OP)
AC-35: Use standardization policy to save spare parts cost[c]	DP-10: Determine equipment economic life based on obsolescence cost[a,b]
AC-36: Use standardization policy to benefit from mechanics' learning curve[c]	DP-11: Determine equipment economic life based on tax advantage[a,c]
AC-37: Use standardization policy to lower operator/labor costs on equipment[c]	DP-12: Determine equipment economic life based on depreciation cost[a,c]
AC-38: Use standardization policy for better relationships with dealers[c]	DP-13: Determine equipment economic life based on maintenance and repair cost[a]
AC-39: Use standardization policy to enhance safety as operators use similar machines[c]	DP-14: Determine equipment economic life based on profit accrued from use[a]
AC-40: Use standardization policy for easier equipment administration[c]	

[a]Hinze and Ashton (1979).
[b]Schexnayder and Hancher (1981).
[c]Tavakoli et al. (1989).
[d]Phair and Angelo (1998).
[e]Nepal (2001).
[f]Nepal and Park (2004).

maintenance costs (Hinze and Ashton 1979; Tavakoli et al. 1989; Navon and Maor 1995; Vorster 2005). For example, through the use of equipment repair cost as a measure, contractors can determine a reasonable time for machine disposal or replacement (Poe et al. 1988). In most cases, economic life, depreciation, investment cost, repair, and maintenance costs of equipment can be used to trigger the contractor's decision regarding how long to keep equipment and when to dispose of it (Vorster 2005). In addition, a piece of equipment should be sold unless the contractor can keep it at a high utilization level (Stewart 2004). Systematic, orderly, and constant replacement practice is required not only to ensure that the equipment fleet retains its value as a productive asset that supports the company's operations, but also to avoid the increasing operating cost of equipment including downtime cost, as well as to maintain availability and reliability of equipment (Vorster 2005).

The following aforementioned statements were used in developing the research hypotheses:

- H1: The acquisition condition has a direct causal effect on downtime consequence;
- H2: The operational practice has a direct causal effect on downtime consequence;
- H3: The maintenance quality has a direct causal effect on downtime consequence; and
- H4: The disposal practice has a direct causal effect on downtime consequence.

Hypothesized Model of Study

Based on the foregoing statements of hypotheses development, the hypothesized model (see Fig. 1) was constructed to provide a framework for investigating the relationships between the research variables. This model is the initial outline of the study, based on theoretical expectations and previous empirical findings. In the model, there are five latent factors: acquisition condition, operational practice, maintenance quality, disposal practice, and downtime consequence. In this case, downtime consequence is the primary dependent variable with the first four latent factors (acquisition condition, operational practice, maintenance quality, and disposal practice) being assigned as the independent variables of the hypothesized model.

Methodology

This section is divided into three parts. The first part focuses on detailed discussions of data collection including the instrument development, measurement scaling design, and data collection method. The second part discusses the tool utilized in the data analysis and the reasons why such a tool was selected. The last part explains the process of how the results were obtained.

Table 2. List of Observed Variables for Downtime Consequence Latent Factor

Number	Observed variable	References
DC-01	High rate of equipment breakdown and repair cost	Day and Benjamin (1991); Nepal and Park (2004)
DC-02	Difficulty in forecasting for proactive maintenance planning	Pathmanathan (1980); Mathew (2004)
DC-03	Low machine availability rate	Pathmanathan (1980); Vorster and De La Garza (1990)
DC-04	High equipment downtime duration and cost	Pathmanathan (1980); Vorster and De La Garza (1990); Tsimberdonis and Murphree (1994); Elazouni and Basha (1996)
DC-05	Difficulty in managing spare parts for equipment	Pathmanathan (1980); Elazouni and Basha (1996)
DC-06	Complication in quantifying downtime duration and cost	Pathmanathan (1980); Vorster and De La Garza (1990); Edwards et al. (2002); Nepal and Park (2004)

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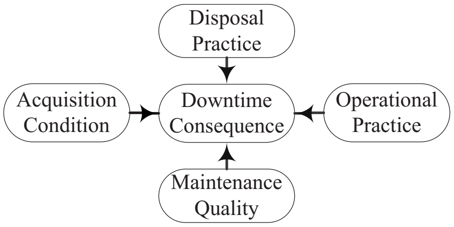

Fig. 1. Hypothesized model of downtime consequence (structural model)

Data Collection

This research employed a questionnaire survey by mail to collect the required data on equipment management practices and downtime consequences from Thai highway contractors. The scope of the study was limited by focusing only on highway contractors currently registered with the Department of Highways (DOH) of Thailand.

At the first stage of questionnaire development, a pilot test was conducted to identify possible inadequacies of the instrument by using face-to-face interviews with an equipment manager from ten different highway contractors. During the pilot test stage, the questionnaire was revised several times based on comments from the interviewees until a valid questionnaire was obtained. Once the pilot test had finished, the questionnaire was finally divided into three parts. Part one is an introductory section that includes questions related to the profile of the respondents and their companies. In part two, the respondents were asked to give a score on the frequency of performing each of the 73 variables on equipment management practices (see Table 1). Responses were on a four-point scale of frequency (never=0; seldom=1; often =2; and always=3). In part three, the respondents were also asked to specify the impact level for each of the six variables on downtime consequences (see Table 2) incurred to their companies in a five-point scale (not significant=0; somewhat significant=1; moderate significant=2; significant=3; and very significant=4). During the data collection stage, the questionnaire was enclosed with a cover letter as well as a self-addressed envelope for mailing back to the researchers. A time period of 11/2 months was allocated for the return of the questionnaire before data analysis commenced.

Model Analysis Tool

Data collected from the questionnaire survey were analyzed using the SEM technique to test the hypothesized model. LISREL 8.5 (Joreskog and Sorbom 2001) computer software was utilized to perform such analysis. Maximum likelihood was selected as the method of model estimation. SEM is a multivariate technique capable of estimating a series of interrelated dependent relationships concurrently (Hair et al. 1995; Kline 1998). This technique was employed in this study due to its superior ability over other multivariate techniques (for example, multiple regression, MANOVA, and canonical analysis), which are limited to representing only a single relationship between the dependent and independent variables (Cooper and Schindler 2003). The ability to model multiple dependent variables from the same set of independent variables simultaneously is the main advantage of SEM, especially if it is possible for one dependent variable to concurrently become an independent variable of another (Reisinger and Turner 1999). SEM can also explicitly represent unobserved concepts (latent factors) using their corresponding observed variables. Moreover, SEM can account for measurement errors occurring during the data collection and modeling processes (Wong and Cheung 2005). Measurement errors represent all sources of residual variance on each observed variable unexplained by its corresponding latent factor, including both random and systematic errors (Kline 1998). In other words, the measurement error indicates the margin of disturbance and bias on a particular observed variable. Converting qualitative data (normally obtained from a questionnaire survey of subjective judgments by respondents) into quantitative data in the form of abstract numerical scales (for example, a five-point scale of 1–5) leads to a large potential for error in the measurement of a variable (Islam and Faniran 2005). Using multiple regression or other statistical techniques cannot accurately account for this error. Thus, applying SEM in the modeling process allows for a more accurate representation of the overall results in a holistic view. Basically, SEM has two components: a measurement and a structural model (Molenaar et al. 2000). The measurement model deals with how well various exogenously observed variables measure their corresponding latent factor. The structural model is concerned with modeling the relationships among latent factors, which is akin to a system of simultaneous regression models.

Model Refinement Process

There are two steps involved in the SEM model refinement process (Cheng 2001). First, the measurement model is tested to validate the measurement instruments (observed variables) of the corresponding latent factor. In this study, the independent latent factors (acquisition condition, operational practice, maintenance quality, and disposal practice) in the hypothesized model were represented by 73 variables (see Table 1) and the dependent latent factor (downtime consequence) was also characterized by six variables (see Table 2). Then the process of variable selection for model improvement is performed over several iterations on a large number of variables to build the most reliable measurement model. If any observed variable does not measure its underlying latent factor, the hypothesized model is modified by dropping those observed variables on a one-by-one basis, according to the modification index, until the model achieves acceptable values of goodness-of-fit (GOF). Finally, the relationships between latent factors of the hypothesized structural model are evaluated. Any nonsignificant path is deleted from the model and the theoretically justified relationships are added one by one (Cheng 2001). During this stage, square multiple correlations (R^2), t-statistics, and GOF measures were utilized to evaluate and advance the fit of the hypothesized structural model until the final SEM model was arrived at (Islam and Faniran 2005). Note that the justification for inclusion of the specific latent factors and their several indicators in the SEM model was not only on the basis of theoretical expectations on the basis of past empirical evidence, but also on the suggested limitation of SEM methodology, i.e., a model should include 5–6 latent factors with at most 20 observed variables (Bentler and Chou 1987). Sample size is another important issue to be considered. This study contains data from 152 respondents, which is considered large enough compared with the recommended sample size of between 100 and 200 units (Hair et al. 1995).

Sample Characteristics

Among a total of 522 distributed questionnaires, 162 contractors replied, constituting an overall response rate of 31.03%. There are

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Table 3. Sample Characteristics ($N=152$ Highway Contractors)

Company profile				Respondent's characteristics			
Size		Experience (years)		Position		Experience (years)	
Large[a]	15 (9.9%)	<10	24 (15.8%)	President/CEO	78 (51.3%)	<10	37 (24.3%)
Medium[b]	69 (45.4%)	10–19	54 (35.5%)	Equipment manager	41 (27.2%)	10–19	59 (38.8%)
Small[c]	68 (44.7%)	20–29	48 (31.6%)	Project manager	25 (16.4%)	20–29	34 (22.4%)
		>29	26 (17.1%)	Others	8 (5.1%)	>29	22 (14.5%)

[a]Extra-first-class contractors.

[b]First- and second-class contractors.

[c]Third- and fourth-class contractors (DOH 2004).

ten questionnaires discarded as unused due to incomplete data. Table 3 shows the sample profile of contractors categorized by company size and experience, and respondent's position and work experience. The majority of businesses were medium-size and small contractors. Approximately two thirds of the contractors have experience in highway construction of between 10 and 29 years. More than half of the respondents are president or CEO of the company (51.3%), followed by equipment manager (27.2%). The majority of the informants have work experience of between 10 and 19 years.

Table 4. Cronbach Alpha Values for Reliability Test of Hypothesized Model

Latent factor	No. observed variables	Cronbach alpha value
Acquisition condition	40	0.8295
Operational practice	6	0.6657
Maintenance quality	13	0.6286
Disposal practice	14	0.7981
Downtime consequence	6	0.8751

Results of Analysis

Path Model Specification

The initial SEM specifications were built based on the hypothesized model shown in Fig. 1. In order to ensure the fitness in grouping of the observed variables into the corresponding latent factors, the Cronbach alpha reliability test was employed. An alpha value ranging from 0.6 to 0.7 is regarded as sufficient; a value in excess of 0.70 is considered as good in reliability testing (Sharma 1996). Table 4 reveals the results of the reliability test. The Cronbach alpha values of the hypothesized model vary from 0.6286 to 0.8751, which conform to the recommended range, indicating that the internal consistency reliability of the initial SEM model is sufficiently acceptable.

After finishing the model refinement stage, the final SEM model was launched (see Fig. 2). The model includes five latent factors, represented by ellipses. Each latent factor is explained by several corresponding observed variables, shown in rectangles. For instance, the acquisition condition latent factor is supposed to be reflected by the measure of five observed variables: AC-08, AC-10, AC-25, AC-28, and AC-33. A set of measurement errors was also provided to indicate the extent to which each particular observed variable is disturbed or biased by other external factors.

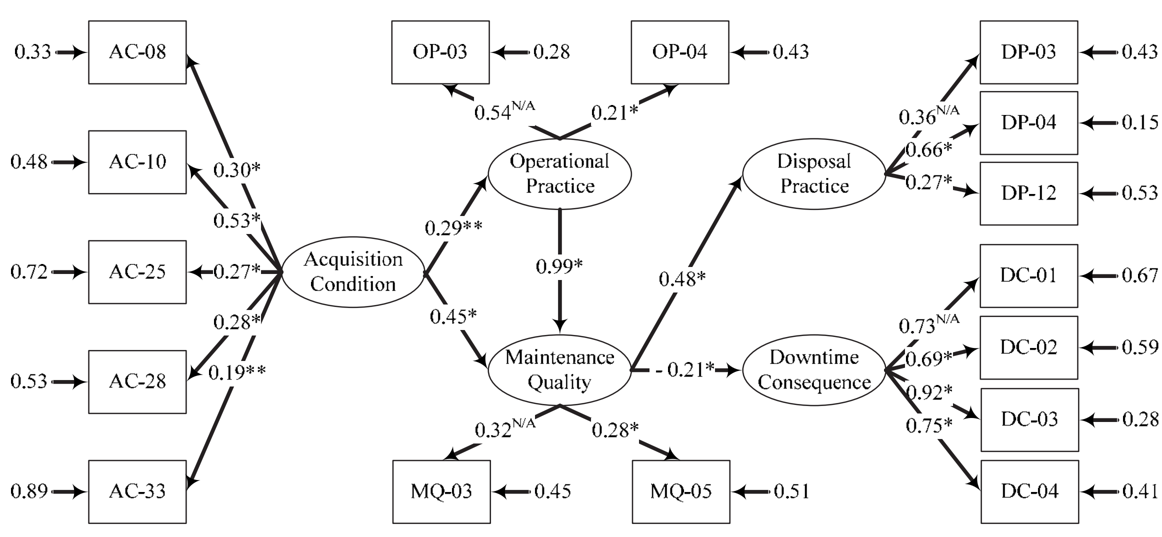

Fig. 2. Final SEM model with path coefficients and measurement errors

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Table 5. Parameter Estimates of Measurement Model

Latent factor	Observed variable	Path coefficient	Standard error	T value	R^2	Measurement error
Acquisition condition	8: Buy equipment based on current & future workloads	0.30	0.07	4.35[a]	0.22	0.33
	0: Buy equipment based on life-cycle cost	0.53	0.10	5.36[a]	0.37	0.48
	5: Buy equipment which composes of simple systems in used condition	0.27	0.09	2.90[a]	0.19	0.72
	8: Buy equipment that is important and frequently utilized in new condition	0.28	0.08	3.42[a]	0.13	0.53
	3: Use renting or leasing strategy to avoid financial burden to the company	0.19	0.10	1.85 [b]	0.14	0.89
Operational practice	OP-03: Provide equipment training by dealers	0.54	N/A[c]	N/A[c]	0.51	0.28
	OP-04: Provide equipment training by external agencies	0.21	0.08	2.60[a]	0.19	0.43
Maintenance quality	MQ-03: Provide equipment maintenance by dealers	0.32	N/A[c]	N/A[c]	0.18	0.45
	MQ-05: Provide preventive maintenance to equipment	0.28	0.08	3.42[a]	0.13	0.51
Disposal practice	3: Dispose or replace equipment when it becomes technologically obsolete	0.36	N/A[c]	N/A[c]	0.23	0.43
	4: Dispose or replace equipment when it becomes inefficient	0.66	0.18	3.58[a]	0.74	0.15
	2: Determine equipment economic life based on the consideration of depreciation cost	0.27	0.08	3.28[a]	0.12	0.53
Downtime consequence	1: High equipment breakdown rate and repair cost	0.73	N/A[c]	N/A[c]	0.44	0.67
	2: Difficulty in forecasting for equipment proactive maintenance planning	0.69	0.10	7.01[a]	0.45	0.59
	3: Low machine availability rate	0.92	0.11	8.20[a]	0.75	0.28
	4: High downtime duration and cost	0.75	0.10	7.73[a]	0.57	0.41

[a] $p < 0.05$.
[b] $p < 0.10$.
[c] N/A = not available.

For example, the variability of the observed variable on the difficulty in forecasting for proactive maintenance planning could be due to the influences of other external factors such as machine workloads and age rather than merely to downtime.

Model Assessment

After the model refinement process was completed, the original 79 variables (73 independent variables and six dependent variables) were reduced to 16 variables, which represent the most significant and important factors in the final SEM model (see Table 5). The ratio of the sample size to the number of model parameters ($152:16 \approx 9:1$) is greater than the suggested minimum ratio of 5:1 (Kline 1998). Hence, it could be interpreted that the model is statistically valid.

The parameter estimates for the measurement model (see Table 5) reveal that path coefficients between latent factors to the corresponding observed variables ranged from 0.19 to 0.92, reflecting that the observed variables satisfactorily describe latent factors. Standard errors of all paths do not illustrate any extremely large values. The t statistics confirm that all paths are statistically significant at 95% confidence level (t value exceeds 1.96) with one exception: the path for the observed variable of acquiring a rental machine to avoid company financial burden is statistically significant at a 90% confidence level (t value exceeds 1.645). The measurement errors of each observed variable are also acceptable as they do not show any exceedingly high values. Therefore, based on the above data, it is justified and acceptable to include the specified latent factors and observed variables in the measurement model.

The parameter estimates of the structural model are displayed in Table 6. This table shows that the path coefficient values and the square multiple correlations (R^2) do not demonstrate any extremely low values, indicating that the results of all paths are favorable. The standard errors also do not reveal any exceedingly high values except for the path from operational practice to maintenance quality. Moreover, it is evident that all paths in the struc-

Table 6. Parameter Estimates of Structural Model

Exogenous construct	Endogenous construct	Path coefficient	Standard error	T value	R^2
Acquisition condition	Operational practice	0.29	0.15	1.94[b]	0.29
Acquisition condition	Maintenance quality	0.45	0.21	2.12[a]	0.55
Operational practice	Maintenance quality	0.99	0.44	2.24[a]	0.64
Maintenance quality	Disposal practice	0.48	0.17	2.75[a]	0.35
Maintenance quality	Downtime consequence	−0.21	0.10	−2.00[a]	0.46

[a] $p < 0.05$.
[b] $p < 0.10$.

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Table 7. Results of Goodness-of-Fit (GOF) Tests for Model Overall Fit

GOF indicator	Recommended value or range for GOF indicator	Hypothesized model	Final model
Chi-square/degree-of-freedom	From 1 to 2[a]	2.16	1.02
P value	⩾0.05[b]	0.008	0.420
	⩾0.2 mostly preferred[c]		
Root-mean-square error of approximation (RMSEA)	⩽0.05[a]	0.124	0.012
Root-mean-square residual (RMR)	⩽0.08[c]	0.113	0.045
Standardized root-mean-square residual (SRMR)	⩽0.10[a]	0.251	0.062
Goodness-of-fit index (GFI)	⩾0.90[c]	0.76	0.92
Adjusted goodness-of-fit index (AGFI)	⩾0.80[b]	0.75	0.89
Non-normed fit index (NNFI)	⩾0.90[b]	0.83	0.98
Comparative fit index (CFI)	⩾0.90[b]	0.79	0.98
Incremental fit index (IFI)	0 (no fit) to 1 (perfect fit)[a]	0.78	0.98

[a]Molenaar et al. (2000).
[b]Cheng (2001).
[c]Reisinger and Turner (1999).

tural model are statistically significant as indicated by t values. The t value of the path from acquisition condition to operational practice is slightly less than 1.96, meaning that this path is statistically significant at the 90% confidence level. The rest of the paths are statistically significant at the 95% confidence level.

Apart from this, to check the overall fit of the model to the data, several GOF statistics provided by LISREL were utilized. Results of the GOF tests for the hypothesized and the final models are depicted in Table 7. Overall, the GOF statistics of the final model conform to the recommended values suggested in the literature (Reisinger and Turner 1999; Molenaar et al. 2000; Cheng 2001) better than the hypothesized model. This indicates that the final model is superior to the hypothesized model in reflecting and characterizing the data.

Discussion of Results

The following section is divided into two parts. Discussion in the first part is on the structural components, while the second is on the measurement components of the final SEM model.

Structural Components of Final SEM Model

Based on Fig. 2, the final SEM model reveals that only the maintenance quality latent factor was found to have a direct influence on downtime consequence. The acquisition condition and operational practice latent factors, on the other hand, were discovered to have indirect causal relationships with downtime consequence, while disposal practice was found to have no significant relationship with downtime consequence. Therefore, the study retains the hypothesis H3 and rejects the hypotheses H1, H2, and H4 accordingly.

Apart from this, the relationships among latent factors in the final SEM model are very different from those in the hypothesized model. Detailed discussions of those relationships for the final SEM model are as follows.

First, it appears that a significant relationship between acquisition condition and operational practice is endorsed, reflecting the fact that operational practice is significantly affected by the equipment acquisition condition. For example, adopting an equipment standardization policy by purchasing fewer brands not only saves labor and inventory costs, but the contractor may also receive training services from machine dealers to improve operator skills (Stewart 1999).

Second, the final SEM model shows that the status of maintenance quality is significantly influenced by the acquisition condition of equipment. Previous literature also confirms this finding (Stewart 1999; Bonnecaze 2005). For instance, by adopting rental equipment, contractors not only benefit from reducing maintenance costs (Smith 2003), they also have greater convenience by receiving maintenance services from their dealers (Bonnecaze 2005.). Further, maintenance costs can be reduced by purchasing fewer brands (Stewart 1999).

Third, operational practice was discovered to have a significant relationship to maintenance quality, indicating that the status of maintenance quality is highly determined by the operational practices. In fact, spending money on operator training was proved worthy of investment since operators gain better understanding of how to maintain their machines and thus enhance the quality of maintenance (Stewart 1998). Variation in the operator's skill is another factor that can influence repair and maintenance costs significantly (Vorster 2004).

Fourth, a significant positive relationship was found between maintenance quality and disposal practice latent factors. This finding suggests that disposal of equipment is directly affected by maintenance quality. Indeed, effective policies for equipment maintenance, repair, and rebuild are capable of extending machine life (Vorster 2005).

Finally, as mentioned above, maintenance quality was found to have a significant negative relationship to downtime consequence. The negative coefficient of the path indicates that the higher the status of maintenance quality, the smaller the chance the contractor shall face downtime problems. This relationship was widely confirmed in the literature (Stewart 1999; Green 1999; Carter 2001; Stewart 2004; Schultz 2005). Contractors can achieve maintenance quality by, for instance, adopting preventive maintenance programs and obtaining maintenance services from dealers (Stewart 2004).

Measurement Components of Final SEM Model

Among a total of 40 observed variables of the acquisition condition latent factor, only five variables are most suitable as indica-

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Table 8. Results of Validation Test

Machine's life-cycle stage	First case (large contractor[a])		Second case (medium contractor[b])		Third case (small contractor)[c]	
	Five most important practices (ordered from most to least important)	Influence to	Five most important practices (ordered from most to least important)	Influence to	Five most important practices (ordered from most to least important)	Influence to
(I). Acquisition	AC-10, AC-28, AC-06, AC-33, AC-08	II, III	AC-28, AC-08, AC-10, AC-25, AC-06	II, III, IV	AC-28, AC-10, AC-36, AC-25, AC-03	II, III, DC
(II). Operations	OP-03, OP-05, OP-O4, OP-06, OP-02	III, DC	OP-02, OP-03, OP-01, OP-04, OP-05	III, DC	OP-02, OP-03, OP-04, OP-01, OP-06	III
(III). Maintenance	MQ-03, MQ-05, MQ-06, MQ-04, MQ-08	II, IV, DC	MQ-05, MQ-03, MQ-02, MQ-06, MQ-08	IV, DC	MQ-05, MQ-08, MQ-03, MQ-02, MQ-01	IV, DC
(IV). Disposal	DP-03, DP-04, DP-02, DP-09, DP-12	—	DP-04, DP-09, DP-07, DP-12, DP-03	—	DP-04, DP-02, DP-09, DP-13, DP-12	DC

Note: DC=downtime consequence.

[a]Extra-first-class contractors.

[b]First- and second-class contractors.

[c]Third- and fourth-class contractors (DOH 2004).

tors of the measurement model. The observed variables, ranked from most to least influential on the acquisition condition, include AC-10, AC-08, AC-28, AC-25, and AC-33 (see Table 5). These five practices are strongly recommended for equipment acquisition. Emphasis should be given to determining the life-cycle cost before acquiring a piece of equipment as this creates the greatest potential for success when trying to improve the status of machine acquisition as well as reduce downtime consequences.

For the operational practice latent factor, after the model refinement process, the original six observed variables were reduced to two attributes: OP-03 and OP-04 (see Table 5). These indicate that obtaining training services from dealers renders the highest potential for success when trying to improve the status of machine operations as well as to eventually minimize downtime consequences.

For the maintenance quality latent factor, results show that the original 13 observed variables were reduced to two attributes: MQ-03 and MQ-05 (see Table 5). Utilizing maintenance services from dealers produces the greatest potential for success when trying to improve the status of maintenance quality as well as reduce downtime consequences.

Regarding the disposal practice latent factor, among the total of 14 observed variables, three variables are qualified for inclusion in the measurement model. The observed variables, ranked from most to least influential on the disposal practice, include DP-04, DP-03, and DP-12 (see Table 5). Disposing or replacing equipment once it becomes inefficient creates the highest potential for success when trying to improve the status of disposal practice.

Further, after completing the model refinement process, a total of six observed variables of downtime consequence latent factor were reduced to four attributes, ranked from most to least influential on downtime consequence, including DC-03, DC-04, DC-01, and DC-02 (see Table 5). It was found that downtime consequence is best measured and characterized by the problem of low machine availability rate.

Validation of Final SEM Model

In order to ascertain the validity and applicability of the research finding, a separate validation test of the final SEM model was then undertaken through a face-to-face structured interview. A validation method used by Lyer and Jha (2006) was employed in the study. The interviewees are equipment managers from three different highway construction companies (one from each of large, medium, and small contractors) with at least 10-year work experience in managing heavy equipment. During the interviews, the interviewees were asked not only to identify and rank the five most important practices capable of minimizing downtime consequences for each particular stage of a machine's life cycle (acquisition, operations, maintenance, and disposal), but they were also asked to specify the relative influences of practices in each particular machine's life-cycle stage to those of other stages. In order to avoid any bias that might occur in the responses, the interviewees were not informed about the current research findings. Results of the validation test (see Table 8) indicate a strong agreement with the findings of the research. It can thus be inferred that the final SEM model is satisfactorily acceptable and valid in the present form.

Conclusion

This research is intended to give an insight into how equipment management practices influence downtime consequences using SEM methodology. According to a range of GOF measures, the final SEM model successfully passes all recommended criteria suggested in the literature. This indicates that the model is sufficiently fit to the data and is acceptable for use in characterizing factors influencing downtime consequences as confirmed by the model validation test.

The final SEM model proposed in this paper reveals several important contributions. First, the model provides a framework for tracing the causes and consequences of downtime and recommends practices for downtime reduction. It suggests that contractors should place a strong emphasis on equipment maintenance as it has a significant influence on downtime and machine disposal practice. Second, the model illustrates how the acquisition condition and operational practice of equipment affect downtime through a direct influence on maintenance quality. Improving machine operational practices could create an approximately twofold positive effect on maintenance quality, compared to the influence on maintenance quality resulting from improving the acquisition condition of equipment. Third, the model ranks equipment management practices according to their importance and effectiveness in reducing downtime consequences. Finally, contractors can utilize the research findings to focus on only the most important

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equipment management practices necessary for avoiding downtime consequences throughout a machine's life cycle. Such practices include determining machine life-cycle cost before acquiring equipment, considering the adoption of training and maintenance services from machine dealers, and using machine efficiency as an indicator for decisions to dispose of or replace equipment. These practices are all strongly recommended as they create the highest potential for success when trying to minimize downtime consequences.

Future studies could be directed toward building a downtime model using a different approach which is capable of characterizing the dynamics of downtime on equipment management practices with the ability to generate a variety of policies from a number of variables. Moreover, the research could be expanded to study the causes and consequences of machine downtime in other types of contracting companies where equipment is also heavily utilized as a primary resource in generating work production.

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