Application of Lean Concepts and Simulation Analysis to Improve Efficiency of Drainage Operations Maintenance Crews

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Abstract: The City of Edmonton's Drainage Operations branch oversees the inspection, maintenance, and repair of the city's drainage network. This network covers an area of 700.6 km^2 to serve the city's growing population of nearly 1 million people. The activities performed by this division consume a large amount of funding and are, therefore, receptive to improvements in productivity. The study presented in this paper was conducted to develop improved work methods and engineered productivity standards for the various drainage operations. The study focused on six crews, which accounted for over 25% of the total drainage operations budget. The six crews were divided based on their respective duties: (1) cleaning mains by low pressure flushing (LPF); (2) cleaning mains by high pressure flushing; (3) scheduled mechanical cleaning of catch basins (CBC); (4) inspecting mains by televising; (5) commercial establishment investigation; and (6) service-line rodding and televising. The study utilized the concept of work simplification and focused on two crew activities—LPF and CBC work tasks—to improve crew work methods, to develop an established work standard, and to verify the proposed improvements based on the simulation model's output. These activities are described in greater detail in two case studies. The work measurement concept was implemented to develop engineered productivity standards for the remaining crews in order to improve their productivity as well. This paper describes the application of an industrial engineering philosophy of work measurement—lean production theory—and the technique of simulation analysis to capture current work methods, generate and test alternative methods, and develop new productivity standards for drainage maintenance operations crews.

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Introduction

As of September 2002, the replacement value of drainage infrastructure accounted for approximately 45% of the total City of Edmonton infrastructure facilities budget (Edmonton 2002; Mohamed et al. 2002). The 1999 efficiency report published by the Office of the City Auditor (OCA), whose goal it was to measure and to assess the rationale behind existing efficiency and productivity standards for drainage operations maintenance crew's fieldwork as well as to justify work crew size and particular levels of supervision, revealed that many crews were inefficient in their overall maintenance activity performance. As a result, the study presented in this paper was conducted as a collaboration of the City of Edmonton's Drainage Services Branch, the OCA, and the University of Alberta's Construction Engineering and Management Group. The study focuses on the application of lean production theory and simulation and uses both work analysis (WA) and work measurement (WM) concepts to develop improved work methods and engineered productivity standards. The study capitalizes on well established principles and techniques for work measurement such as those listed in Matias 2001 and Panico 1982. The proposed work standards follow the concept used by Kellie 1984, Niebel 1982, Qusnamer 2000, and Salim 1994. The concept of (WM) and (WA) has been widely used for construction activities including for labor (Dosset 1995; Thomas 1990), equipment (Gransberg 1998; Hrebar 1997) and for maintenance activities (Westerkamp 1999). Researchers have utilized different techniques for (WM) including Just-In-Time (Ballard 1995; Tommelein and Li 1999; Tommelien and Weissenberger 1999), utilizing computer-aided system (Christian and Hachey 1996), and five-minute rating (Liou 1989).

The principles of lean-thinking are adapted from lean production philosophy developed by the manufacturer, Toyota, under the supervision of engineer Taichi Ohno (Howell 1999). The term "lean" was employed to reflect both the waste reduction characteristic of Toyota's developed production system and to contrast

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J. Constr. Eng. Manage., 2006, 132(3): 291-299

this new form of production with the more traditional craft and mass forms of production. Ohno advocated a shift in the attention of developers from craft production (worker productivity) and mass production (machine productivity) to the entire production system. The underlying philosophy of lean production theory is the avoidance, elimination, or reduction of waste. Waste is considered in lean production theory as performance criteria, particularly, the failure to meet the unique requirements of a client. In other words, any time, space, or material used while performing an activity that does not directly contribute value to the finished product is considered waste. In general, the construction industry has rejected lean production theory due to the traditional nature of those working within construction (Eaton 1997). Nonetheless, extensive research has been done, which supports the benefits of lean production theory. De Solminihac et al. (1997) introduced new technologies to existing construction practices and used these technologies to analyze the situation in Chile in four planned stages: (1) a description of construction methods; (2) efficiency and quality diagnosis; (3) construction work evolution in productivity, quality, and cost curves; and (4) through an analysis of the completion and fulfillment of study objectives. The impact of mobile warehousing, concrete plant, organizational policy changes, as well as team-oriented conduct demonstrated an increase in productivity, which resulted in a decrease in complaints. Koskela and Leikas (1997) used practical experiments to explore the benefits of lean thinking and to verify the potential of lean production theory in the construction industry. Participating companies in this pilot study achieved improvements such as increases in productivity, quality, and worker participation and decreases in errors related to order information and production cycle.

Computer simulation is defined as a process of designing a mathematically logical model of a real-world system and experimenting with the model on a computer (AbouRizk and Hajjar 2000). However, the utility of simulation in the construction industry was believed to be minimal due to the complexity of simulation methodologies and an ignorance regarding their operation. As a result, several general purpose simulation languages such as *SIMSCRIPT*, *GPSS/H*, *SLAM*, and *SIMAN*, were introduced and modified. In construction research, *CYCLONE* (CYCLic Operation Network was developed.) It was a foundational step toward developing the interests of construction industry members in the application of computer simulation in their field (AbouRizk et al. 1992). This program was followed by the introduction of simulation-specific programming environments, which allowed users to write simulation-specific code or to access an accompanying functional library for general purpose simulation (GPS) and for special purpose simulation (SPS) (AbouRizk and Mohamed 2000).

This paper presents the results of research that integrated simulation using lean principles with the current work methods performed by the City of Edmonton Drainage Services maintenance crews. The challenge is to determine whether the development and establishment of productivity standards produced effective gains in productivity and whether the application of lean theory provided any productivity improvement for the crews of drainage operations using GPS models. The study focused on six activities accounting for 25% of the total drainage operations budget. The activities of these six work crews are: (1) cleaning mains by low pressure flushing (LPF); (2) cleaning mains by high pressure flushing (HPF); (3) scheduled mechanical cleaning of catch basins (CBC); (4) inspecting mains by televising (MTV); (5) commercial establishment investigation (CEI); and (6) serviceline rodding and televising (SLR). The LPF activity was selected as one of the pilot studies for evaluating these methodologies; the CBC activity was also used in the evaluation. The research resulted in the development of a productivity standard based on current work methods combined with the examination and modification of these work methods.

Low Pressure Flushing (LPF) Crews

The mainline LPF activity is a preventive maintenance and inspection activity undertaken at the City of Edmonton by 12 crews of three laborers each. LPF activities are divided into three major components: (1) work preparation steps; (2) work steps; and (3) work completion steps. Each of these steps is subdivided into a number of tasks, described as follows.

Work Preparation

The LPF crew begins by obtaining the flushing plans for the day. The next task requires the crew to perform an inspection for the vehicle to ensure that the vehicle is safe and functional and to confirm that all equipment and material necessary to perform the activity is present. The crew then drives to the first work location, parks the truck, sets up traffic control devices, and puts on personal protective equipment.

Work Steps

Each work location consists of a number of mainline stretches between manholes. The original work method started by surface and mirror inspection of the manholes at the work site. The crew opens a manhole, inspects it for condition and debris, such as sticks or twigs, removes any debris if necessary, and documents any deficiencies on a special report, then moves on to the next manhole. The flushing work begins after these tasks are completed at the high-point manhole on the work site. The crew unloads a hose and uncoils it from the nearest hydrant to the high-point manhole. A flushing valve and backflow preventer are attached to the hydrant. The hose is then attached to the backflow preventer. The hose is then hung above the base of the manhole or is inserted into the mainline and the manhole opening is secured. A worker starts to open the hydrant valve gradually while others monitor the flow of water in the manholes. Two crew members travel to each manhole in the downstream direction and monitor the water flow at each manhole. If the flow is not adequate or the manhole is beginning to back up, they signal the hydrant operator to close the flushing valve or flush at a slower rate. Flushing is continued until the line runs clear. Two or three manholes are then rechecked at random to verify that the line is clear.

After completing all the manholes in the work site, the crew members return to the high-point manhole, close the hydrant, pump standing water from the hydrant body, and remove the hose and the valve. The crew foreman then documents the time of the hydrant water use. After these tasks are completed, the crew moves to another work site and repeats the same steps as described above until the end of the day.

Work Completion

After completing the last work site in a day, the crew returns to the operations yard. They clean, inspect, and store all equipment and submit all reports to the drainage preventive maintenance foreman.

J. Constr. Eng. Manage., 2006, 132(3): 291-299

Table 1. Work Elements of LPF Activity

Number	Element description	NO[a]	AT[b]
2	Vehicle inspection	3	6.165
3	TR01	4	17.942
4	Park truck (SI)01	126	0.314
5	Remove MH cover (SI)	140	0.124
6	Inspect/check (SI)	140	0.254
7	Close MH cover (SI)	135	0.114
8	Cleanup/load (SI)	121	0.334
10	Move to next MH (SI)	123	0.766
11	Park truck	15	0.638
12	Unload equipment	18	1.140
13	Attach backflow	8	2.482
14	Open HP MH	8	0.083
15	Inspect MH	7	0.435
16	Remove debris	13	3.074
17	Place air gap device	15	1.226
18	Attach hose, hydrant	15	2.080
19	Monitor flushing	10	28.421
20	Move to first MH	14	0.828
21	Park truck number 2	111	0.270
22	Open MH	69	0.114
23	Inspect MH	67	0.805
24	Clear debris	8	3.862
25	Close MH	67	0.101
26	Load equipment	104	0.299
27	Move to next MH	128	0.906
28	Recheck MH	62	0.750
29	Monitor termination	11	3.404
30	Return to HP MH	11	1.798
31	Close gate valve	16	1.834
32	Disconnect and load	16	4.174
34	Remove, load air gap	12	1.236
35	Close MH	8	0.203
40	Idle Time	8	10.373
41	Personal Time	14	9.965
42	Excessive Work	1	1.033
43	Instruction	1	0.598
44	Productive Interrupts	3	1.905
45	Unassigned Work	1	1.466
47	TR02	22	2.892
48	TR03	4	15.109
49	TR04	1	3.188
50	TR05	6	3.447
51	Refuel	2	4.022

[a]NO=number of observations.

[b]AT=average time.

LPF Work Simplification Study (Using Simulation Model)

The LPF activity was broken down into a number of subelements during the work simplification study for collecting data on the time spent by the crew members of these elements. The same element breakdown was used to build a simulation model for the activity. Table 1 shows a list of these work elements.

A GPS tool was used to model the LPF activity. The model is built in a hierarchical form representing different levels of detail for the activity. Fig. 1 shows the highest level of the hierarchy where the activity is broken into: preparation elements for the beginning of the day, traveling elements, surface inspection elements, flushing elements, and completion elements for the end of the day. Each of these high-level activities contains a second level of detail, in which those subelements required to complete the activity are entailed. A base model was created to represent the original work method used by the LPF crews. It simulates the work of one typical working day. The model was run 100 times to collect statistics regarding the number of sites finished per day. The base model shown in Fig. 1 displayed a production of 7.72 sites/day with a range of 6.03–8.99 sites/day, which is consistent with the actual observed rates for the crews. Once the base model is created, alternative work methods can be tested to examine their impact on the daily production. The first modification that was proposed was to eliminate the initial surface inspection activity that took place before starting the flushing. The elimination of this activity showed an increase in production to an average of 11.74 sites/day. Another modification included parallel inspection of manholes during the flushing activity, resulting in an average production of 13.64 sites/day.

These improvements were easily implemented in the simulation model by disconnecting or adding elements to the model layout. Fig. 2 shows a cessation of the surface inspection activities in order to test the first modification. The simulation model provided a flexible tool for testing the significance of implementing these modifications. The negative consequences of implementing these modifications were not included in the model because these practices were not used; therefore, there is no actual time data for them. However, the model still gave a good indication of the potential areas of improvement in the activity.

Current Catch Basin Cleaning (CBC) Methodology

There are two members of the work crew in charge of the CBC activity: Equipment Operator III and Laborer I/II. Catch basin cleaning is initiated due to a complaint of backflow in the residential or commercial building. In response to this complaint, the crew cleans the catch basins along bus routes and freeways assigned by their foreman (normally an area of the city is assigned). The crew will also respond to emergencies as necessary. The process of mechanical cleaning of catch basins can be divided into three major components: (1) work preparation; (2) work steps; and (3) work completion; these components are also further subdivided into various tasks. Fig. 3 displays the overall CBC process.

Work Preparation

The foreman begins by briefing the two-person crew on the situation and assigns them a residential address from which the complaint originated. A thorough vehicle check is performed to ensure that the vehicle is safe and functional for operation. The equipment and materials necessary to perform the activity are also accounted for. After putting on personal protective equipment, the crew travels to the first location.

Work Steps

Once arriving at the worksite, the truck is parked and traffic control devices are set up. The crew opens and marks the catch basin (CB) to physically indicate work completion. Several vacuum pipe segments are assembled and attached to the truck unit. The

J. Constr. Eng. Manage., 2006, 132(3): 291-299

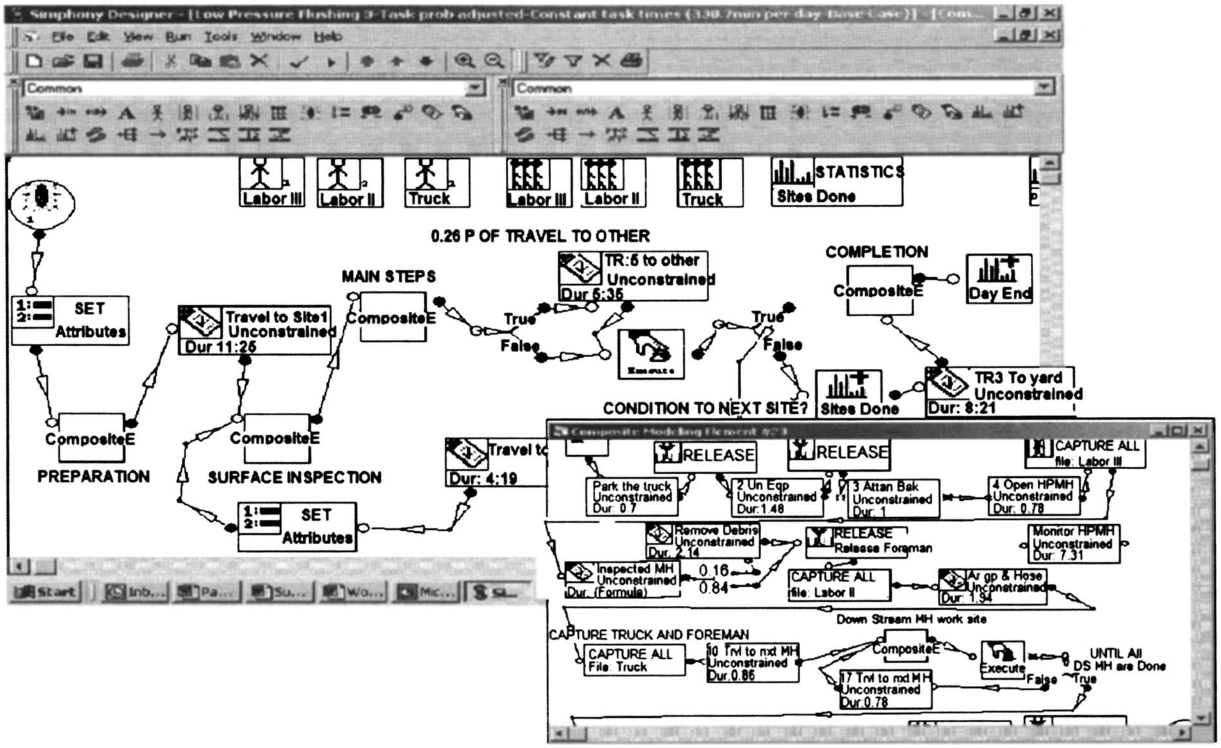

Fig. 1. Hierarchical model for low pressure flushing activity

operator lowers the vacuum into the CB and begins clearing out debris. Depending on the condition of the CB, the laborer may wash the inside of the CB while the vacuum is turned on. Sometimes, a wooden stick is used to remove debris, such as twigs, which the vacuum would be unable to remove. The vacuum pipe is then raised out of the CB and the CB is closed. All traffic control devices are stored and the crew travels to the next location to repeat the process. This cycle continues until the debris tank of the truck unit is full and the debris is discarded at a designated area of the operations yard. It is not always warranted to travel to the yard from a distant work location in order to dump the accumulated debris. In these situations, the debris water is dumped into the mainline to free some space in the debris tank. If the water tank needs filling, the truck is filled at a nearby hydrant; otherwise, the truck will be filled at the operations yard.

Work Completion

Upon arrival at the yard, the crew cleans, inspects, and stores all equipment used during the shift. All paperwork is completed and then submitted to the foreman.

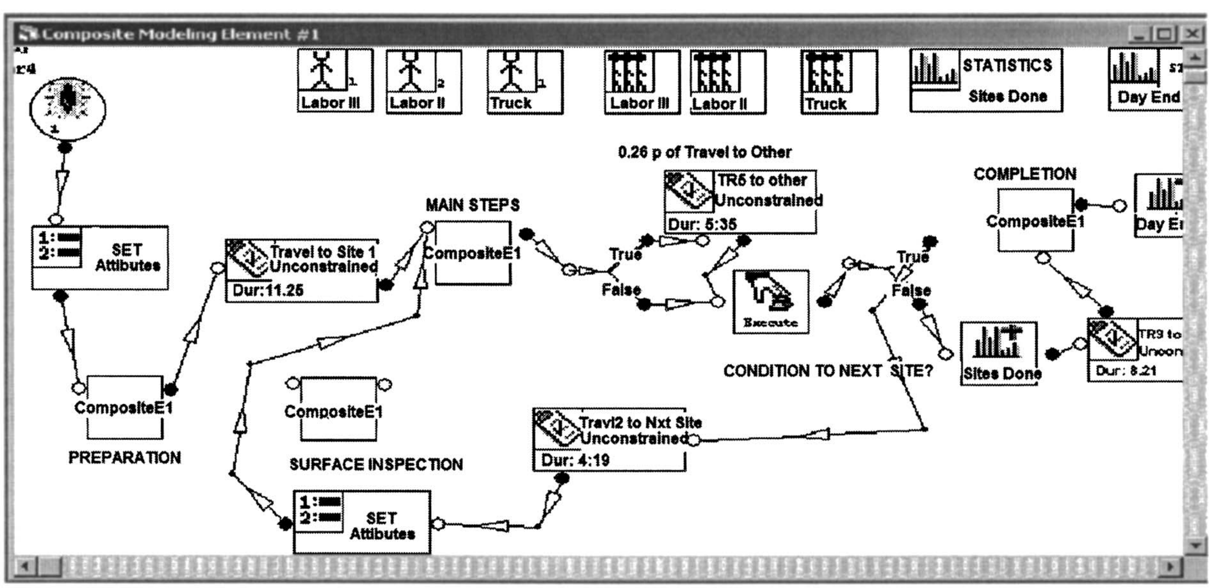

Fig. 2. Elimination of preinspection activity of manholes

J. Constr. Eng. Manage., 2006, 132(3): 291-299

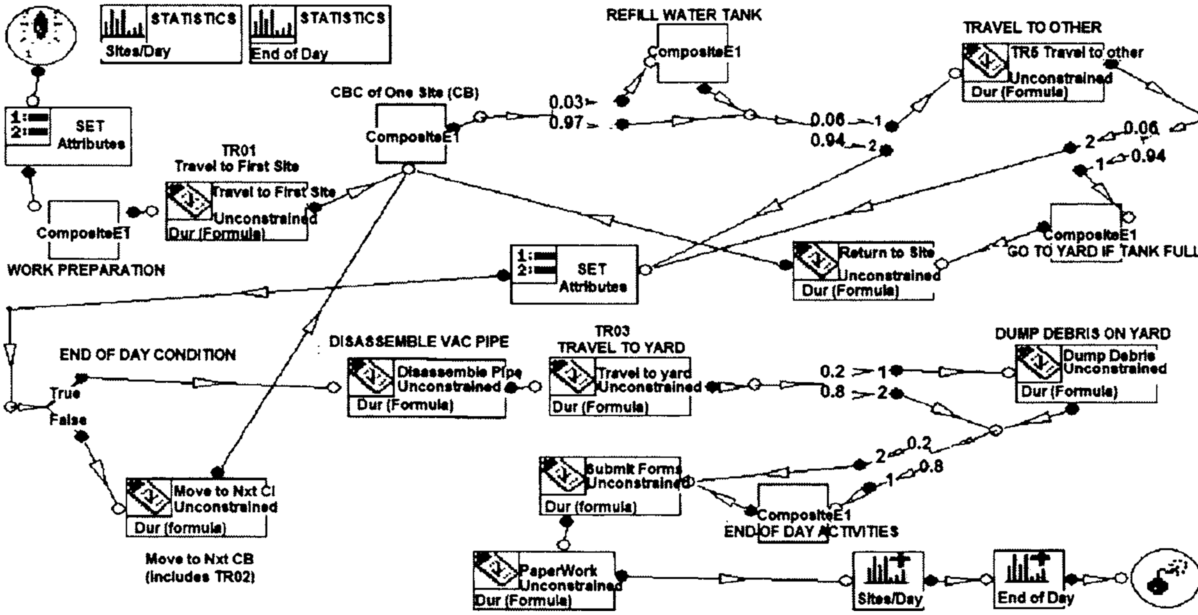

Fig. 3. Current CBC general purpose simulation parent window (Agbulos 2003, with permission)

Lean-Thinking Application

The CBC activity was broken down into a number of tasks and then further subdivided into work elements for use in the time study. In addition, each element of the work process was designated either as a value-added (VA) or a nonvalue-added work step. A VA process is composed of either operation steps or a combination of operation and inspection steps in which the basic work performed is valuable to the customer and advances the process. "Open CB," for example, is a VA process step. In order to advance the cleaning process, the vacuum must be inserted into the catch basin. This action will justify that "Open CB" is a value-added work step. Nonvalue-added (NVA) process steps are those steps that are not considered either an operation step or a combined operation and inspection step. Handling, transportation, delay, inspection, storage, and rework steps are examples of work elements that do not bring value to the customer. Also, although some activities do make a positive impact on improving safety, activities such as vehicle inspection, setting up traffic cones, and lowering and raising vacuum pipes, fall under the description of

Table 2. Basic Process Step Symbols and Descriptions

Process type	Description	NA/NVA
Operation	Any value-adding step. Directly moves a process forward (O/I & O).	VA
Handling	Loading and unloading: objects, equipment, and accessories. Also making adjustments to equipment and accessories.	NVA
Transportation	Any action that moves something, including objects, people, and information.	NVA
Inspection	Includes quality and quantity inspections, reviews, and authorization.	NVA
Delay	Unscheduled delays of materials, parts, products, and people.	NVA
Storage	Scheduled delay of materials, parts, or products.	NVA
Rework	Any unnecessarily repeated operation step.	NVA

Table 3. Part of CBC Element Breakdown and VA/NVA Identification (Agbulos 2003, with Permission)

Element	Process step cycle time	Normal time (*x* frequency)	Process step	VA/NVA
Get instructions	11.01	11.01(×1.00)	Operation	VA
Vehicle inspection	16.05	16.05(×1.00)	Inspection	NVA
Park truck and Traffic control	11.68	0.47(×24.6)	Operation	VA
Assemble vacuum pipe	7.34	2.16(×3.4)	Handling	NVA
Open CB	8.52	0.26(×32.2)	Operation	VA
Mark CB	3.96	0.17(×22.9)	Operation	VA
Lower vacuum into CB	14.19	0.47(×30.1)	Handling	NVA
Vacuum debris	37.46	1.29(×29.1)	Operation	VA
Use stick puller	1.35	2.70(×0.5)	Operation	VA
Wash CB/vacuum	6.29	1.97(×3.2)	Operation	VA
Raise vacuum pipe	7.14	0.25(×28.4)	Handling	NVA
Disassemble vacuum pipe	5.34	1.62(×3.3)	Handling	NVA
Close CB	6.28	0.20(×31.0)	Operation	VA
Load traffic cones	11.30	0.52(×21.6)	Storage	NVA
Move to Next CB	42.43	1.39(×30.6)	Transportation	NVA
Clean equipment	16.67	10.42(×1.6)	Operation	VA
Store equipment	0.79	0.72(×1.1)	Storage	NVA
Paper work	6.82	9.75(×0.7)	Operation	VA

J. Constr. Eng. Manage., 2006, 132(3): 291-299

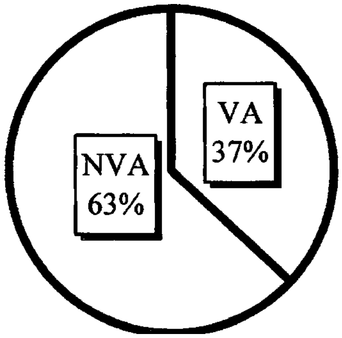

Fig. 4. CBC breakdown of VA versus NVA minutes

NVA steps, since they can be performed by a service crew. Table 2 summarizes the basic process steps used in work simplification. By utilizing these symbols, the NVA process tasks can be identified visually. Table 3 represents part of the element breakdown for the CBC maintenance activity. Column 3 represents the total accumulated time over the entire shift. For example

$$NT = RT/NO = 374.7/291 = 1.29$$

where NT=normal time in the "vacuum debris" task; RT=raw time; and NO=number of observations.

Therefore, the "process step cycle time" for the "vacuum debris" step will equal normal time multiplied by the frequency which is, more precisely, 1.29×29.1, or 37.46 min.

Potential means for reducing the fraction of nonvalue-added tasks in order to increase the fraction of value-added work steps were also investigated; value-added and nonvalue-added tasks should possess a reasonable ratio—at minimum 50/50. The ideal for this level of task, or work step, is an 80:20 ratio, which will minimize the amount of NVA steps found in the entire business process. If the NVA steps are not minimized at the task level, 90–98% of the entire business process will be nonvalue adding. However, any improvement in the overall productivity of the crew is acceptable and shows progress in the right direction. The breakdown of the VA and NVA process steps for the CBC crews are 37 and 63%, respectively, as illustrated in Fig. 4. This indicates that the crew is inefficient in both its work methods and in the deployment of workers. The crew, through the application of lean concepts, better scheduling, routing, and developed engineered productivity standards, could have significantly increased their performance. The predominant NVA steps include transportation, handling, and delays, accounting for 29, 25, and 7%, respectively, of the total time on the job. The delay time consists mainly of unrelated work (53%), personal time (8%), excessive work (14%), and idle time (22%).

Developing suggestions to improve performance in all crews requires the input, support, and consultation of training personnel, crew members, management, and Occupational Health & Safety (OH&S). Most improvement ideas, however, have only been discussed with the Office of the City Auditor and are used solely for illustrating the potential gains in productivity subsequent to implementation. Technological, advancements, in some instances, are the only possible means of improving the cycle time of a process step and the productivity of a crew. In many cases, the keys to enhancing the crew's productivity involved slight changes to the process combined with technological advancements.

Simulation Application for Current Situation

The current CBC GPS model uses a hierarchy that represents different levels of detail for the activity. The model represents a typical workday, although it does not include delay time, which is the lost time associated with machine breakdown and unforeseen traffic delays. The highest level of the hierarchy (parent-level), as shown in Fig. 1, represents the work preparation, work steps, work completion, and transportation elements. Actual catch basin cleaning is found at the lowest level of the hierarchy (child level), as shown in Fig. 5. The model runs for 100 simulation days, collecting statistics on the number of locations (or catch basins) cleaned per day. The output of the model revealed that the mean

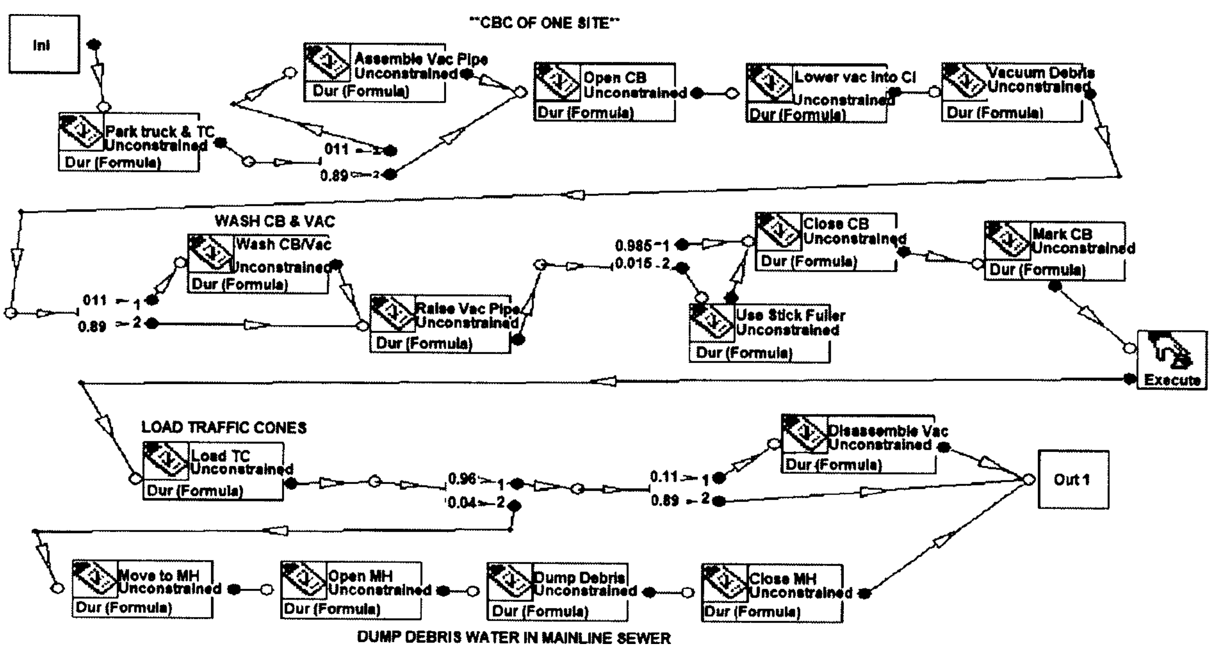

Fig. 5. Current CBC simulation model child window of "CBC of one site" (Agbulos 2003, with permission)

J. Constr. Eng. Manage., 2006, 132(3): 291-299

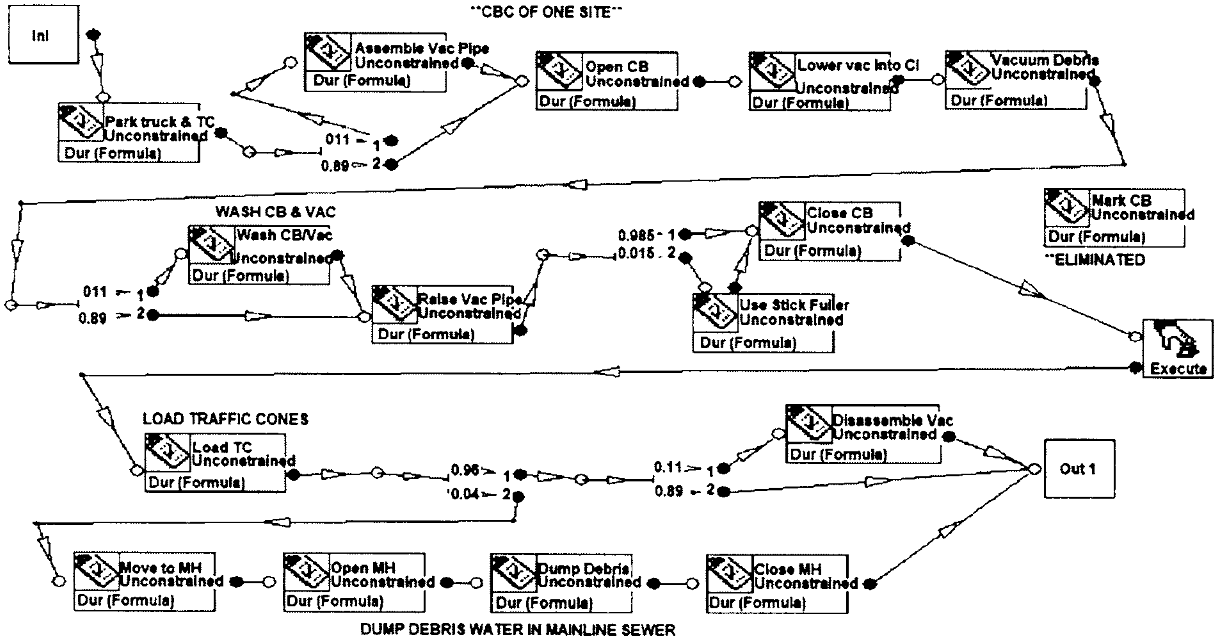

Fig. 6. Modified "CBC of one site" work method

productivity of the current work method is 42.52 locations/day and ranges from 15 to 54 locations/day.

Applied Lean Thinking

The current CBC method demonstrates a state of nearly complete saturation, that is, not many modifications to the work process are available. Fig. 6 displays the modified CBC model. "Mark CB" element can be eliminated works because it can be performed by the laborer at any time during the cleaning of the CB and does not need to be modeled. Although it is a value-adding work step, based on observing the crews during the data collection period, it seems to be the only appropriate modification possible at this time. As a result, there will not be much difference in the ratio of nonvalue-added tasks to value-added tasks. In terms of the implementation of an organization-wide automated labor timesheet system, the data collected do not seem appropriate for implementing lean theory within a simulation model because of the relatively short cycle time of the "Paper work" task. It was not captured fully during the time-study data collection period. After implementing the suggestions, the productivity improves from 42.52 to 44.25 sites/day. An increase of 1.73 sites/day or 4% proves that an enhancement in productivity by lean thinking, although small, is possible. In addition, Fig. 7 displays the difference in productivity gained before and after the application of lean principles. For instance, at a probability of 42%, the productivity is higher for the modified work method than for the current work method. See Table 2 for a complete summary of the results.

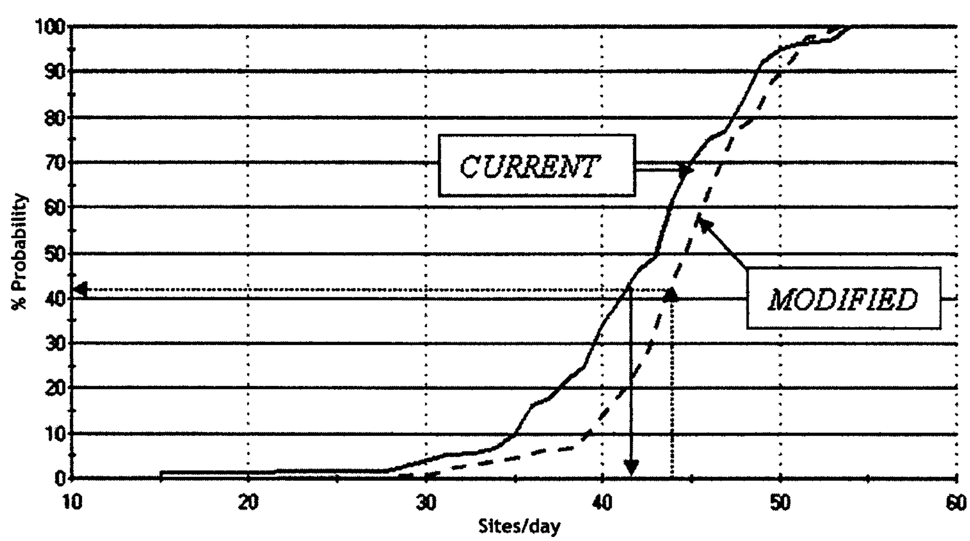

Fig. 7. Cumulative distribution functions of current and modified CBC methods (Agbulos et al. 2003, with permission)

J. Constr. Eng. Manage., 2006, 132(3): 291-299

Table 4. Summary of Results after Applied Lean Thinking to Simulation Models (Agbulos et al. 2003, with Permission)

Productivity effects summary					
			Simulation results		
Crew	Historic daily throughput	Work measurement	Current methods	Improved methods	Potential change (%)
CEI	6.68 sites/day	13.18 sites/day	13.93 sites/day	16.24 sites/day	+16.6
SLR	3.66 sites/day	3.99 sites/day	3.76 sites/day	4.16 sites/day	+10.6
CBC	43.49 sites/day	40.17 sites/day	42.52 sites/day	44.25 sites/day	+4.00
HPF	525.38 m/day	523.39 m/day	580.73 m/day	607.96 m/day	+4.69
MTV	345.87 m/day	360.53 m/day	366.35 m/day	382.08 m/day	+4.29

Summary of Results

The results of the application of lean-thinking concepts to GPS models as developed by the Univ. of Alberta for work crews are summarized in Table 4. The "Historic daily throughput" was calculated based on an accumulated average over a 5 years period (1995–2000). The "Work measurement" data are the current daily accomplishments based on a 90% confidence level and 5% precision. The "Potential % change" is the percentage increase in productivity of the work crews. CEI and SLR work steps demonstrated the greatest productivity gain, and therefore, these steps would have a higher priority over the rest of the crews in terms of implementation and investigation by management, training personnel, and OH&S. In addition, a cost-benefit analysis and an organization-wide commitment and cooperation by all parties involved would be required prior to any implementation.

Limitations

The reality of this research is that simulation models cannot account for every potential scenario. As a result, models were developed using probability branches. Each of these branches was attached to an element (or work step) and was assigned a probability unless the element was assumed to occur every cycle. Activities were either assumed to take place after every cycle (entire shift) of the actual maintenance work (such as in mainline televising) or as elements taken out of sequence that could occur at any moment (e.g., delays such as unrelated work, excessive work, idle time, personal time, productive interruption, and instruction) and were subsequently assigned a probability value (percent). The models assumed a continuous workflow; additionally, certain instances of the application of lean concepts to current drainage operations maintenance crews rely on assumptions. These assumptions had to be made due to either poor quality data or in the event that data had not been collected at all. An assumed reduction, based on judgments drawn from observing work crews during a work element's cycle time, occurred whenever there was the suggestion of introducing a new technology or tool, such as the automated labor tracking method, a more versatile mainline camera, or even the tool belt. Having such technologies in place may increase the accuracy of cycle-time reduction in a task. Finally, all suggestions must undergo consultation and gain support from Drainage Operations management, training personnel, and OH&S.

Conclusions

This paper presented a study that involved the development, testing, and verification of engineered productivity standards. These aims were accomplished through work simplification techniques and work measurement concepts. The use of simulation tools helps to identify effective changes to the existing work methods. The study focused on the five drainage activities: low pressure flushing, high pressure flushing, inspecting mains by televising, industrial waste inspection, and catch basin cleaning. It began with a pilot study on low pressure flushing. After collecting adequate data, a production standard was developed based on original work methods. The newly developed work method for LPF was implemented in a pilot crew and subsequently applied to all 12 LPF crews. The results of the developed work method on LPF improved the productivity of the LPF crew from flushing 2556.3 to 2,820 m of sewer line/day.

The paper also illustrated a 4.00% improvement in CBC productivity that can be attained by applying lean theory to current CBC work methods. Though the results are successful, that is, improvements in productivity have been demonstrated by applying lean concepts and by using simulation as a means for achieving productivity improvement, the extent of the benefits of such a study can only be experienced through implementation.

The detailed investigation and the description of the framework for integrating lean theory and simulation methodologies provide the tools necessary to improve labor productivity for drainage operations maintenance activities. The pilot study demonstrated that a substantial decrease in financial and human resources could be achieved. The success of the pilot study paved the way to develop similar processes for other drainage operations crews.

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