

Synchronization-based model for improving on-site data collection performance

Ming-Kuan Tsai ^{a,*}, Jyh-Bin Yang ^b, Chang-Yu Lin ^a

^a Department of Civil Engineering, National Chiao-Tung University, 1001 Ta Hsueh Road, Hsinchu 300, Taiwan

^b Institute of Construction Management, Chung-Hua University, 707 Sec. 2 Wu Fu Road, Hsinchu 300, Taiwan

Accepted 13 July 2006

Abstract

Comprehending activity status is essential to successful project management. When construction workers report activity information, project managers understand activity progresses. This procedure forms information exchange and flow. However, the lack of up-to-date information still causes project problems (such as increasing unnecessary costs, making erroneous decisions and improper activity scheduling), and highlights the importance of on-site data collection. For improving this condition, this study integrates two managerial philosophies (“theory of constraints (TOC)” and lean construction) to propose a synchronization-based model. When this model was applied for a material management case study, asynchronous operations accompanied with unnecessary subprocesses were recognized as an influence on on-site information production and transmission. This study then applied synchronous operations based on worker cooperation to resolve these problems, and evaluated the efficiency obtained by the identified measurements. The proposed model offers not only a prototype of synchronous on-site data collection, but also a mechanism for activity performance improvement.

© 2006 Elsevier B.V. All rights reserved.

Keywords: Theory of constraints; Lean production; Lean construction; Information management; On-site data collection; Synchronization

1. Introduction

Comprehending activity and site status is essential to successful project management. Most construction companies require their staff to fill in various site reports including labor, equipment, material and progress reports. Project managers then use these reports to control activity progress and plan schedules. This procedure forms information exchange and flow. However, unauthentic on-site data collection not only causes a lack of proper information but also produces many problems, such as making erroneous decisions and increasing project costs [1]. This issue highlights the important relationship between on-site data collection and information flow.

Previously, besides recording activity details with pen and paper, most construction workers needed to complete site reports through manual operations and data transfer, such as using

calculators to compute material usage and working hours [2]. Project managers thus wasted time in waiting for and searching these completed reports while checking activities and schedules. Clearly, time-consuming paperwork is a constraint on information flow from on-site data collection to off-site data analysis, eventually becoming obsolete owing to the impossibility of just-in-time information exchange [3].

Recently, integrating Information Technologies (IT) and computerized systems to increase efficiency for on-site data collection has been valued, and has become a basic component of project management [4]. Automated data identification systems (including bar coding, optical character recognition (OCR), magnetic stripe (MS), and radio frequency (RF)) are common applications to assist construction workers in completing site reports [5–8]. For example, when scanning bar codes instead of handwriting data, construction workers can directly transfer material names and quantities into computerized material reports.

Additionally, more and more construction companies have applied computer-based management information systems (MISs), rather than paper-based management, to analyze complex

* Corresponding author. Tel.: +886 3 5712121; fax: +886 3 5716257.

E-mail addresses: twmksai@ms95.url.com.tw (M.-K. Tsai), jyhbin@chu.edu.tw (J.-B. Yang), cylin@mail.nctu.edu.tw (C.-Y. Lin).

site information. The use of the Internet to accelerate information transmission and reduce communication barriers has led to the development of project-specific web sites [9]. When construction workers connect to MISs to store activity details using the Internet and electronic devices (e.g., laptops and personal digital assistants (PDAs)), project managers immediately obtain integrated site reports. Numerous researchers have demonstrated that IT-based on-site data collection not only offers more working efficiency for construction workers but also delivers up-to-date information for project managers [2,4,8–10].

Nonetheless, when construction workers perform IT-based on-site data collection, asynchronous operations (defined as two or more interdependent processes that are separately executed yet can be simultaneously executed) accompanied with unnecessary subprocesses (defined as executed subprocesses that require resource and offer no efficiency for activity results) remain to interrupt information flow and influence the downstream processes. For instance, during materials checking, construction workers use bar-code applications to report material details. When material statuses are changed, bar-code labels need to be updated to avoid incorrect information. Namely, incorrect bar-code labels lead to the asynchronous completion of checking materials and recording material details. Scanning incorrect bar-code labels seems to be an unnecessary subprocess.

This study integrates two managerial philosophies (“theory of constraints (TOC) [11,12]” and lean construction [13,14]) to propose a synchronization-based model for the above issue. While a material management case study is examined, this model offers continuous directions and stages to improve the recognized asynchronous operations and unnecessary subprocesses. Besides evaluating the efficiency by several identified measurements, this study shows the improvements between asynchronous and synchronous operations (including cycle time, process and flow transparency, activity productivity and information interdependence), and confirms a prototype for synchronous on-site data collection. For widely achieving synchronous operations, a synchronous system based on this prototype is developed in a companion paper [15].

2. Information flow and on-site data collection

Effective on-site data management (including on-site data collection, and data transfer, integration and storage) ensures that site information can be accurately represented [2,4]. Therefore, the objectives of information management and flow include: satisfying information requirements of project participants to avoid activity problems, schedule delays and decision errors; providing new perspectives and standard managerial tools; enhancing communication and cooperation to achieve project management functions, and so on [16–19].

When construction workers report site status, the results consist of the information produced from a series of continuous processes and subprocesses. Integrating these interdependent processes and subprocesses into a flow raises an improvement level, and creates a structured understanding to resolve existing problems [20,21]. Direct impacts of blocking or delaying one flow process can influence the next process and the whole

efficiency. Similarly, as the source of information flow, on-site data collection affects off-site data analysis and project schedules. Consequently, this study focuses on on-site data collection including interdependent processes and the formed flow.

Fig. 1(a) illustrates the original procedure for collecting material details at construction sites. Construction workers executed six main processes to fulfill the requirements for material management while performing material reports. Construction workers first checked materials (process 1), and then filled in material records with pen and paper (process 2). When returning to the site offices, construction workers confirmed (process 3), corrected (process 4) and submitted (process 5) these records. Office staff stored these records (process 6) and used them to produce material reports. After reading the delivered reports (off-site data analysis), construction managers gained an understanding of the material statuses.

Since construction workers asynchronously performed the above processes, the procedure for completing on-site data collection was time-consuming. As a result, besides the increased project costs, the lack of timely material information led to poor decisions and schedules [1,2]. Unfortunately, this condition is very common in the construction industry. According to the research for tunnel construction operations, an optimized project implies that all activities are synchronized to minimize the waiting or idling time and results in 100% resource utilization [22]. Hence, efficient on-site data collection does not merely imply letting information flow to operate.

Interestingly, while construction workers apply IT applications for on-site data collection, the simultaneous performance of two or more processes increases the activity efficiency. Meanwhile, the above six processes are combined to form a new activity flow. For example, when construction workers simultaneously submit and store completed reports via the Internet, returning to site offices to deliver reports is unnecessary. Fig. 1(b) illustrates that the updated on-site data collection for IT-based applications includes three main processes: “checking materials and filling in records” (process 1), “confirming and correcting records” (process 2) and “submitting and storing records” (process 3).

However, in addition to carrying other devices for on-site data collection, construction workers cannot execute application devices while both hands are unavailable. For instance, when controlling machines to transport materials at construction sites, construction workers have difficulty in applying laser scanners to read bar codes. Accordingly, some environmental factors prevent construction workers from acquiring and exchanging information. Because of these conditions, checking materials and filling in records (process 1) are separately completed to form asynchronous operations. Meantime, these operations cause unnecessary subprocesses (e.g., waiting for the delivered data) and discontinuous information flow.

Consequently, Fig. 1(c–d) show that asynchronous operations and unnecessary subprocesses commonly occur in process 1 and affect the relation between processes 1 and 2. When asynchronous operations are synchronized and unnecessary subprocesses are eliminated, Fig. 1(e) displays that the synchronous on-site data

collection allows the processes 1 and 2 to become closer to each another. Meanwhile, the whole cycle time is also reduced, since the operation time is condensed. Comparing Fig. 1(e) with Fig. 1(a–b), the off-site data analysis of information flow can be executed early.

Furthermore, TOC philosophy underpins the working principles for planning system improvement [23]. Lean construction resting on production management principles is designed to better meet customer needs while reducing resource use [13]. Since these philosophies offer new methods for achieving the desired

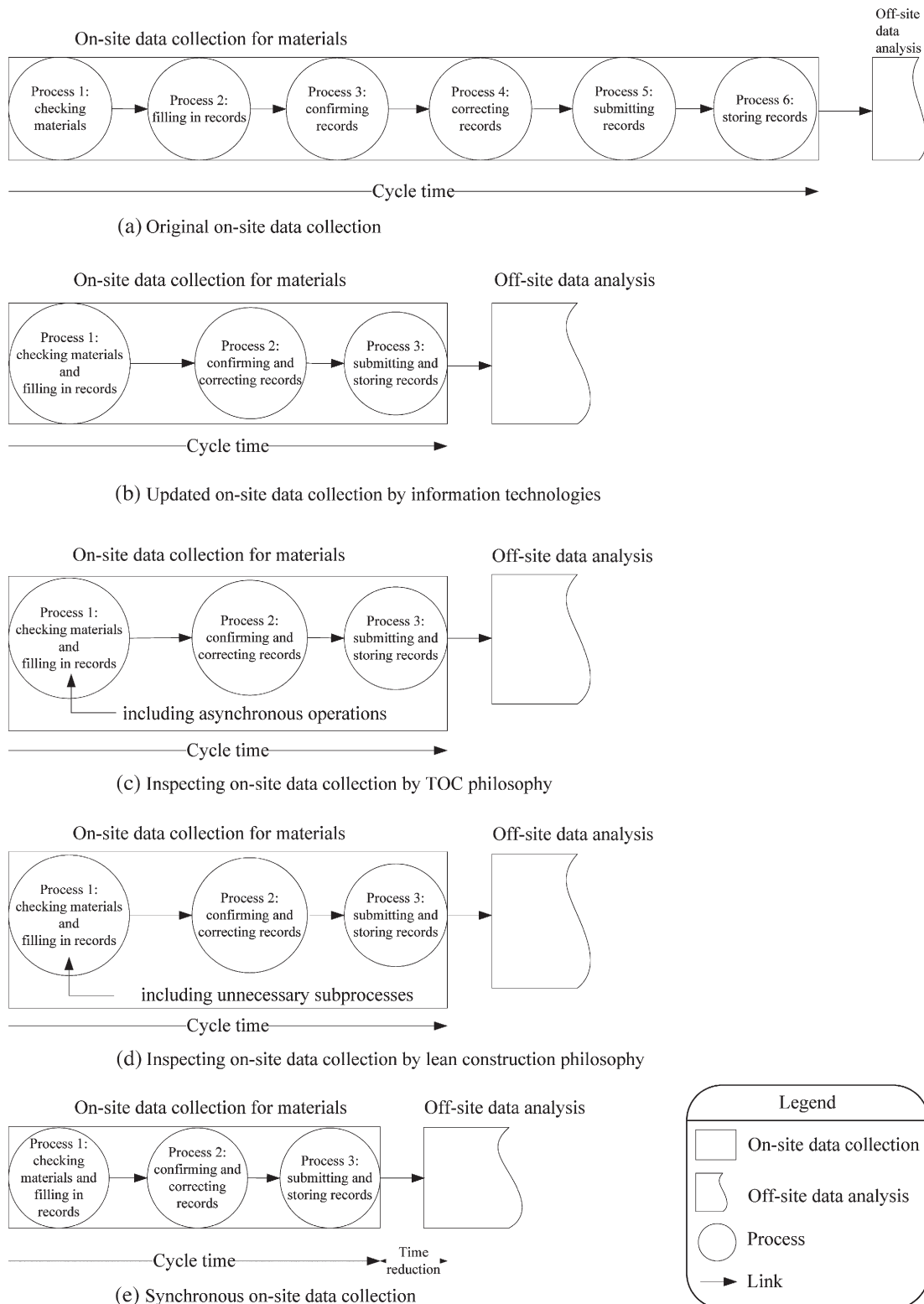


Fig. 1. Process relationships for different on-site data collection approaches.

objective (achieving synchronous on-site data collection), this study applies them to develop a synchronization-based model.

3. Applied managerial philosophies

3.1. Theory of constraints (TOC)

Based on the TOC, manufacturing systems seem to be chains connected by numerous elements; however, these chains will break at the weakest link and become discontinuous regardless of the strength of other links. Each system contains one weakest link that ultimately limits performance [11,12,24,25]. Hence, the recognized weakest link can be termed as the main constraint. Because improving any non-constraints other than the main constraint does nothing to enhance overall strength, resolving the main constraint is the basic solution to increasing system performance. Similarly, the above concepts properly describe the relationship for interdependent processes and on-site data collection discussed in this study.

To implement this philosophy, Goldratt proposed five sequential steps (step 1: identifying the constraint; step 2: exploiting the constraint; step 3: subordinating everything else to the above decision; step 4: elevating the constraint, and step 5: going back to step 1) to examine and eliminate the main constraint of a system [12]. Three operational measurements (Throughput (Tp), Inventory (Iv) and Operating Expense (OE)) and three bottom line measurements (Net Profit (NP), Return on Investment (ROI) and Cash Flow (CF)) were developed and recommended to determine the system improvement.

Based on the direct and indirect relationships of operational and bottom line measurements, Goldratt and Fox stated that when the Tp is increased without adversely affecting the Iv and OE, the three bottom line measurements are simultaneously increased [11]. The same result occurs when the OE is decreased without adversely impacting the Tp and Iv. However, decreasing the Iv directly increases only the ROI and CF, since the indirect impact of Iv on the three bottom line measurements is typically estimated through the additional delivery. Consequently, if the Tp is increased and the Iv and OE are decreased, the NP, ROI and CF are also increased [11,12,24].

Although the essence of TOC seems to just focus on the main constraint, the improved system may encounter new interdependence and variations. Continuous improvement is necessary, because the optimum performance of the whole system is not the same as the sum of all the local optima [24]. Thus, Goldratt suggested that inertia should not be allowed to cause system constraints. The goal of TOC philosophy is always to find out and break a main constraint to achieve better system performance [12,23].

3.2. Lean production and construction

While Ohno (a chief engineer of the Toyota Motor Company) was the first to propose the lean production, more and more researchers and companies have investigated the related concepts [26]. In the lean production, a process can be classified to two different types: unnecessary and necessary. An unne-

cessary process (or called “waste”) occurs when it uses resources (e.g., time, manpower, equipments and cost) to make a zero or negative contribution to the system; otherwise, it is a necessary process [13,26]. Skipping these unnecessary processes involved in manufacturing procedures does not influence the results, and enhances the efficiency of resource usage.

In contrast, unnecessary processes in construction and manufacturing arise from the same activity-centered thinking [14]. Thus, lean construction, applying the concepts of lean production to reduce project cost and duration for construction domains, is proposed. When lean construction is implemented, the differences between the original and improved managerial procedures include: developing clear objectives for the executed process, ensuring concurrent design for the product and process, and offering maximum performance for project participants [14].

A growing number of case studies relating to the lean construction have been discussed. For example, Koskela depicted the feasibility of applying the new production philosophy for construction management [13]; Finch examined the role of stand-alone or embedded systems in the context of a lean approach [21]; Caldas and Soibelman showed the automated text classification methods supporting the implementation of pull techniques in construction management information systems [27]; and Howell and Ballard explained the implications and key production principles of lean construction [28].

In sum, the above studies describe the activity efficiency improved from reducing waste, variability and cycle time; simplifying systems by minimizing the number of components and steps; increasing value, output flexibility and process transparency; building continuous improvements; and so on [13,21,27–29]. Consequently, integrating TOC and lean construction philosophies with on-site data collection provides a helpful method of improving on-site data collection performance (e.g., reducing operation time), eliminating unnecessary subprocesses (e.g., waiting for the inspection results) and reaching better efficiency (e.g., increasing working productivity) to smooth information flow.

4. Synchronization-based model

Although TOC was designed for application in for-profit companies, a number of alternatives have been suggested to modify the expressions of TOC measurements (e.g., Throughput and Inventory) to reflect progress towards non-monetary goals [24]. Comparing the original and improved systems is a direct method for understanding whether the desired improvement goal has been achieved. Consequently, according to the TOC and lean construction philosophies, this study proposed a synchronization-based model offering five sequential stages and six interactive measurements for inspecting activity flow.

The five stages (Fig. 2) include: process analysis and integration (stage 1) for combining interdependent processes into an activity flow; problem identification (stage 2) for focusing on the activity flow to recognize the main problem; solution generation (stage 3) for resolving the determined problem; performance evaluation (stage 4) for understanding the obtained efficiency through the defined operational and bottom

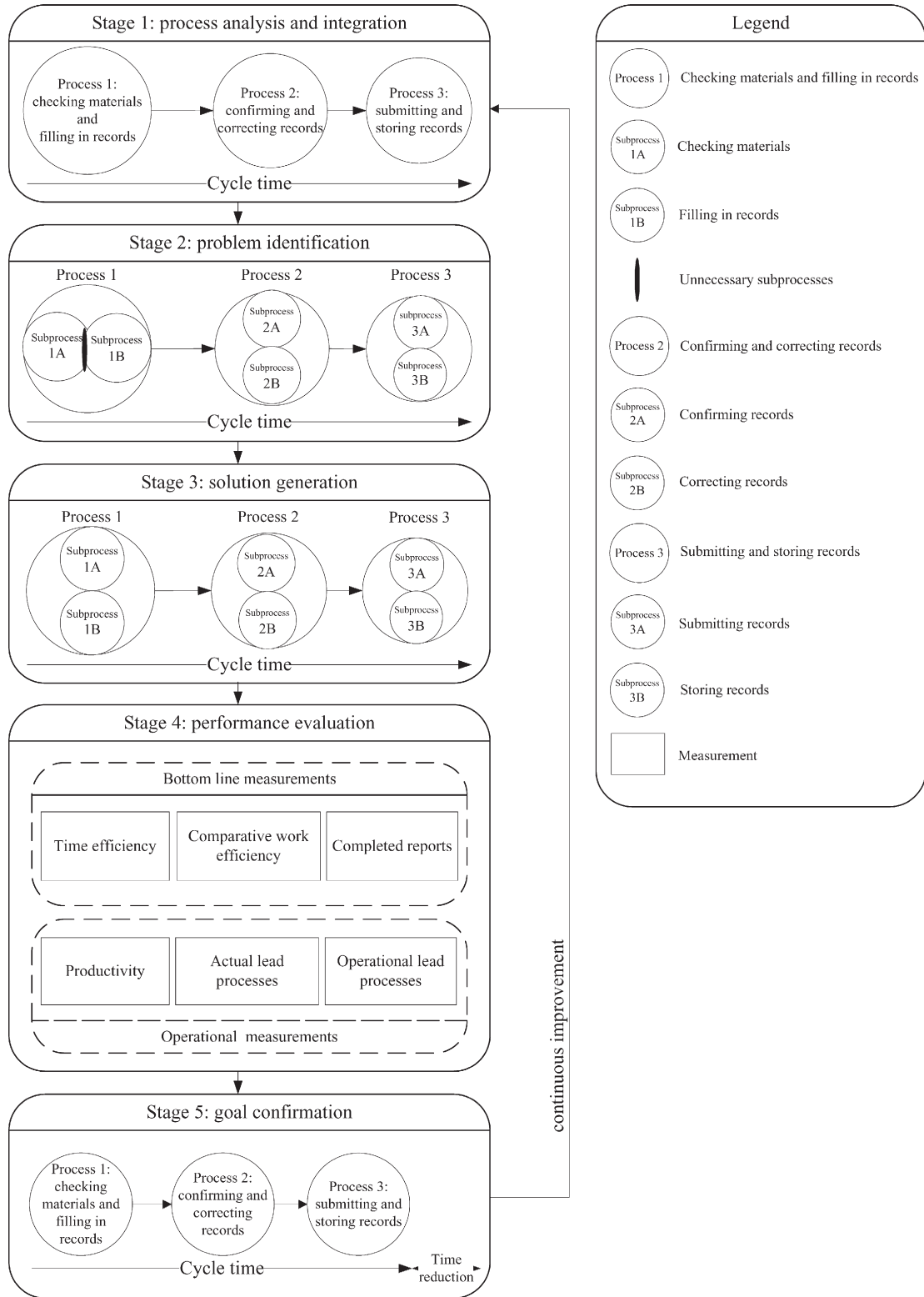


Fig. 2. Synchronization-based model for on-site data collection.

line measurements, and goal confirmation (stage 5) for implementing the improved activity flow. Meantime, because of the new interdependency of processes, subprocesses and activity flow, continuous improvement is the way for achieving higher performance requirements.

Fig. 2 (stage 1) displays that building an activity flow consisting of various interdependent processes and subprocesses is the first key step in performance inspection. This flow helps to identify the problems influencing activity performance. The cycle time for completing the whole flow includes execution,

communication, inspection, wait and move time. The above subprocesses, processes, and cycle time represent activity productivity and performance.

When a process or a subprocess is delayed by existing problems, the activity flow is affected to be discontinuous. This discontinuous flow not only wastes resources (e.g., operation time and project cost) but also reduces activity productivity. Moreover, although several problems exist, resolving the main one (called a “constraint” in TOC philosophy) is the key to increasing visible performance, because this problem is the weakest link in the whole flow. Hence, stage 2 (Fig. 2) aims to identify the main problem. Observing and recording actual activity conditions are direct methods of achieving the above purpose.

This model classifies the executed processes (including subprocesses) into actual (defined as the designed processes for completing an activity) and operational (defined as the additional executed processes for completing an activity) lead processes to decide solutions for the recognized main problem in stage 3 (Fig. 2). A proper solution needs to simplify the actual lead processes, avoid the operational lead processes, and reduce operation time and resource waste. When this solution is applied for the inspected activity, testing results must be evaluated to understand the efficiency obtained.

To evaluate the system improvement, this model provides operational (defined as the measurements for reflecting activity performance) and bottom line (defined as the measurements for illustrating efficiency improvement) measurements in the stage 4 (Fig. 2). Because the operational measurements directly and indirectly impact the bottom line measurements, these relationships determine whether the improved flow other than the original flow successfully creates more activity performance. Thus, this model confirmed the desired goal in stage 5 (Fig. 2). If a higher activity performance is required or efficiency improvement fails to satisfy expectations, this model also permits continuous improvement to repeat the above five stages to continuously inspect the formed flow. To summarize, the proposed synchronization-based model is an integrative approach for improving activity performance.

5. Model implementation

This study applied the proposed model to a material management case study. The interdependent processes for collecting on-site material data were first integrated into a connected flow. After observing and measuring the actual activity procedures, this study identified the main problem affecting the information production and transfer in the next stage. A solution was then suggested for the recognized conditions in the third stage. Subsequently, the fourth stage demonstrated the performance improvement as evaluated through the operational and bottom line measurements. Finally, this study confirmed the desired goal.

5.1. Process analysis and integration

The case study was a 120-day maintenance project (including floor-repair, wall-painting, water-proofing, roof-drainage, and

related activities) for a five-story building. The construction workers had used laptops to complete all Internet-based documentation (including activity, material, equipment, labor, and related reports), and then submitted these reports from the construction site to the remote databases via WLAN (Wireless Local Area Network) environments. These Internet-based applications were kept in web servers that consisted of the Microsoft Windows 2003 server and IIS 6. Clearly, the on-site data collection was performed as shown in Fig. 1(b) since construction workers completed processes 1 to 3 using IT applications.

After discussing daily activities related to site reports with the construction workers and managers, this study focused on the procedures of collecting on-site material data to identify existing problems. Since various materials (e.g., cement, paint, sand and asphalt) were used in different ongoing activities, three individual material reports (inventory, use and requirement reports) required completion during the daily working period. Table 1 and Fig. 3(a–c) show the material details and screenshots for the material records.

Additionally, while suppliers delivered materials, construction workers confirmed that the ordered materials matched the delivery receipts, and then entered the results into the material inventory report. Construction workers also filled in the material use report when activity workers received and used materials. If the materials were of low quantity or new activities were processed, construction workers had to prepare materials and fill in the material requirement report.

When this study understood the flow for completing material reports, stage 1 (Fig. 2) shows that the cycle time of each completed record was from processes 1 to 3. To comprehend the relationships of operation time and processes, this study measured the total cycle time while Construction Worker 1 (Fig. 4) performed various material records. Importantly, the above total cycle time was the sum of the cycle time of each record, but excluded the move time while Construction Worker 1 switched to the next cycle for on-site data collection.

In other words, after completing a material record, Construction Worker 1 walked to another location to perform the next material record. This move time was ignored, since Construction Worker 1 did not check the materials. However, Construction Worker 1 put the laptop on the floor (or in some other place) and walked two meters to check the materials, then returned to the laptop and completed the record. The cycle time contained the move time, because Construction Worker 1 had checked materials. Based on the average cycle time (Table 2),

Table 1
Various material records including material details

Record types	Material details
Material inventory record	Defined material number; material name; material quantity; storing location; supplier name; material test, and testing report number.
Material use record	Defined material number; material name; used quantity; activity name; activity location, and worker name.
Material requirement record	Requirement date (month and day); defined material number; material name; material quantity; activity name, and activity location.

(a) material inventory record

(b) material use record

(c) material requirement record

Fig. 3. Required material records.

this study analyzed the test results to identify the main problem below (stage 2 of Fig. 2).

5.2. Problem identification

Table 2 illustrates that the average cycle times for material inventory, use and requirement records were 240, 173 and 116 s. However, compared to other processes, Construction Worker 1 spent most time on executing process 1 (230, 170 and 113 s for the three records, respectively). Based on the observations of this study, the most common situations were those in which Construction Worker 1 kept away from the laptop and had unavailable hands for information production while checking materials. Fig. 2 illustrates that subprocess 1A (checking materials) delayed the interdependent subprocess 1B (filling in records) to cause asynchronous operations, and thus increased the operation time. After completing process 1, Construction Worker 1 spent less time on processes 2 and 3. Because Construction Worker 1 was using the laptop, subprocesses 2A–2B and 3A–3B (Fig. 2) were synchronously completed.

Fig. 2 (stage 2) displays that asynchronous operations (checking materials and filling in records asynchronously) existed in process 1 to influence other processes and on-site data collection. Hence, process 1 was the main problem. Besides asynchronous operations, the unnecessary subprocesses (such as move and wait) affected the cycle time, efficiency of data input and output, duplicate steps, process transparency, and so on. For example, when the hands of Construction Worker 1 were busy with materials

checking, the interdependent processes (subprocess 1B and processes 2 and 3) waited for the ongoing process (subprocess 1A). Moreover, difficulties in accessing the laptop could lead to Construction Worker 1 spending more time on moving to complete records. Meantime, the link of processes 1 and 2 required more time than that of processes 2 and 3. Therefore, this study proposed a solution to improving the above recognized conditions.

5.3. Solution generation

In this study, Construction Workers 1 and 2 (Fig. 4) were arranged to synchronously cooperate to complete on-site data collection using direct communication. Fig. 4 illustrates the synchronous operations:

- Steps 1A and 1B — checking materials and filling in records: To synchronize the subprocesses 1A and 1B (stage 2 of Fig. 2), Construction Worker 1 gave the material details to Construction Worker 2 verbally when checking the materials. Simultaneously, Construction Worker 2 filled the material data into the Internet-based documents through a laptop and WLANs.
- Steps 2A and 2B — correcting and confirming records: When completing an initial material record (defined as a draft record before being stored in the databases), Construction Worker 2 informed Construction Worker 1 of the written details to confirm validity of the data. If the initial material record was incorrect, Construction Worker 2 modified the

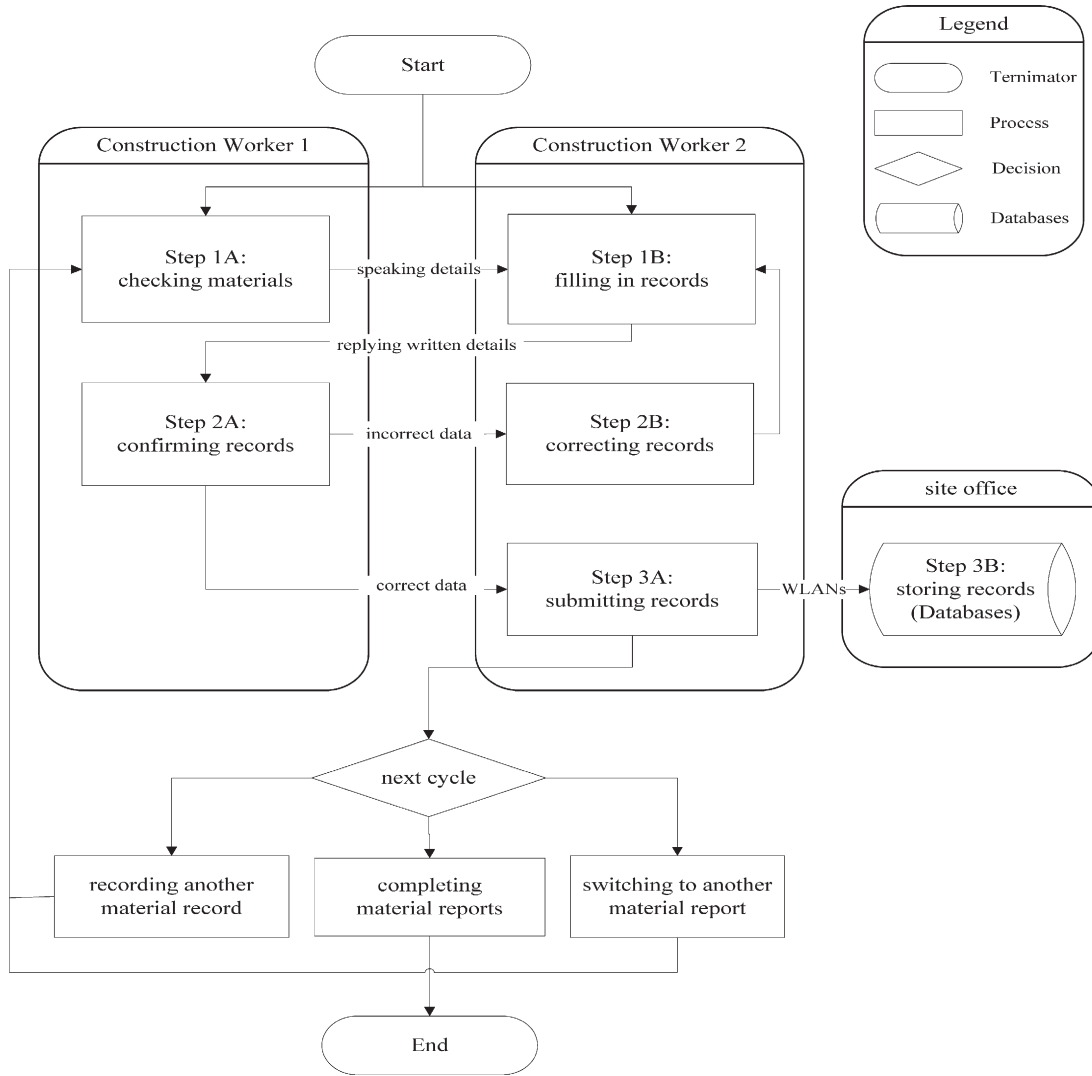


Fig. 4. Synchronous operations between two construction workers.

erroneous data. Visibly, this communication was the link between processes 1 and 2 (stage 3 of Fig. 2).

- Steps 3A and 3B — submitting and storing records: When the initial record was correct or the data modifications were completed, Construction Worker 2 immediately submitted the record. The servers, then, automatically saved the record. Additionally, the database server consisting of the Microsoft SQL Server was another important component for keeping the material records. Since the proposed solution only changed the existing on-site data collection operations, this study still applied the original database framework and tables.

After completing one material record, Construction Workers 1 and 2 could perform another record, switch to a different material report, or finish on-site data collection.

Before testing the synchronous operations at the construction site, Construction Workers 1 and 2 practiced synchronous on-site data collection several times. Besides speaking material details, Construction Worker 1 also filled in material reports to obtain the test results for asynchronous operations. Although

Construction Workers 1 and 2 had different typing speeds, this study ignored this issue to simplify the measurement analysis.

During the seven working day period used for system tests, this study ensured that the Internet-based applications and

Table 2
Average cycle time for on-site data collection

Types of records	Operation time (s)			
	Process 1 (checking material and filling in records)	Process 2 (correcting and confirming records)	Process 3 (submitting and storing records)	Cycle time (s)
Material inventory record	230	10	Close to 0	240
Material use record	170	3	Close to 0	173
Material requirement record	113	3	Close to 0	116

WLAN environments were executed properly. For example, Fig. 5 displays that construction managers at the site office accessed the material inventory report because the records delivered from the construction site were saved into the databases successfully. Test measurements (Table 3) included the following: completed records (records), actual lead processes (a-proc), returns (defined as that Construction Worker 1 returned to the laptop to fill in records), erroneous data (errs), operational lead processes (o-proc), total lead processes (t-proc) and total cycle time (TCT). This study then evaluated productivity (prod), time efficiency (TE), comparative work efficiency (CWE) and other relative improvements according to the test results in stage 4 (Fig. 2).

5.4. Performance evaluation

5.4.1. Operational measurements

Table 3 shows that the total number of completed material records for both asynchronous and synchronous operations was the same in the test period. Construction Worker 1 spent 10,329 s on completing 56 material records in the asynchronous operations. The total lead processes were 196 including 168 actual lead processes, 7 erroneous data and 21 returns. The productivity was calculated based on Eq. (1):

$$\text{productivity} = \left(\frac{\text{records}}{\text{TCT}} \right) \times 100\% \tag{1}$$

where records=the amount of completed records; and TCT=the total cycle time.

Hence, the total productivity was 0.005422.

On the other hand, Construction Workers 1 and 2 required 9455 s to complete the same material records in the synchronous operations. The total lead processes were 173 including 168 actual lead processes, 5 erroneous data and no returns. The total productivity was 0.005923. Obviously, the synchronous operations other than the asynchronous operations required less cycle time. Meantime, because operational lead processes (consisting of erroneous data and returns)

were reduced in the synchronous operations, total lead processes (consisting of actual and operational lead processes) were improved.

This study then used Eqs. (2)–(4) to determine various improvements:

$$\text{improved productivity} = \left\{ \frac{[(\text{prod})^S - (\text{prod})^{AS}]}{\text{prod}^S} \right\} \times 100\% \tag{2}$$

$$\begin{aligned} &\text{improved actual lead processes} \\ &= \left\{ \frac{[(\text{a-proc})^{AS} - (\text{a-proc})^S]}{(\text{a-proc})^{AS}} \right\} \times 100\% \end{aligned} \tag{3}$$

$$\begin{aligned} &\text{improved operational lead processes} \\ &= \left\{ \frac{[(\text{o-proc})^{AS} - (\text{o-proc})^S]}{(\text{o-proc})^{AS}} \right\} \times 100\% \end{aligned} \tag{4}$$

where (prod)^S=the productivity in the synchronous operations; (prod)^{AS}=the productivity in the asynchronous operations; (a-proc)^{AS}=the actual lead processes in the asynchronous operations; (a-proc)^S=the actual lead processes in the synchronous operations; (o-proc)^{AS}=the operational lead processes in the asynchronous operations; and (o-proc)^S=the operational lead processes in the synchronous operations.

Excepting actual lead processes, the total productivity increased 8.46% (Eq. (2)) and the total operational lead processes decreased 82.14% (Eq. (4)). Accordingly, Fig. 6(a) displays the combined direct and indirect impacts for applying synchronous operations in on-site data collection. Although the actual lead processes were identical for the asynchronous and synchronous operations, the indirect impacts of actual lead processes were discovered in the bottom line measurements (including the time efficiency, comparative work efficiency and completed reports).

number	material	quantity	location	supplier	testing	testing report
pi0112	iron pipe	5	5 floor	D supplier	no testing	no testing reports
pvc1322	pvc bearing	10	4 floor	B supplier	no testing	no testing reports
ce1132	cement	20	5 floor	A supplier	no testing	no testing reports
ca3101	canvas	50	5 floor	F supplier	no testing	no testing reports

Fig. 5. Material inventory report.

Table 3
Test results in asynchronous and synchronous operations

Day	Record types				Asynchronous operations							Synchronous operations							TE	CWE
	Inv ^a	Use ^b	Req ^c	Total	a-proc	Returns	Errs	o-proc	t-proc	TCT (sec)	prod	a-proc	Returns	Errs	o-proc	t-proc	TCT (sec)	prod		
1	4	5	2	11	33	4	2	6	39	1990	0.005528	33	0	0	0	33	1887	0.005829	5.18%	15.38%
2	1	5	0	6	18	2	0	2	20	1145	0.005240	18	0	1	1	19	1005	0.005970	12.23%	5.00%
3	2	3	1	6	18	3	0	3	21	1187	0.005055	18	0	0	0	18	1045	0.005742	11.96%	14.29%
4	0	6	2	8	24	2	1	3	27	1299	0.006159	24	0	2	2	26	1180	0.006780	9.16%	3.70%
5	2	4	0	6	18	3	2	5	23	1243	0.004827	18	0	0	0	18	1110	0.005405	10.70%	21.74%
6	5	4	1	10	30	4	2	6	36	1962	0.005097	30	0	1	1	31	1857	0.005385	5.35%	13.89%
7	1	6	2	9	27	3	0	3	30	1503	0.005988	27	0	1	1	28	1371	0.006565	8.78%	6.67%
Total				56	168	21	7	28	196	10,329	0.005422^d	168	0	5	5	173	9455	0.005923^e	8.46%^f	11.73%^g

^a Material inventory record.

^b Material use record.

^c Material requirement record.

$$^d \frac{56}{10,329}$$

$$^e \frac{56}{9455}$$

$$^f \left[\frac{(10,329-9455)}{10,329} \right] \times 100\%$$

$$^g \left[\frac{(196-173)}{196} \right] \times 100\%$$

5.4.2. Time efficiency

Time efficiency was a measurement to understand the difference in total cycle time between asynchronous and synchronous operations, and to identify whether the constraint and unnecessary subprocesses were reduced. Eq. (5) was applied to determine this efficiency:

$$\text{time efficiency (TE)} = \left\{ \frac{[(TCT)^{AS} - (TCT)^S]}{TCT^{AS}} \right\} \times 100\% \quad (5)$$

where $(TCT)^{AS}$ = the total cycle time in the asynchronous operations; and $(TCT)^S$ = the total cycle time in the synchronous operations. Excluding actual load processes (Fig. 6(c)), both productivity (Fig. 6(b)) and operational lead processes (Fig. 6(d)) directly affected time efficiency.

Fig. 6(b) displays that when the productivity for completing the same reports increased, the time efficiency also increased. According to the prod and TE columns of Table 3, all test results satisfied this condition. Additionally, because synchronous operations decreased the operational lead processes (Fig. 6(d)), the time efficiency for activity completion was increased. For

instance, since the operational lead processes were fewer for synchronous operations than for asynchronous operations in Day 4 of Table 3, the time efficiency increased 9.16%.

Although the actual lead processes did not impact the time efficiency directly, Fig. 6(c) displays that the actual lead processes had an indirect impact on the time efficiency through the operational lead processes. If the initial completed records which were produced in process 1 contained few erroneous data to perfect the actual lead processes, the operational lead processes decreased and the time efficiency increased because Construction Worker 2 did not spend time correcting erroneous data. For example, the asynchronous operations included two erroneous data in Day 5 of Table 3; however, the synchronous operations had no erroneous data. Thus, the time efficiency increased 10.7%.

Furthermore, Table 3 shows that the range of time efficiency was from 5.18 to 12.23%. While this study combined the direct and indirect impacts from operational measurements, the total time efficiency increased 8.46% in the synchronous operations.

Meanwhile, Fig. 7 illustrated that the cumulative cycle time of synchronous operations compared to that of asynchronous operations was reduced together with cumulative working days. The total cycle time was reduced by 874 s.

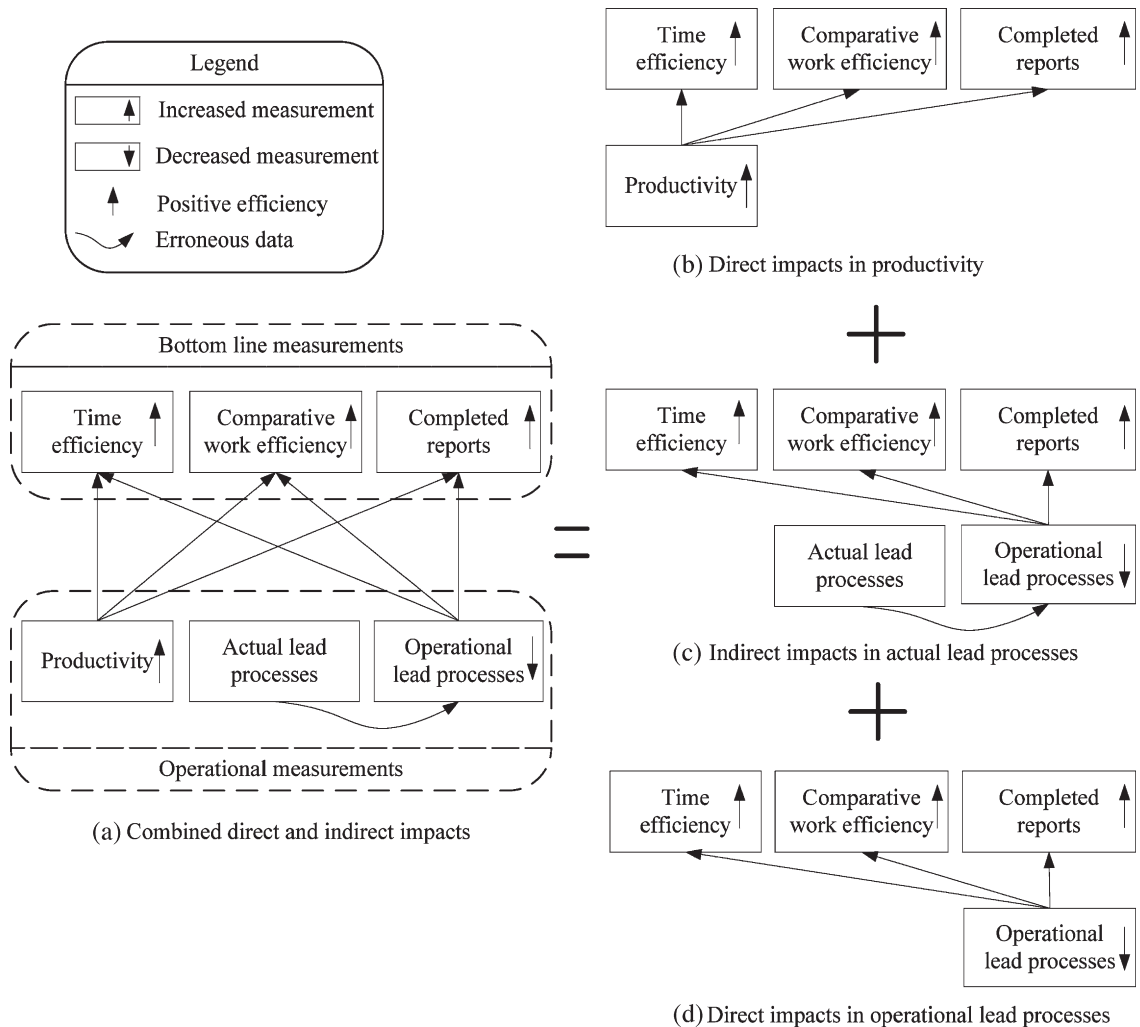


Fig. 6. Direct and indirect impacts in synchronous operations (a modification from [11]).

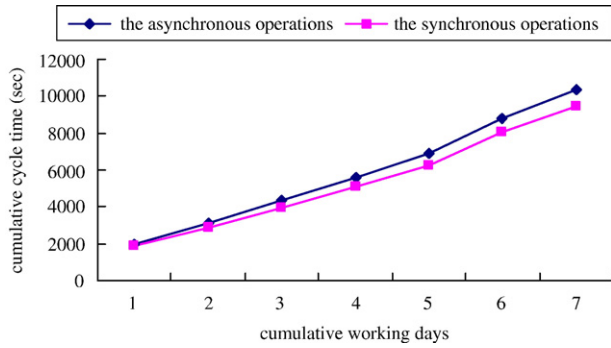


Fig. 7. Cumulative cycle time for seven working days.

5.4.3. Comparative work efficiency

For asynchronous and synchronous operations, comparative work efficiency was used to determine the improvement in total lead processes. Avoiding the unnecessary subprocesses of main processes was helpful to reduce the process complexity and cycle time. Moreover, productivity for activity completion could also be enhanced in this way. This efficiency was calculated by Eq. (6):

$$\text{comparative work efficiency (CWE)} = \left\{ \frac{[(t - \text{proc})^{\text{AS}} - (t - \text{proc})^{\text{S}}]}{(t - \text{proc})^{\text{AS}}} \right\} \times 100\% \quad (6)$$

where $(t - \text{proc})^{\text{AS}}$ = the total lead processes in the asynchronous operations; and $(t - \text{proc})^{\text{S}}$ = the total lead processes in the synchronous operations.

While synchronous operations increased productivity because the total cycle time was reduced by the decreased total lead processes, comparative work efficiency for activity completion also increased (Fig. 6(b)). For example, because of the 11.96% (Eq. (2)) increase in the productivity of synchronous operations on Day 3 (Table 3), the comparative work efficiency increased 14.29%. Fig. 6(c) states that the actual lead processes indirectly impacted the comparative work efficiency. Initial completed records produced in process 1 were delivered from the actual lead processes to the operational lead processes. If the erroneous data (one component of the operational lead processes) were reduced, the initial completed records were quickly transferred from process 2 to process 3. According to the test results of Table 3, the synchronous operations of Days 1, 5 and 6 had fewer erroneous data for increasing the comparative work efficiency.

Besides, the other component (returns) of operational lead processes also influenced the comparative work efficiency. Table 3 illustrates that all comparative work efficiencies were increased since Construction Worker 1 did not return to the laptop to enter data during the synchronous operating period. Therefore, when the operational lead processes (Fig. 6(d)) were reduced, the comparative work efficiency increased for activity completion.

While this study evaluated the obtained comparative work efficiency, Table 3 shows that the improvement range was from 3.7 to 21.74%. Certainly, synchronous operations other than asynchronous operations had the better comparative work efficiency, because the total comparative work efficiency reached 11.73%. Besides, Fig. 8 displays that the difference of cumulated total lead

processes in the asynchronous and synchronous operations increased continuously with increased number of working days.

5.4.4. Completed reports

Goldratt and Fox depicted that the Cash Flow of TOC measurements was an indicator of firm survival [11]. For firms with sufficient money, cash flow was not important; while for firms without sufficient money, nothing else was important. Similarly, if Construction Workers 1 and 2 failed to complete the required material reports through synchronous operations, the improvement of on-site data collection was useless; otherwise, this improvement was useful. Hence, it was important to determine whether Construction Workers 1 and 2 completed their material reports on schedule.

Based on the above discussions, the synchronous operations not only increased the productivity (8.46%, Eq. (2)) but also decreased the operational lead processes (82.14%, Eq. (4)). Meanwhile, the actual lead processes including fewer erroneous data contributed indirectly to the synchronous operations. Therefore, when the improved operational measurements were achieved, Construction Workers 1 and 2 successfully completed all records using the synchronous operations (Fig. 6(b–d)).

5.5. Goal confirmation

To resolve asynchronous operations and unnecessary subprocesses for the case study examined here, two construction workers synchronously collaborated to complete the required material reports through direct communication. Based on the test results, in addition to the synchronous on-site data collection, the improvements of asynchronous operations compared to synchronous operations are listed below.

- Cycle time: Although asynchronous and synchronous on-site data collection involved the same required processes, during the period of synchronous operations, construction workers performed fewer subprocesses. Synchronous operations thus required less cycle time for activity completion.
- Processes and flow transparency: Besides reducing unnecessary subprocesses for synchronous operations, construction workers clearly understood ongoing subprocesses and focused on them. This condition helped avoid that the interdependent subprocesses influenced the formed processes and combined

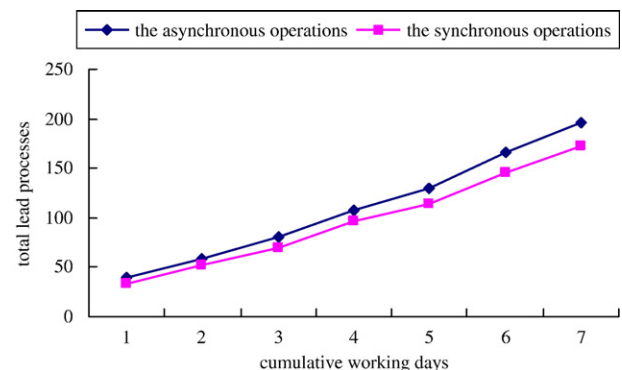


Fig. 8. Cumulative total lead processes for seven working days.

flow. When receiving the delayed site information, project managers could more easily identify problems associated with synchronous operations.

- Activity productivity: Executed processes and cycle time were the keys to determining activity productivity. Synchronous operations ensured the whole activity flow against time-consuming subprocesses better than asynchronous operations did for the same activity. Because of the simplified processes and cycle time, construction workers obtained higher productivity (the increased efficiency for the present case study was 8.46%) when applying synchronous operations for on-site data collection.
- Information interdependence: For synchronous operations, the information produced was immediately delivered from a process to the next interdependent process. The completed on-site information improved the lack of proper information for the required off-site data analysis. Because of the increased space provided to resolve the unexpected problems, all project participants benefited from this compact interdependent relationship.

6. Conclusion

To provide just-in-time information for project management and participants, more and more construction companies apply IT-based applications to collect and deliver construction site data. However, when the interdependent processes of on-site data collection are combined into a flow, it is clear that asynchronous operations and unnecessary subprocesses exist in inhibiting information production and delivery. Thus, improving this problem is important for increasing on-site data collection performance.

This study proposed a synchronization-based model for achieving the above purpose, and applied this model to a material management case study. While on-site material reports were executed, common conditions were that construction workers kept away from application devices and had unavailable hands for recording material details. As a result, asynchronously checking materials and filling in records influenced the following processes and information flow. This study then applied worker cooperation to synchronize these two subprocesses.

Based on the efficiency improvement evaluated by the identified measurements, construction workers had less operation time, fewer working processes and enhanced activity productivity when completing on-site material reports through the synchronous operations. Consequently, this study represents a prototype of synchronous on-site data collection. Meantime, the proposed model can be applied in various project activity flows, e.g., cash flow, resource waste, labor requirements and operation machines, to improve performance.

References

- [1] N. Dawood, A. Akinsola, B. Hobbs, Development of automated communication of system for managing site information using internet technology, *Automation in Construction* 11 (2002) 557–572.
- [2] S. Kiziltas, B. Akinci, The need for prompt schedule update by utilizing reality capture technologies: a case study, *Proc. Construction Research Congress, ASCE, San Diego, 2005*, pp. 163–167.
- [3] J.M. De la Garza, I. Howitt, Wireless communication and computing at the construction cobsite, *Automation in Construction* 7 (1998) 327–347.
- [4] S. Shahid, T. Froese, Project management information control systems, *Canadian Journal of Civil Engineering* 25 (1998) 735–754.
- [5] W.J. Rasdorf, M.J. Herbert, Automated identification system — focus on bar coding, *Journal of Computing in Civil Engineering* 4 (3) (1990) 279–296.
- [6] W.J. Rasdorf, M.J. Herbert, Bar coding in construction engineering, *Journal of Construction Engineering* 116 (2) (1990) 261–279.
- [7] A.D. Russell, Computerized daily site reporting, *Journal of Construction Engineering and Management* 119 (2) (1993) 385–402.
- [8] R. Navon, O. Berkovich, Development and on-site evaluation of an automated materials management and control model, *Journal of Construction Engineering and Management* 121 (12) (2005) 1328–1336.
- [9] T. Thorpe, S. Mead, Project-specific web sites: friend or foe? *Journal of Construction Engineering and Management* 127 (5) (2001) 406–413.
- [10] T. Froese, Models of construction project information, *Journal of Computing in Civil Engineering* 10 (3) (1996) 183–193.
- [11] E.M. Goldratt, R.E. Fox, *The Race*, North River Press, New York, 1986.
- [12] E.M. Goldratt, *What is this Thing Called Theory of Constraints and How Should It Be Implemented?* North River Press, New York, 1990.
- [13] L. Koskela, Application of the new production philosophy to construction, CIFE Technical Report #72, Stanford University, 1992.
- [14] G.A. Howell, What is lean construction-1999, Proceedings IGLC-7, Berkeley, CA, 1999. (available at <http://www.leanconstruction.org/readings.htm>).
- [15] Ming-Kuan Tsai, Jyh-Bin Yang, Chang-Yu Lin, Integrating Wireless and Speech Technologies For synchronous On-site Data Collection, *Automation in Construction* (in press).
- [16] J.J. Adrian, *Construction Productivity Improvement*, Elsevier Science Publishing Co. Inc, New York, 1987.
- [17] P. Brandon, M. Betts, *Integrated Construction Information*, E and FN SPON, London, 1995.
- [18] D.K.H. Chua, L.J. Shen, Key constraints analysis with integrated production scheduler, *Journal of Construction Engineering and Management* 131 (7) (2005) 753–764.
- [19] D.A. Marchman, *Construction Scheduling With Primavera Enterprise (Second Version)*, Thomson Learning Inc, New York, 2003.
- [20] K.J. Fergusson, P.M. Teichoiz, Achieving industrial facility quality: integration is key, *Journal of Management in Engineering* 12 (1) (1996) 49–56.
- [21] E. Finch, Embedded Internet Systems: applications in construction, Proceedings IGLC-6, Brazil, 1998. (available at <http://www.ce.berkeley.edu/~tommelein/IGLC-6>).
- [22] J.Y. Ruwanpura, S.M. AbouRizk, K.C. Er, S. Fernando, Special purpose simulation templates for tunnel construction operations, *Canadian Journal of Civil Engineering* 28 (2001) 222–237.
- [23] S. Rahman, Theory of constraints. A review of the philosophy and its applications, *International Journal of Operations & Production Management* 18 (4) (1998) 336–355.
- [24] H.W. Dettmer, *Goldratt's Theory of Constraints*, ASQC Quality Press, Wisconsin, 1997.
- [25] D.K.H. Chua, L.J. Shen, S.H. Bok, Constraint-based planning with integrated production scheduler over Internet, *Journal of Construction Engineering and Management* 129 (3) (2003) 293–301.
- [26] T. Ohno, *Toyota Production System*, Cambridge, Mass, 1988.
- [27] C.H. Caldas, L. Soibelman, Automated classification methods: supporting the implementation of pull techniques for information flow management, Proceedings IGLC-10, Brazil, 2002. (available at <http://www.leanconstruction.org/readings.htm>).
- [28] G. Howell, G. Ballard, Implementing lean construction: understanding and action, Proceedings IGLC-6, Brazil, 1998. (available at <http://www.leanconstruction.org/readings.htm>).
- [29] P.-A. Cullen, B. Butcher, R. Hickman, J. Keast, M. Valadez, The application of lean principles to in-service support: a comparison between construction and the aerospace and defence sectors, *Lean Construction Journal* 2 (1) (2005) 87–104. (available at <http://www.leanconstruction.org/readings.htm>).