Modeling the Dynamics of Heavy Equipment Management Practices and Downtime in Large Highway Contractors

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Abstract: Machine downtime is invariably perceived as one of the most critical problems faced by highway contractors. Attempts to reduce downtime often result in failure due to the dynamic behaviors between equipment management practices and downtime. This paper is thus intended to highlight the dynamics of heavy equipment management practices and downtime in large highway contractors and utilizes them as a framework in constructing a simulation model using a system dynamics approach. Face-to-face interviews were conducted with equipment managers from five different large highway contractors in Thailand. The finding reveals that, to be successful in alleviating downtime, contractors must view their practices on equipment management as an integration of multiple feedback processes, which are interrelated and interdependent with downtime. Based on various validation tests, the simulation model is deemed appropriate in representing the equipment management system as related to downtime of large highway contractors. The research is of value in facilitating better understanding on the dynamics of equipment management practices and downtime as well as their interdependency.

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Introduction

In the construction industry, the tangible benefits of using machinery are obvious as greater productivity, performance, cost reductions, and improved competitiveness for contractors can be obtained. This is particularly so in highway construction organizations where a variety of construction equipment has been heavily deployed as a major resource in generating work production. However, managing construction equipment effectively is not an easy task since the contractor is required to dynamically interact with various parties and activities. Highway contractors are thus invariably plagued by a number of equipment management problems. Downtime resulting from machine breakdown during operations is of prime concern in views of contractors (Prasertrungruang and Hadikusumo 2007). Indeed, equipment practices and policies are some of the most important factors that affect machine downtime significantly (Elazouni and Basha 1996). Variation in practices regarding the flow of factors (e.g., spare parts, operators, equipment, mechanics, and information) over time is claimed as a major cause of the dynamics of downtime (Nepal and Park 2004). Nevertheless, to date, little efforts have been made to study the effect of less tangible factors (e.g., equipment management practices) on downtime, which control the dynamic behavior of the system, particularly in the construction context (Edwards et al. 2002). Hence, this research attempts to address this issue by exploring and highlighting key dynamic structures of equipment management practices and downtime inherent in each particular stage of machine lifecycle and then uses them as a framework in building a system dynamics (SD) simulation model. Scope of this study covers merely on large highway contractors with five types of heavy equipment for highway construction (see Table 1) as machine weight is one of the major indicators of downtime and maintenance cost (Edwards et al. 2002). It is noted that weight interval for each equipment type is also assigned in order to allow for machine generalization.

Applications of SD in Construction Decision-Making

By nature, construction project management is considered as a complex system (Richardson and Pugh 1981). Several researchers have adopted a SD methodology to model construction project. For instance, Richardson and Pugh (1981) introduced a SD model for project management. This model concentrates on schedule overrun controlled by the magnitude of the workforce and rework. Subsequently, large-scale projects using fast-track procurement were modeled using the SD approach (Huot and Sylvestre 1985). The results reveal that the major problems in project failure are problems of quality, productivity, and worker morale. The SD was also used to model rework in construction (Love et al. 1999). Results show that rework is predominantly attributable to designer's errors, design changes and construction errors. To solve this problem, teamwork between design and construction people, training, and skill development must be emphasized.

In the context of construction equipment management, the use of SD in modeling the dynamics of downtime is highly promising (Nepal and Park 2004). It was proposed that downtime and its consequences on construction equipment are significantly influenced by many factors: equipment-related factors, site-related

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Table 1. Types and Size of Highway Construction Equipment in the Study

No.	Equipment types	Weight interval (kg)	Examples of model
1	Motor grader	14,000–19,000	140H
2	Hydraulic excavator	19,000–24,000	320C
3	Asphalt paver	11,000–15,000	BG-225
4	Vibratory and pneumatic tire compactor	7,000–13,000	CP-433C
5	On-highway truck	7,000–10,000	FM360

Note: Caterpillar (2004); Volvo Group (2006).

factors, project-related factors, company's policies, crew-level factors, site management actions, and force majeure.

Equipment Management Practices and Downtime

As the challenge of selecting, managing, and maintaining the equipment asset becomes more complex and costly every day, effective management of these assets directly fuels the success for business by significantly minimizing direct and indirect costs of equipment while still concurrently ensuring high availability of equipment productivity. Realizing the right practices on equipment management is dependent on where the machines are in their lifecycle. Indeed, equipment management practices can be categorized into four groups: machine acquisition, operations, maintenance, and disposal. Key practices in each particular stage of machine lifecycle include, for example, procurement decision approach (equipment acquisition stage), safety and training programs (equipment operational stage), schedule PM inspection and standby repair-maintenance facilities (equipment maintenance stage), equipment economic life and replacement decisions (equipment disposal stage) (Prasertrungruang and Hadikusumo 2006).

When the machine fails during operations, it is said to be "down or unavailable" which means that it is waiting for repair and thus incurring downtime (Nagi 1987). Typically, downtime duration consists of three major components, including (1) administrative time: time required for communication flow from user to manufacturer, time required for commercial formalities, and hours necessary to report a machine failure and give work directions for maintenance; (2) supply time: time when repair is delayed due to nonavailability of spare parts and materials necessary to perform maintenance; and (3) active repair: time when technicians are working on the equipment to actually commission it including both preventive and corrective maintenance (Komatsu 1986). To minimize the consequential impact of downtime, contractors may opt to seek for substitute equipment, wait until the repair finished, accelerate work pace, modify work schedule, or transfer crews to other works (Nepal and Park 2004).

Research Methodology

This section is divided into two parts. The first part aims to discuss the method for data collection, while the other explains the process for data analysis in order to achieve the research objective.

Data Collection

The research uses data collected from face-to-face interviews with five large highway contractors located in Bangkok and the surrounding provinces in Thailand. An equipment manager with at least 10 years work experience was selected as the interviewee for each of the participated contractors. A convenience sampling technique was used in identifying not only the sample contractors but also the interviewees. The interview checklist is in a semistructured format in order to cover both open and closed-end dialogs. During the interviews, causal relationships between each pair of variables were disclosed and confirmed by the interviewees. Data from other sources (e.g., repair and maintenance cost database, equipment procurement records) was also collected as supplemental to the interviews. There are two types of data administered in the study: quantitative and qualitative. For data in the quantitative form, respondents were asked about the actual amount or quantity of the specified variable (e.g., repair and maintenance costs in dollars per month). In qualitative variables, a rating scale in a percentage format was provided with an explanation to respondents (i.e., 0%=extremely low, 25%=low, 50%=medium, 75%=high, and 100%=extremely high) for each of the specified variables. To avoid any misinterpretation, full attentions were given to experts by the authors regarding definition of the variables and workings of the checklist. Table 2 shows the variables' profile and sources for the study.

Data Analysis

Data collected from all five large contractor cases was administered using within-case as well as cross-case analysis approaches (Eisenhardt 1989). First, within-case analysis was employed to reveal the data characteristics for each particular contractor case. Then, attempt was made to draw the integrated picture among all contractor cases regarding the generic feedback structures of equipment management practices and downtime using cross-case analysis approach. The generic feedback structures were rechecked again with experts for validation until they are satisfactorily valid. Next, the generic feedback structures were used as a foundation in constructing the generic SD simulation model, using Powersim software. During this step, a number of stock and flow diagrams, which are all connected together in the generic SD model, have been identified. "Stock" represents accumulated quantities that change over time, while "flow" controls the changing rate of quantity going into or out of the stock (Sterman 2000). An example of stock and flow diagram is shown in Fig. 1. In this case, backhoe defect, which was modeled as a stock, gradually rises during equipment operations (flow in) but reduces after performing repair and maintenance tasks (flow out). Four variables (i.e., operator skill, spare parts quality, backhoe condition upon acquisition, and backhoe collateral damage) were modeled to have an influence on equipment operations (defect generation rate), while two variables (i.e., PM effort and repair and maintenance quality) were modeled to have an influence on repair and maintenance tasks (defect reduction rate). Data are required for these variables to set as initial conditions of the SD model before generating a time-series simulation output.

After data from each of the five contractor cases was input separately into the generic SD model, five applied SD models could be launched. Each of the applied SD models was then subjected to a number of validation tests to ensure that the model is structurally and behaviorally valid. Upon passing all validation

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Table 2. Variables' Profile and Sources

Variable type	Variable	Value	Unit	Data source
Numerical (quantitative)	Machine repair unit cost, machine maintenance unit cost, breakdown rate, and invested equipment under repair	Actual amount or number	Dollars/item/month	Repair and maintenance cost database
Numerical (quantitative)	Number of invested equipment, Initial equipment purchasing value, equipment quality upon acquisition, initial equipment age, and time to adjust invested equipment	Actual amount or number	e.g. items, dollars/item, percentage, years	Equipment procurement records
Numerical (quantitative)	Equipment lead time, time to adjust rental equipment, time to return rental equipment, number of rental equipment, invested equipment on site, penalty cost rate for idle equipment, initial workload of equipment, work scope capacity goal of equipment, equipment productivity, normal insurance and tax unit costs of equipment, normal fuel unit cost, normal monthly operator wage, normal unskilled/skilled operators, normal unskilled/skilled mechanics, and normal equipment life	Actual amount or number	e.g. items, years, dollars/item/ month, cubic meters/item/ month, dollars/liter, persons	Interviews with equipment managers
Rank (qualitative)	Normal invested/rental equipment fraction, normal equipment standardization percentage, rental facility availability, machine budget status, normal equipment utilization, expected equipment workload, supervision level for equipment, spare parts return percentage, design complexity, and site condition uncertainty	Arbitrary value in scale of 0–100%	0% (very low) to 100% (very high)	Equipment managers' perceptions

tests, the generic SD model is deemed valid in representing the equipment management system as related to downtime of large contractors.

Generic Feedback Structures

After a consensus among all five large highway contractor cases was made regarding the dynamic behaviors of equipment management practices and downtime, the generic feedback structures could be delivered which are categorized into five components as follows.

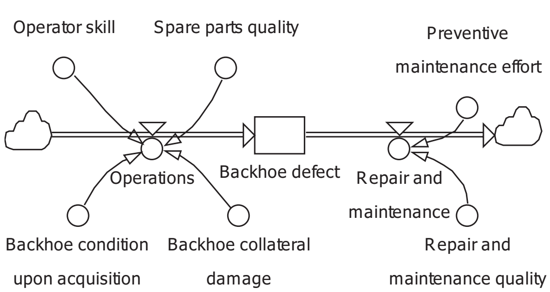

Fig. 1. Example of model structure of backhoe defect

Equipment Acquisition Feedback Structure

The dynamic behavior of equipment acquisition structure is pictorially shown in Fig. 2. This comprises of three reinforcing loops (R1–R3 in Fig. 2). By adopting machine standardization practice (R1 in Fig. 2), operator productivity is boosted due to ease of using similar machines, leading to more profit gained and less budget constraint (Koster 1964). This fact explains why large contractors strengthen their standardization preference. Moreover, as a result of standardization strategy deployment, relationship between contractors and dealers is stronger, leading to less schedule pressure on mechanics and thus eventually less machine budget constraint (R2 in Fig. 2). With less budget constraint, more machines can be purchased in new condition (R3 in Fig. 2), causing less breakdown frequency, less repair backlog, and less resource idleness, which leads to even less equipment budget constraint (Stewart 1999). The contractors, hence, can continually acquire more machines in good condition.

Equipment Operational Feedback Structure

Equipment operational feedback structure (Fig. 3) illustrates the fact that large contractors emphasize the importance of using subcontractors as one of the strategy in equipment management (Arditi and Chotibhongs 2005). By employing this strategy, not only does project autonomous team level increases (R1 in Fig. 3) but the contractor's work capacity could be also fostered (R2 in

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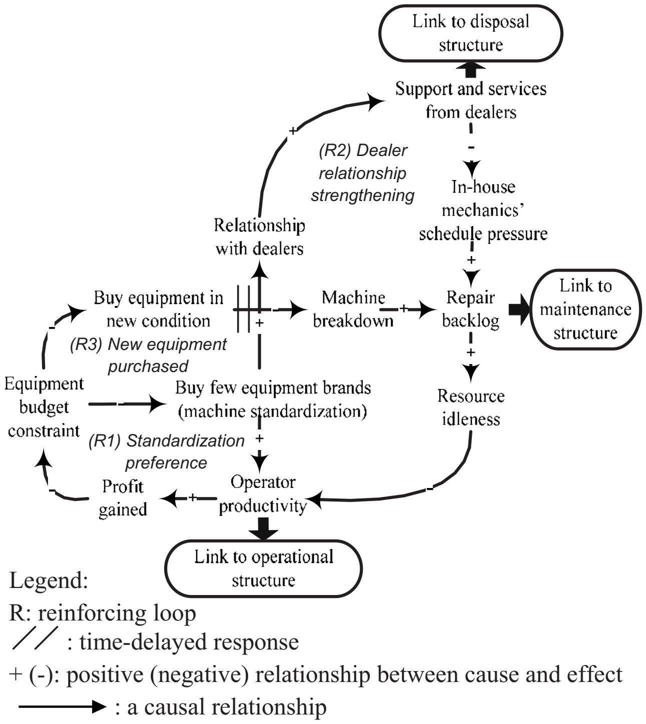

Fig. 2. Equipment acquisition feedback structure

Fig. 3), leading to even more subcontractors employed in job sites eventually. However, as the contractors' work capacity increases, they are capable of handling more projects simultaneously, thus incurring higher workload but after passing a certain amount of delay. This induces even more needs to hire more subcontractors involved in the job sites (R3 in Fig. 3).

Equipment Maintenance Feedback Structure

For equipment maintenance feedback structure (Fig. 4), main focus on this is on the preventive maintenance (PM) effort provided by in-house mechanics. PM effort is eroded by two reinforcing loops: mechanics' schedule pressure and operator schedule pressure (R1 and R2 in Fig. 4, respectively). The higher the mechanics' and operator schedule pressure, the less the PM effort will be and vice versa (Nepal and Park 2004). However, PM effort is enhanced by the effect of management commitment in PM reinforcing loop (R3 in Fig. 4). The higher the management commitment in PM, the greater the PM effort for equipment will be and vice versa. In particular, to adjust or balance the PM effort to a desired level, adoption of maintenance services from dealers is a good alternative (B1 in Fig. 4). It is noted that the occurrence of severe breakdown is expected to delay by providing quality maintenance and avoiding of equipment misuses during operations. In addition, giving periodical inspection can indeed gradually eliminate machine defects in order to attain a better equipment condition (Phair and Angelo 1998).

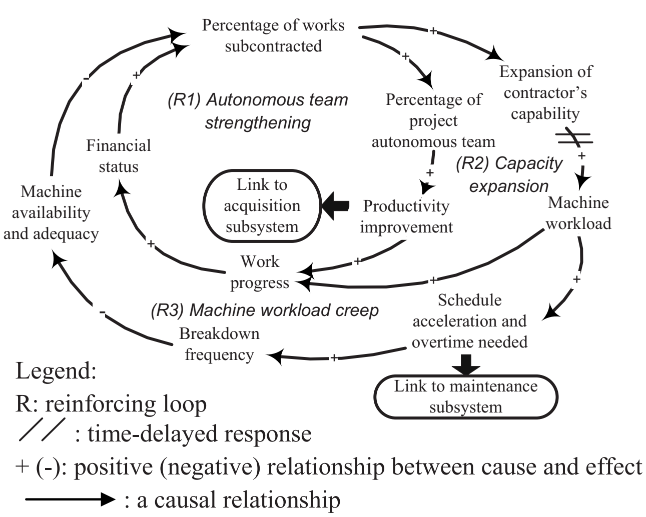

Fig. 3. Equipment operational feedback structure

Equipment Disposal Feedback Structure

In making a decision to dispose of equipment, machine market value is of prime consideration for large contractors (R1 in Fig. 5). As the contractors frequently adopt support and services from dealers, their machines are continually maintained in good condition and thus having higher market value (Stewart 2000). As a consequence, the contractors tend to dispose the machines regularly before their market value is too low. This fact causes the equipment to be more productive than before, leading to even better equipment budget status. Contractors can now constantly received services from dealers in order to retard a decline of machine market value.

Equipment Downtime Feedback Structure

Machine downtime in large contractors is influenced by three reinforcing loops (R1–R3 in Fig. 6) and three balancing loops (B1–B3 in Fig. 6). Regarding the reinforcing loops, mechanics' schedule pressure (R1 in Fig. 6), operator schedule pressure (R2 in Fig. 6), as well as schedule disruption and acceleration (R3 in Fig. 6) are of major factors worsening downtime. The higher the mechanics schedule pressure, operator schedule pressure, and schedule disruption, the greater the duration of downtime (Nepal and Park 2004). However, high amount of downtime could be adjusted or balanced by three balancing loops: repair outsourced adjustment (B1 in Fig. 6), mechanics' skill adjustment (B2 in Fig. 6), and operator skill adjustment (B3 in Fig. 6). Applying repair outsourcing strategy as well as improving skills by providing trainings to mechanics and equipment operators are effective options in reducing downtime. Nevertheless, the benefit of training for operators and mechanics, which is a better knowledge and skill, is always delayed and thus retards the quality improvement of equipment operations. It is evident that breakdown incident is controlled by the level of machine defects. Equipment is supposed to fail once its defects gradually reach to a certain level. The incurred delay thus indicates time to repair the equipment.

Generic System Dynamics Model Subsystems

This section aims at describing the structural components of the generic SD model, which are in fact the key elements of the formal simulation model for large highway contractors. The model consists of five subsystems including, resources, quality, performance, work pressure, and financial subsystems. Each subsystem comprises several sectors, which are constructed as referenced to their corresponding feedback structures (see Fig. 7). The conceptual basis of the model subsystems was preliminarily de-

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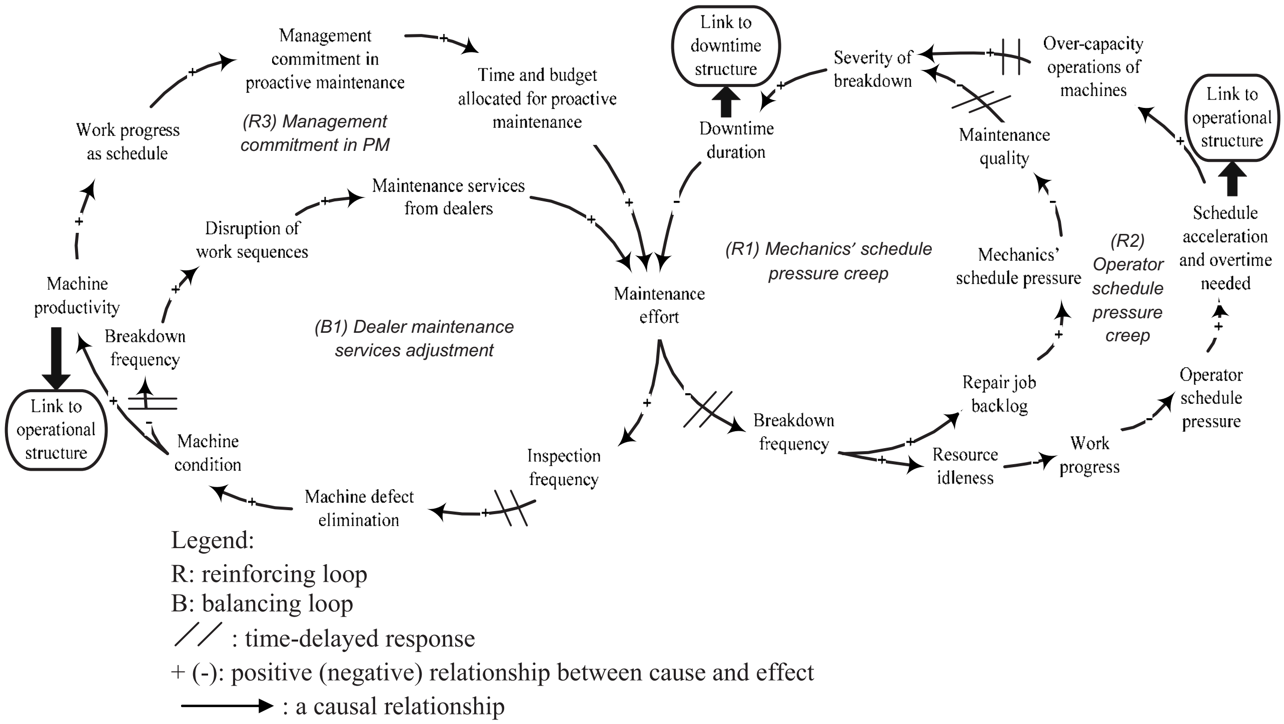

Fig. 4. Equipment maintenance feedback structure

rived from literature reviews such as infrastructure project management model (Nguyen and Ogunlana 2005), design-build project management model (Chritamara et al. 2002), manufacturing organizational model (Keating et al. 1999), and equipment management downtime (Nepal 2001). Descriptions for each of the model subsystem are provided as follows.

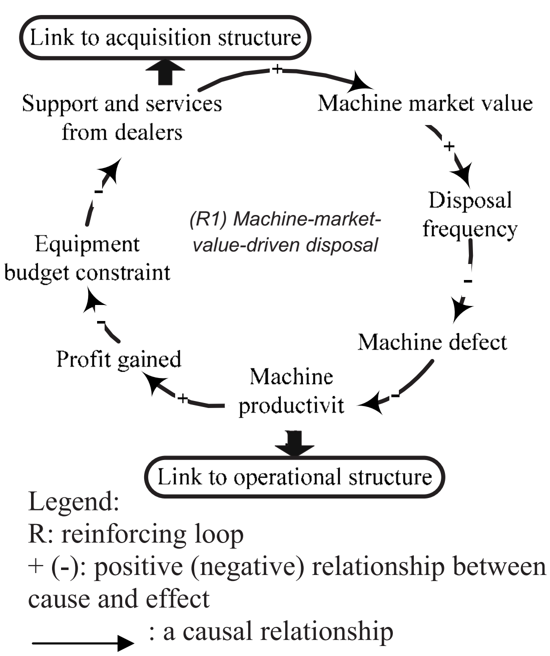

Fig. 5. Equipment disposal feedback structure

Resources Subsystem

The resources subsystem comprises of six sectors: invested equipment, rental equipment, operators, mechanics, subcontractors, and

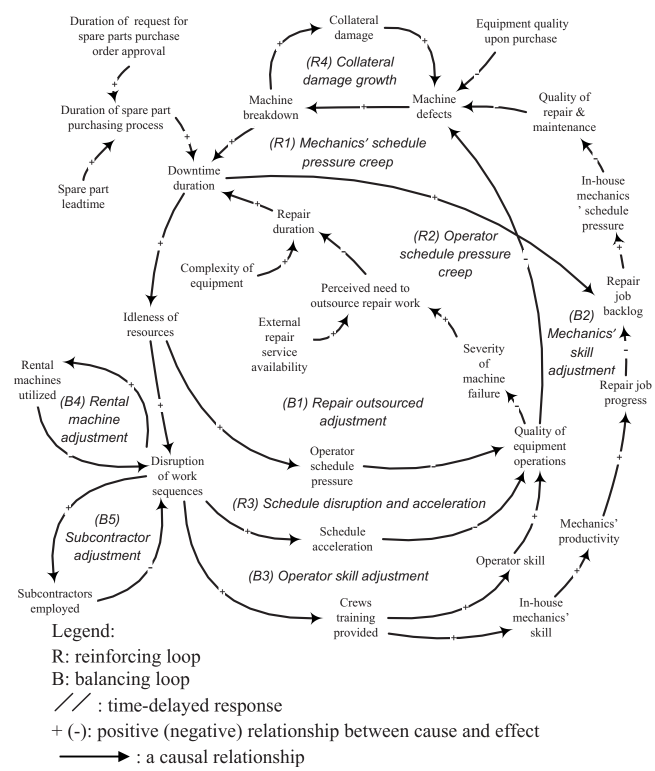

Fig. 6. Equipment downtime feedback structure

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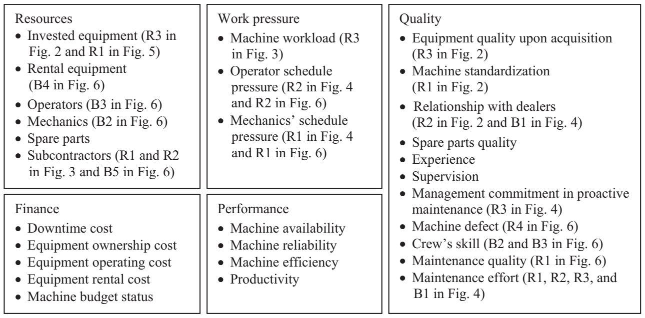

Fig. 7. Generic SD model structure of large contractors

spare parts (see Fig. 8). Each of the sectors was modeled and interconnected to each other in the system. The invested equipment sector (e.g., backhoe) consists of three stocks: invested backhoes, invested backhoes on site, and invested backhoes under repaired. "Invested backhoes" represents total backhoes invested by a contractor. Backhoes can flow out of invested backhoes by disposal or flow through "invested backhoes on site." Once backhoes that are working on site breakdown, they become failed backhoes, which flow into "invested backhoes under repaired," and then flow back again to invested backhoes on site when repair is finished. Rental equipment, which was modeled as a stock, increases upon adoption of more rental machines (flow in) but depletes when returning them back to dealers (flow out). Workers in the company are represented by operators and mechanics, which were modeled as stocks. They were also disaggregated into competent and incompetent workers. Upon complete learning and training processes, incompetent workers then become competent workers. The number of workers increases due to more recruitment (flow in) but decreases when they leave the company (flow out). Similarly, subcontractors were modeled as a stock, which increase due to more employment (flow in) but reduce upon the completion of subcontracted works (flow out). For spare parts, they are modeled as stocks, namely, "parts on order" and "parts in stock." Parts on order are delivered to parts in stock, while some defective parts, once discovered, are returned from parts in stock to parts on order.

Quality Subsystem

There are various sectors modeled to signify quality in equipment management. Many of them were modeled as a rating scale ranging from 0% (extremely low) to 100% (extremely high) rather than a quantitative formula since they are perceived, by nature, as "soft" or "qualitative" variables. These comprise sectors such as equipment quality upon acquisition, machine standardization, relationship with dealers, spare parts quality, experience, supervision, management commitment in proactive maintenance, and machine defect. However, others are modeled as a formula. For instance, maintenance quality sector is modeled as the ratio between maintenance cost and repair cost, whereas crew's skill is defined as the ratio between the number of competent workers and total workers. PM effort is determined by total mechanics' working hours less total machine repair time.

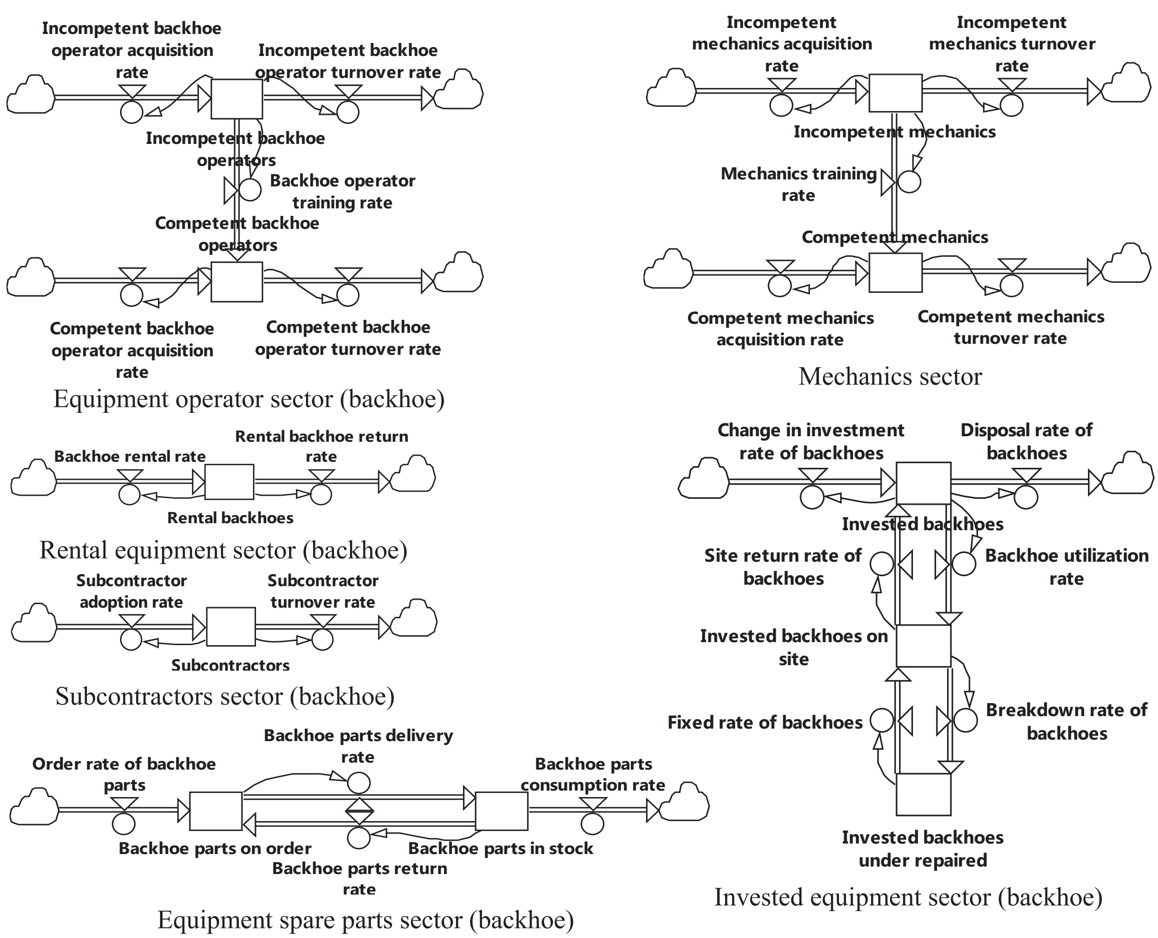

Fig. 8. Stock and flow diagrams of resource subsystem

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Performance Subsystem

This subsystem is made up of four sectors: machine availability, reliability, efficiency, and productivity. The formula of machine availability is given as the discrepancy between total invested backhoes and invested backhoes under repaired, divided by total invested backhoes, while the formula of machine reliability is labeled as the discrepancy between invested backhoes on site and invested backhoes under repaired, divided by total invested backhoes. In the model, machine efficiency is characterized as having an inverse relationship with machine defects. The greater the machine defect, the less the equipment efficiency. For machine productivity sector, various factors were found to have an influence to current equipment productivity including, fatigue, supervision, operator schedule pressure, machine reliability, experience, and machine defect. Current equipment productivity is reported with an extent of information delay.

Financial Subsystem

This subsystem consists of four sectors: downtime cost, equipment ownership cost, operating cost, and machine budget status. Downtime cost is the cost resulting from machine breakdown during operations. In the model, downtime cost is quantified from a combination of equipment substitution cost, operator and labor idle cost, equipment idle cost, dependent equipment idle cost, dependent operator and labor idle cost, and repair cost of the failed machine. Equipment ownership cost signifies the cost that is fixed regardless of utilization. This includes depreciation, and insurance and tax. On the other hand, equipment operating cost represents the cost that is incurred as a result of work operations consisting of operator and labor wage, repair and maintenance cost, and fuel cost. Equipment rental cost represents the cost incurred from the rental equipment. Last, in modeling machine budget status, it was built as a stock with a rating scale ranging from 0% (extremely low machine budget status) to 100% (extremely high budget status). Machine budget status rises due to an increase of equipment work progress (flow in) but declines as a result of high downtime cost pressure and heavy equipment investment relative to the disposal rate of machinery (flow out).

Work Pressure Subsystem

Work pressure subsystem presents a modeling description of machine workload as well as the schedule pressure of operators and mechanics. In practice, workload piles up due to an increase of work creation rate (flow in) but depletes as a result of work completion rate (flow out). Work creation rate is determined by a discrepancy between desired work scope capacity of equipment and current equipment workload, while work completion rate is governed by the productivity of machines working on site. In the model, the formulas for both of the operator and mechanics' schedule pressure are in the similar form. Schedule pressure was defined in this study as the discrepancy between workers (i.e., operators and mechanics) sought and the current number of workers, divided by total workers. The higher the discrepancy between workers sought and the current number of workers (worker inadequacy), the greater the schedule pressure incurred.

Model Validation

In order to confirm the credibility of the generic SD model, several validation tests provided by Sterman (2000) were adopted. The validation tests have been grouped into two categories: structural validation and behavior validation test. Each of the five applied SD model was separately validated by experts using data input from its corresponding contractor case.

Structural Validation Test

To pass the structure validation test, the model structure must not contradict the knowledge regarding the structure of the real system (Forrester and Senge 1980). Various tools and procedures were used in assessing structural adequacy of the model such as model boundary chart, stock and flow diagrams, model equations and graphical relationships, and expert opinions. The test of boundary adequacy using model boundary chart was employed to check whether the fundamental variables have been included in the model. The variables in the model were listed from the literature review, expert opinion, and the companies' database (e.g., repair and maintenance records). This test was performed concurrently with the step of feedback structure development. All parameters in the model therefore have a clear real-life meaning. Due to the ability to distinguish between accumulation and flow rates of the variables, stock, and flow diagrams were adopted as a diagrammatic representation of the system. The stock and flow diagram aids the writing of SD model equations since it has almost all the details required for writing the equations systematically, such as definitions of stocks, flows, auxiliary variables, constants, as well as graphical relationships among variables. By using the Powersim software, all equations and relationships input were automatically inspected thoroughly regarding the correctness of the dimensions in the model in order to ensure its dimensional consistency. Further, the extreme condition test was also conducted. This test was performed to experiment with the model at extreme conditions (e.g., spare parts shortage, equipment acquisition delay, machine unavailability, zero equipment operator, and lack of equipment maintenance). The extreme conditions were used to detect mistakes in the model structure that may force the system to generate an impossible behavior. During the extreme condition test, the model was found robust enough to behave in a realistic fashion. For instance, given no equipment assigned on site, work progress rate of the model becomes zero and operator schedule pressure rises up drastically. Also, when PM effort is no longer given to equipment, equipment reliability drops continually and mechanics' schedule pressure drops rapidly at the first glance but heavily piles up later on due to more machine downtime incurred.

Behavior Validation Test

In validating the model behavior, behavior reproduction test was performed. The main purpose of this test is to find if the model generates the same mode of behavior as observed in the real system (Sterman 2000). The test is executed by comparing model output and historical data (reference mode) qualitatively, including modes of behavior, shape of variables, asymmetries, and relative amplitudes. Variables selected as a reference mode consist of monthly repair cost, mechanics' schedule pressure, machine budget status, and number of machine operators. The comparisons of the trend line show the similarity between the reference modes and the model outputs (see Fig. 9). Further, to build more confidence, sensitivity analysis was also adopted to determine how sensitive the model is to the change in the value of selected parameters as it is imperative to know the degree to which the model may change due to a variety of reasonable alternative as-

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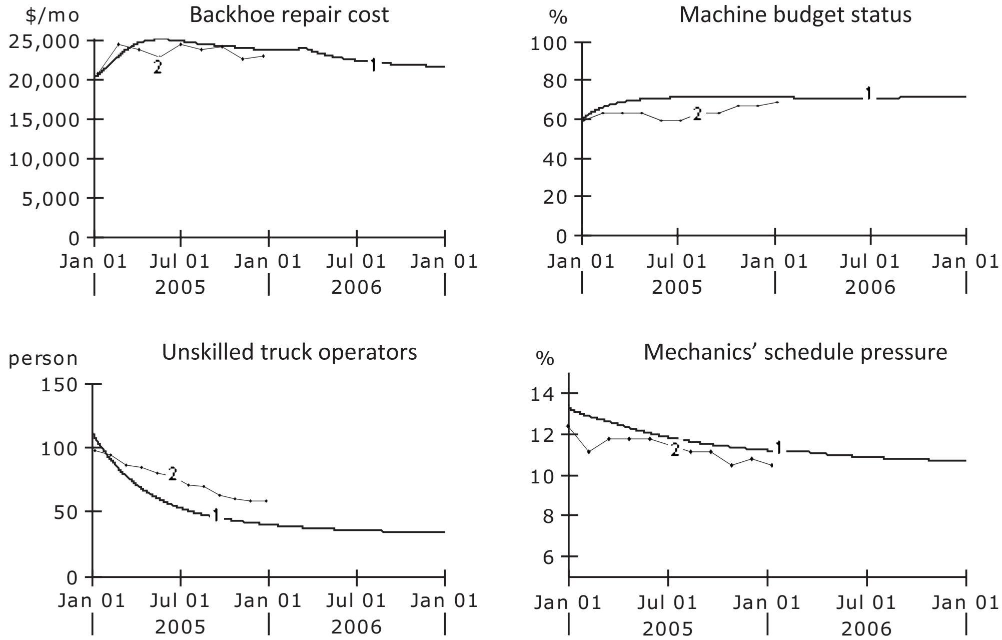

Fig. 9. Comparisons of model base run and historical data of selected variables for large contractors

sumptions (Richardson and Pugh 1981). Results show that the model is sensitive to various parameters such as machine quality upon acquisition, management commitment in proactive maintenance, relationship with dealers, and spare parts quality.

Conclusions

The aim of this paper is to give an insight into the dynamics of equipment management practices and downtime in large highway contractors. The dynamics of equipment management practices and downtime are presented through five generic feedback structures: machine acquisition, operations, maintenance, disposal, and downtime. Each of the feedback structures is interrelated and used as a framework in constructing the generic SD simulation model. A number of validation tests were used to ensure that the model is structurally and behaviorally valid.

To be successful in managing downtime, equipment management practices must be perceived as a combination of multiple feedback processes, which are interrelated to machine downtime. Indeed, downtime is interdependent and stimulated by three reinforcing cycles: schedule disruption and acceleration, operator schedule pressure creep, and mechanics' schedule pressure creep. Even though downtime can be tackled through adoption of three balancing cycles (i.e., repair outsourced adjustment, operator skill adjustment, and mechanics' skill adjustment), their expected benefits are always delayed, which retard or sometimes deteriorate the scenarios if contractors opt to stop the improvement processes. In addition, downtime is partly minimized through the reduction of disruption of work sequences by activating another two balancing cycles (i.e., rental machine adjustment and subcontractor adjustment). With high downtime, PM efforts are eroded, which in turn even worsen the scenarios as the reinforcing cycles of operator schedule pressure creep and mechanics' schedule pressure creep have now been activated. However, contractors can mitigate this problem through adoption of balancing cycle of dealer maintenance services adjustment and the reinforcing cycle of management commitment in proactive maintenance.

Future work could be directed toward studying the interactions among equipment policies that have been addressed in the study. This would be useful especially when there are multiple performance tradeoffs involved among the stated policies (e.g., adopting participatory multiskilled training policy may cause more fatigue to equipment operators and thus reduce the operator's effort in performing the autonomous maintenance policy). Additional case studies are also needed to validate the effectiveness and practicability of the proposed system and make further adjustments for a more reliable system.

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