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Integrating wireless and speech technologies for synchronous on-site data collection

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Abstract

Efficient on-site data collection is important for ensuring timely information flow and successful project management. Although applying information technologies and electronic devices to reduce time-consuming manual paperwork has been valued, one previous study has indicated that asynchronous operations with unnecessary subprocesses still affect information production and transmission. Implementing synchronization-based processes is a solution to enhancing on-site data collection performance. However, these synchronized processes based on worker cooperation still have room to improve their efficiency. Continuous improvement is essential to satisfying this objective. This study thus develops a synchronous system integrated with wireless and speech technologies to enhance the cooperation between construction workers and application devices. System tests and efficiency evaluation in a material management case study demonstrate that this system increased productivity, reduced operation time and simplified subprocesses for activity completion. The synchronous system not only represents a novel application for on-site material management, but also provides a framework for applying wireless and speech technologies for similar on-site information management.

Keywords: Synchronous on-site data collection; Wireless technology; WLAN; Bluetooth; Speech application; Information management

1. Introduction

Efficient on-site data collection is critical to proper information flow and successful project management. Project managers require up-to-date statuses of activities reported by construction workers to control project schedules and prevent possible problems. This requirement addresses the interdependency between on-site data collection and information flow [1,2]. Because on-site data collection is the basic component of composing information flow, construction workers possibly spend 30–50% of their working time recording and analyzing the obtained data [3].

Construction companies have increasingly valued that manual paperwork is time-consuming and staff-dependent. Applying automated data identification systems (e.g., bar coding, global positioning system (GPS) and radio frequency identification (RFID)), electronic devices (e.g., laptop and PDAs) and the Internet to simplify information generation and share has become a conventional means of collecting on-site data [4–8]. Computerized management information systems (MISs) offer a more flexible means for project managers to understand site statuses than paper-based systems do [9]. Therefore, off-site data analysis can integrate with on-site data collection.

However, construction workers suffer various problems during on-site data collection. Common situations include the following: completing individual data to form records and reports; requiring different application devices for collecting data; keeping away from application devices because of another ongoing process; impossibly executing application devices while both hands are unavailable, and environmental factors that interrupt information exchange. These situations not only affect the following processes, but also break information flow. Several studies also have demonstrated that inadequate communication and incorrect information influence progress control and project management [3,10,11].

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A previous study has demonstrated the feasibility of applying a synchronization-based model to solve the above problems [12]. When implementing this model in material management, 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) were found to delay the information production and transfer. Synchronous operations, i.e., the cooperation between two construction workers, were adopted to resolve these problems. Based on the efficiency evaluation, synchronous operations offered enhanced activity productivity, lower cycle time, fewer executed subprocesses and clearer flow transparency than asynchronous operations did.

Since new interdependence and variations have emerged, this study has recognized that the above synchronous on-site data collection still has room to increase its efficiency. For instance, an additional construction worker increased the labor cost for worker cooperation. Besides continuous improvement for this synchronous on-site data collection, this study developed a synchronous system integrated with wireless and speech technologies to enable the cooperation between construction workers and application devices via direct communicate. After the system tests, analytical results show that this synchronous system can efficiently help construction workers to complete various on-site data collection requirements.

2. Synchronous on-site data collection

If the information obtained at the end of on-site data collection flow is considered as a final product, then the information produced in different processes appears to be a works-in-process. Because construction workers complete all processes and subprocesses (defined as lead processes, e.g., filling in and checking data) of this flow, a works-in-process is transferred to a product (e.g., site reports) [12–16]. When a process or a subprocess is blocked, information delivery will be interrupted. Thus, project managers cannot understand the site statuses or control ongoing activities. To improve this condition, the synchronization-based model offers sequential stages (process integration, problem identification, solution generation, performance evaluation and goal confirmation) and interactive measurements (operational and bottom line measurements) [12].

This model was applied to a case study on material management. Fig. 1 (stage 1) illustrates that interdependent processes and subprocesses were combined to form a connected flow to raise the improvement level in the first stage. During the period of a 120-day maintenance project for a five-story building, different activities (including floor-repairing, wall-painting, water-proofing, roof-draining and related activities) required various materials (e.g., cement, paint, sand and PVC pipes). Construction Worker 1 (Fig. 2(A)) reported on-site material details to project managers to perform project schedule.

Besides checking materials, Construction Worker 1 also filled the inspection results in the Internet-based material documents (including inventory, use and requirement documents as shown in Table 1 and Fig. 3(A–C)) by the laptop and wireless local area networks (WLANs). Construction Worker 1 submitted and stored material records in the remote databases after confirming the initial completed records (defined as the draft records before being stored in the databases) and correcting erroneous data. Since the computerized MIS automatically arranged these completed records, project managers accessed timely material reports at site offices.

However, some common causes of discontinuous information flow were identified while actual working statuses were observed. For instance, when busy with other ongoing processes, Construction Worker 1 had unavailable hands to record data. Fig. 1 (stage 2) indicates that the operation for process 1 (including subprocesses 1A and 1B) not only seemed to be asynchronous, but also contained unnecessary subprocesses (such as returning to laptops to fill in material data).

Construction Worker 1 spent less time on processes 2 and 3 than on process 1 while using the laptop. Given that they were executed simultaneously, subprocesses 2A–2B and 3A–3B (stage 2 of Fig. 1) were synchronous operations. In other words, asynchronous operations were viewed as the main cause of delay in information exchange and operation time. Synchronizing the recognized asynchronous subprocesses was the essential to accelerating the formed process to transfer information for the next independent processes. When this improvement decreased operation time and the number of unnecessary subprocesses, the whole productivity for activity completion would increase.

To achieve the above objective, a solution was proposed to form synchronous operations in stage 3 of Fig. 1. According to the properties of the executed processes and subprocesses, this model classifies the lead processes into actual lead processes (defined as the designed processes for completing an activity) and operational lead processes (defined as the additional executed processes for completing an activity). For example, three processes comprised an activity flow (stage 3 of Fig. 1). When an error occurred, construction workers modified this error to deliver a correct material record. Hence, the actual lead processes were three and the operational lead process was one.

Since the actual lead processes were not changed in the examined case study, the applied solution needed to reduce the number of operational lead processes. Fig. 2(B) shows that two construction workers synchronously cooperated to complete on-site data collection via direct communication. Construction Worker 2 filled the hearing data into material reports while Construction Worker 1 checked materials and spoke details. Direct communication enabled subprocesses 1A and 1B to occur at the same time, and smoothed the interrupted information flow. The recognized unnecessary subprocesses (e.g., move and wait) were also eliminated.

The obtained efficiency improvement for the above synchronous on-site data collection was evaluated in stage 4 (Fig. 1). The productivity (defined as the rate at which construction workers generated total material records through total cycle time), actual lead processes and operational lead processes were determined as operational measurements. The activity performance was obtained by combining these measurements with the total cycle time (defined as the time for completing all material

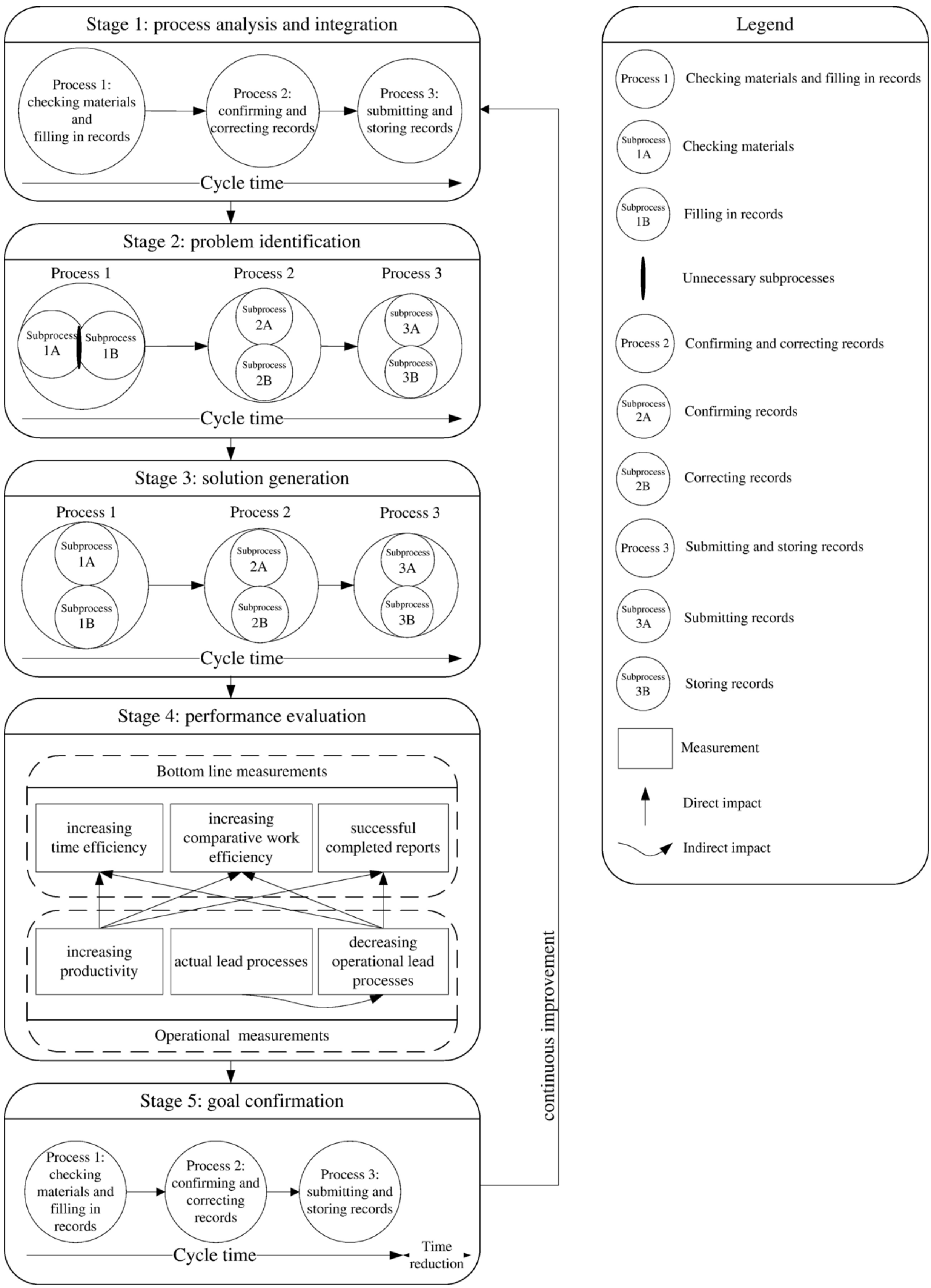


Fig. 1. Synchronization-based model and synchronous on-site data collection [12].

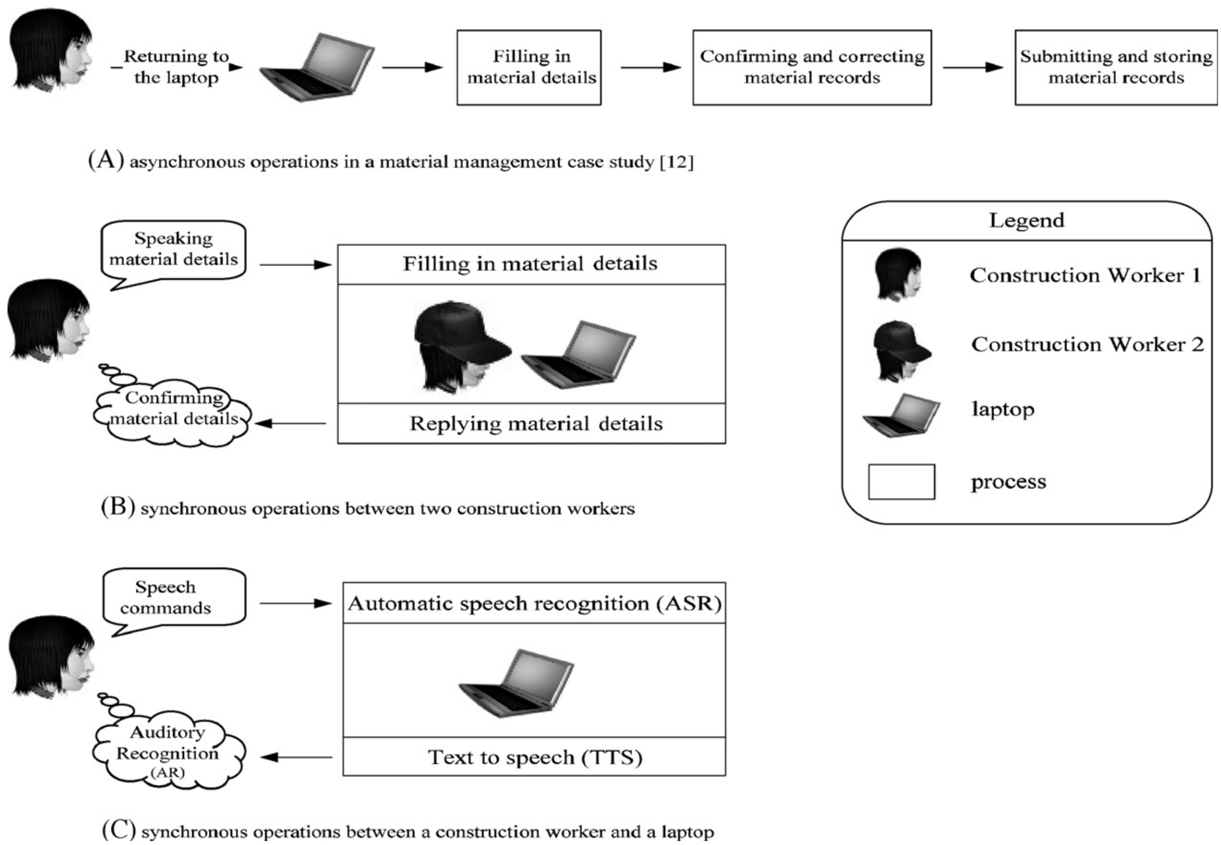


Fig. 2. Improving on-site data collection through various approaches.

records). Changes in operational measurements were reflected in bottom line measurements (defined as the measurements for illustrating the efficiency improvement).

After Construction Workers 1 and 2 completed all tests, measurement results indicate that the applied solution increased productivity by lowering the cycle time and the number of operational lead processes. Additionally, the time efficiency and comparative work efficiency were increased. The construction workers efficiently completed all required material reports.

This model confirmed that the applied solution reached the desired objectives (synchronizing asynchronous operations and reducing unnecessary subprocesses) in stage 5 (Fig. 1). The improvements of asynchronous operations compared to synchronous operations included: reducing cycle time for activity completion; increasing process and activity transparency, and preventing the influence among independent subprocesses. This synchronous on-site data collection not only benefited most project participants, but also moved up other relevant information flows, such as off-site data analysis and material preparations.

Table 1
Various material records including material fields

Record types	Fields
Material inventory record	The seven required fields are: (1) defined material number; (2) material name; (3) material quantity; (4) storing location; (5) supplier name; (6) material test, and (7) testing report number.
Material use record	The six required fields are: (1) defined material number; (2) material name; (3) used quantity; (4) activity name; (5) activity location, and (6) worker name.
Material requirement record	The seven required fields are: (1–2) requirement date (month and day); (3) defined material number; (4) material name; (5) material quantity; (6) activity name, and (7) activity location.

3. Study problem and objective

Based on the above synchronous on-site data collection, this study recognizes that the actual lead processes do not directly benefit the bottom line measurements (stage 4 of Fig. 1). In other words, synchronous worker cooperation did not completely satisfy on-site data collection requirements, because application systems seemed to be asynchronous for data completion. For instance, these systems required manual operations to obtain on-site information. Performing continuous improvement for synchronous on-site data collection is the key to improving activity efficiency.

Besides focusing on actual lead processes for improving inefficient subprocesses, this study developed a synchronous system to ensure the cooperation between construction workers and application devices. Construction workers can communicate directly with the synchronous system during the working period. Meantime, this system automatically completes speech recognition and on-site information without manual assistance. The expected objective is to increase the performance of synchronous on-site data collection.

4. System implementation

According to the synchronization-based model, five continuous stages were useful for inspecting the emerged interdependence and variations for synchronous on-site data collection (Fig. 4). Consequently, worker communications were first analyzed to understand how they were related to information production. The main problem caused by an additional construction worker was determined in the next stage. To resolve this problem, a wireless-supporting and speech-enabled system was developed in the third stage. After the system tests, the system performance was evaluated from the identified measurements in the fourth stage to determine the effects among the operational and bottom line measurements. Finally, the results were analyzed, indicating that implementing the proposed system can increase productivity and efficiency.

4.1. Process analysis and integration

Before a synchronous system was developed, the asynchronous and synchronous operations were first analyzed to classify the influence for on-site data collection. According to Fig. 1 (stage 2), since Construction Worker 1 asynchronously executed the subprocess 1A, interdependent subprocess 1B and other processes passively waited in a queue, causing a lag in the connected flow. Hence, asynchronous on-site data collection was viewed as a "push" information system, releasing information based on manual classification. The retrieval methods were also controlled by human experts [17].

In contrast, synchronous on-site data collection (stage 1 of Fig. 4) was a "pull" information system automatically releasing information based on system statuses [17]. Fig. 2(B) indicates that when Construction Worker 1 said a sentence: "Bill used five bags of cement to repair a wall in the third floor", Construction Worker 2 knew the details of the used material from the dialogues including: worker (Bill), material (cement), quantity (5 bags), activity name (wall repair), and activity location (third floor). Construction Worker 2 simultaneously filled the recognized material details into the corresponding fields. Therefore, synchronous operations allowed the interdependent processes and subprocesses to draw actively from the queue and speed up information delivery.

4.2. Problem identification

Although the two construction workers cooperated well with each other, this prototype for synchronous on-site data collection still had two problems. One recognized problem was the labor cost increased by an additional construction worker (stage 2 of Fig. 4). Reducing expense and increasing profit are important for most project managers. Hence, if applying a synchronous system for on-site data collection can maintain the same efficiency as well as worker cooperation, the labor costs can be economic.

Another problem identified was that Construction Worker 2 still spent time manually entering data in subprocesses 1B and 2B (Fig. 2(B)), since the Internet-based material documents consisted of numerous material records and individual fields.

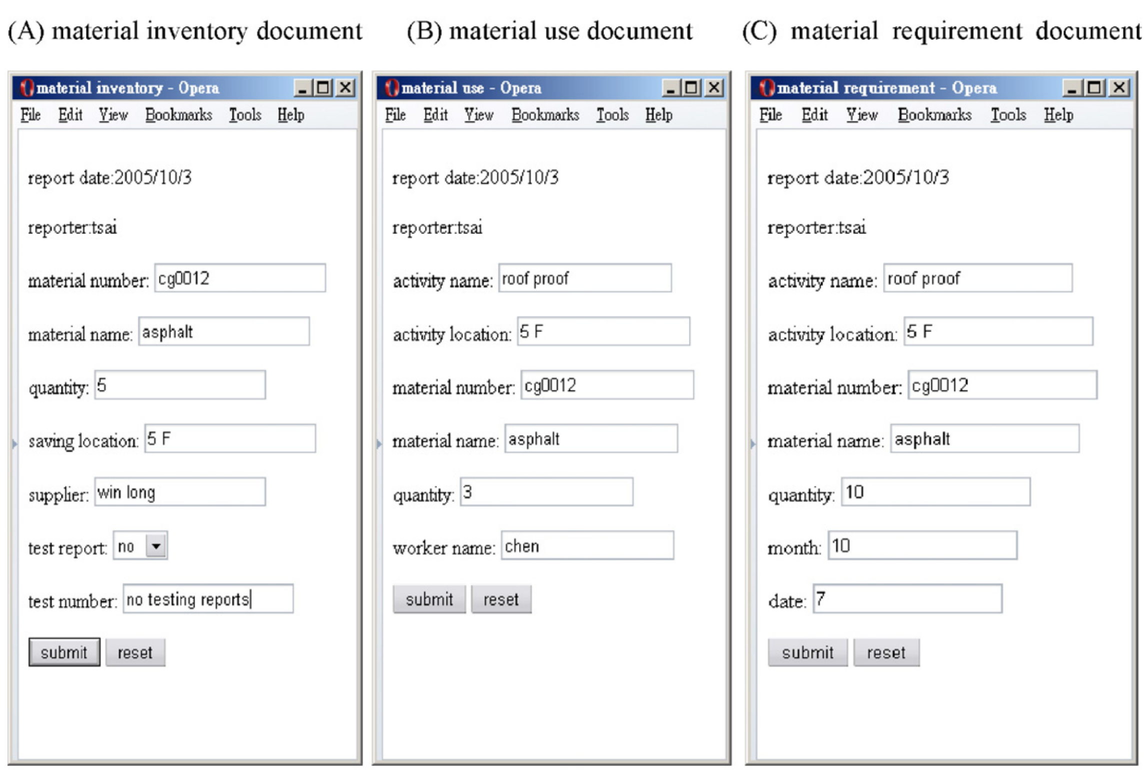


Fig. 3. Required material reports [12].

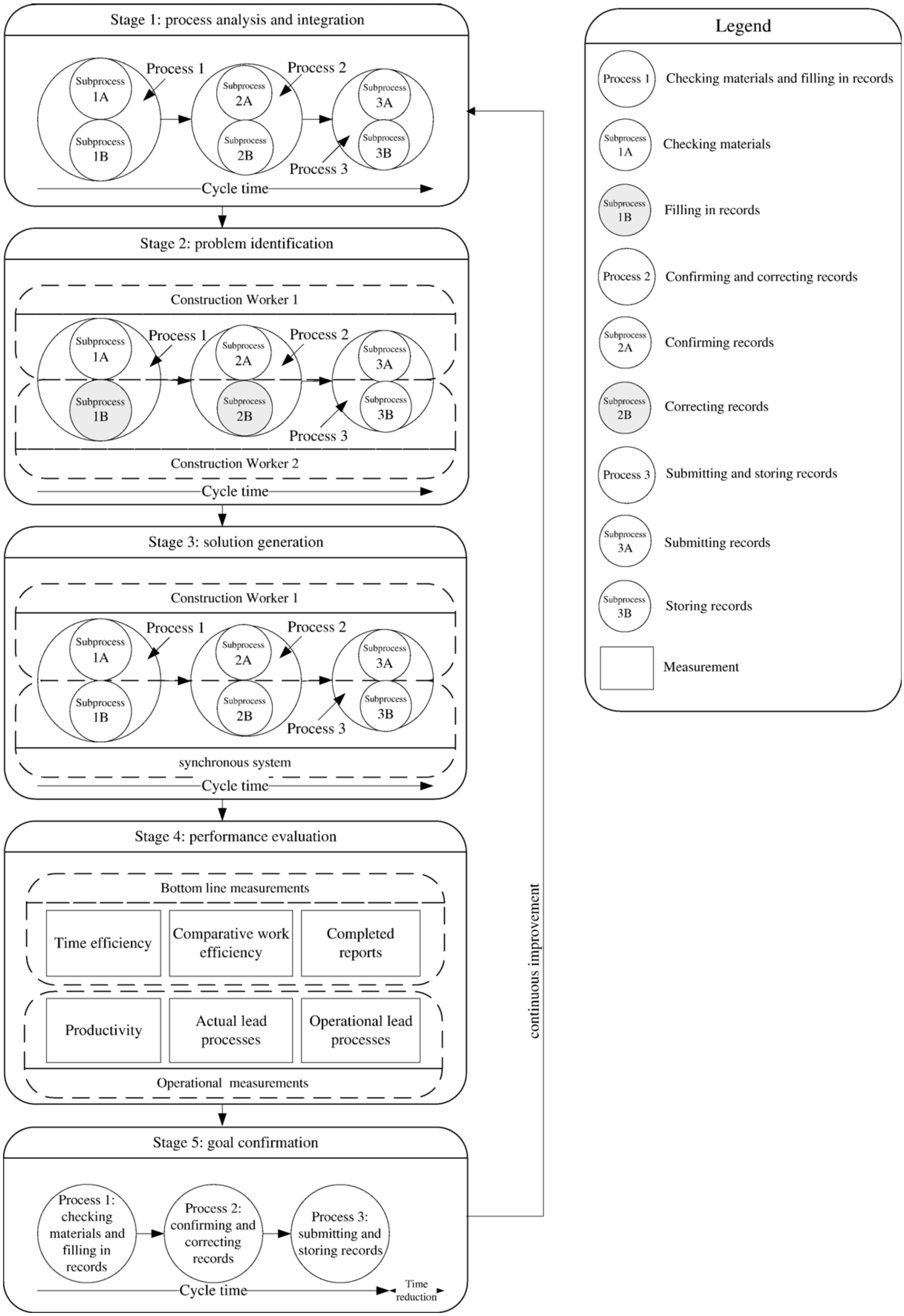


Fig. 4. Applying synchronization-based model for system implementation.

Construction Worker 2 had to switch various fields to fill in data when performing material reports. This data entry was inefficient and asynchronous. In summary, the main problem was that an additional construction worker not only increased labor cost, but also performed manual data entry. Developing a communication-enabled system that can complete all material fields once is the key to improving performance of synchronous on-site data collection.

4.3. Solution generation

The analysis of the previous two stages shows that an ideal synchronous system should directly receive speech-format sentences; correctly recognize the material details in sentences; intelligently complete material records, and automatically confirm the completed material records with construction workers. This study thus applied wireless and speech technologies to achieve synchronous information delivery and simulate human communication.

4.3.1. Integrated information technologies

4.3.1.1. Wireless technologies. The Internet is a popular platform, which can overcome barriers and speed up communication. Many case studies have successfully applied the Internet in construction domains. For instance, project-specific web sites give construction personnel new ways of designing and simplifying complex projects [18], and web-based construction systems assist project managers in exercising project control [19]. Analytical results clearly reveal that Internet-based applications can be adopted in most construction projects.

However, construction workers may have difficulty in exchanging information through wired links when performing activities at outside environments. Wireless technologies offer solutions to resolving information interruptions, and permit information to flow quickly [20]. Various studies have concluded that wireless environments can be used to transfer information between construction sites and offices [21,22]. Recently, two wireless techniques (WLAN and Bluetooth technologies) are much popular [23].

WLAN is a wireless protocol based on Institute of Electrical and Electronics Engineers (IEEE) 802.11 standards, and enables project participants to obtain Internet access conveniently. Many construction companies thus integrate the Internet and WLANs in project and information management. For instance, a mobile site level data collection system has been implemented for piling works [21], and an integrated system using standard wireless and portable devices enhances the evaluation processes during on-site bridge inspection [22].

Moreover, construction workers can also exchange data synchronously among different devices through Bluetooth technology. Telephony companies use this technology in walkie-talkie applications (e.g., Bluetooth headsets and cell phones), because the wireless link can reach 30 ft [24]. Unfortunately, although walkie-talkie applications are synonymous with the construction industry [20], Bluetooth technology has seldom been applied in project management.

Thus, integrating the above wireless technologies with the synchronous system for on-site data collection benefits information production and transmission. Construction workers can report material details with application devices using direct communication and Bluetooth technology, when they had unavailable hands to record data (Fig. 2(C)). Meantime, the completed material records can be immediately submitted for project participants within WLAN environments.

4.3.1.2. Speech technology. Fig. 2(C) shows the necessary components for successful communication between construction workers and the synchronous system. When construction workers speak commands, the system executes speech recognition to confirm the received commands. This procedure is "automatic speech recognition (ASR)" [25]. After completing ASR, the system responds the results to construction workers through speech synthesis. This procedure is "text to speech (TTS)" [25]. While hearing the speech-format responses, construction workers understand whether the commands have been executed correctly. This procedure is "auditory recognition (AR)" [26]. Importantly, these communication procedures are much closer to human conversations (Fig. 2(B)). Hence, Washburn used speech recognition for on-site collection of license plate data, and described the good potential to apply speech technology for processing jobs [27].

Research on speech applications indicates that most people can speak over 160 words per minute, but type less than 40 words a minute [28]. Speech entry other than manual data entry appears to complete material records quickly. Fig. 2(C) illustrates that the speech-enabled system can automatically recognize and transfer material data into material records through ASR, while receiving the spoken sentences. Meanwhile, this system immediately informs the completed records to construction workers through TTS. If the recognized data are incorrect, construction workers can then reprocess speech recognition to modify the erroneous data. Because speech technology proves more flexibilities and benefits, this study applies this technology as the main communication tool for the synchronous system.

4.3.2. System development

This study adopted the XHTML+Voice standard [29] and other programming languages (e.g., ASP.Net [30] and JSP [31]) to combine speech functions with existing Internet-based material documents. Fig. 5 shows the system flowchart in the developed synchronous system. The key processes were detailed as follows:

- Steps 1A and 1B—checking materials and filling in records: When checking materials at the construction site, construction workers spoke the details through the Bluetooth headset. Meanwhile, the synchronous system analyzed the contained material data to fill the recognized results and the homologous material number into records based on the grammar rules (defined as a set of utterances including words and phrases [29]).

  For instance, in Fig. 6, Construction Worker 1 spoke "the manden company delivers 15 units PVC pipes in 1 floor and

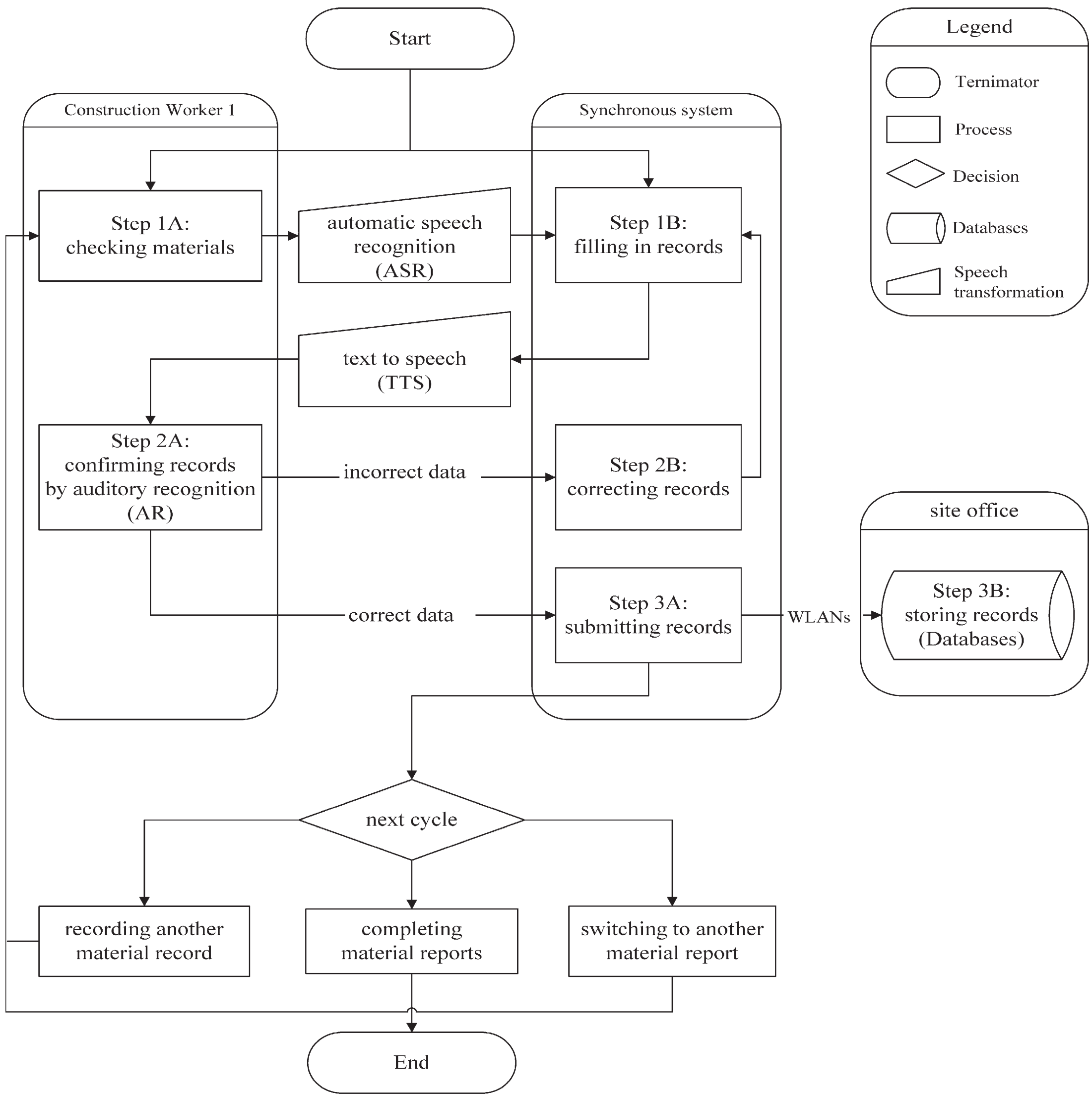


Fig. 5. Flowchart for synchronous system.

no test" when performing a material inventory record. The synchronous system automatically completed the record including material number (pi0022), supplier name (manden company), quantity (15 units), material name (PVC pipes), stored location (1 floor) and material test (no test).

- Steps 2A and 2B—correcting and confirming records: To connect the processes 1 with 2 (stage 3 of Fig. 4), the synchronous system informed the initial completed data through speech synthesis to construction workers to confirm the recorded data while finishing speech recognition. After hearing the speech responses, construction workers understood whether these records were correct. If the recorded data were correct, then construction workers switched to the next step; otherwise, the erroneous data of initial completed records needed to be modified.
When a spoken sentence did not contain all material details or the recognized data were incomplete, the synchronous system asked construction workers to reply the missing data. Similarly, while discovering erroneous data, construction workers applied speech commands to correct data or cancel the record. For example, Fig. 7 shows that while the system recognized "1 floor" to "2 floor", Construction Worker 1 spoke "location" to reprocess speech recognition to correct data.
- Steps 3A and 3B—submitting and storing records: When these records were correct or the data modifications were completed, construction workers submitted and saved the records into the databases via speech. Although the database server (the Microsoft SQL Server) was another important component, this study did not change the original database framework and tables, because the synchronous system is the combination of speech functions and Internet-based material documents.

After completing one material record, construction workers could perform other material records, switch to another material report or exit the system to finish on-site data collection.

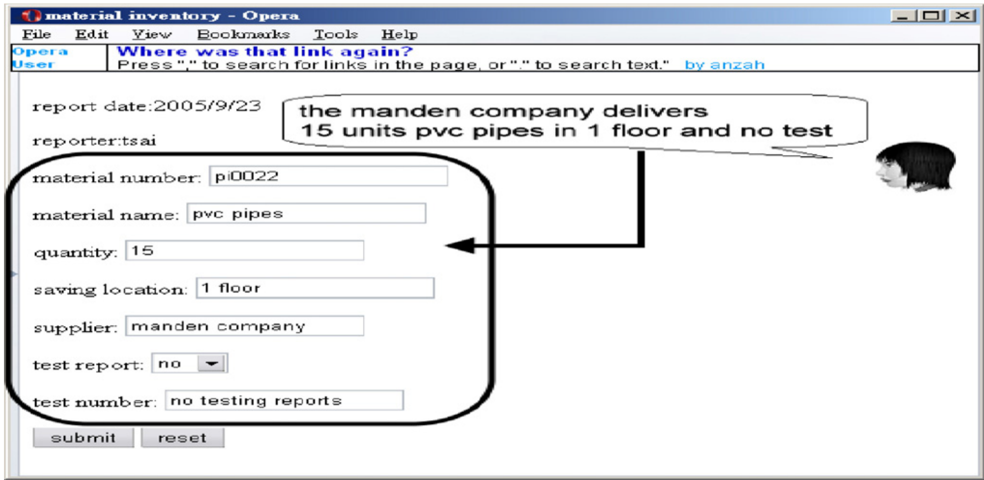


Fig. 6. Completing a material inventory record via speech.

Grammar rules are crucial to improving the accuracy of speech recognition and simplifying the individual subprocesses for entering data. If these rules are clearly defined, then the synchronous system can recognize and identify the spoken data easily. Consequently, this study integrated activity details (including the activity date, activity names, activity locations, activity workers and necessary materials) stored in the project databases with grammar rules. For instance, the activity locations of this case study were defined as five floors. When construction workers performed material records, the synchronous system automatically connected to project databases to receive the necessary data regarding activity locations, and to form grammar rules. Fig. 7 shows that the synchronous system successfully analyzed the floor name contained in a spoken sentence.

Speech application results indicate that the accuracy rate of speech recognition over 200,000 vocabularies reached 99% [29]. By contrast, since this case study required only a small vocabulary (50 words), the synchronous system could offer good accuracy for construction workers during the system tests. However, some words sound similar, such as "sand" and "send", affecting the accuracy of speech recognition. This study first tested the developed grammar rules to determine the accuracy of this system and to classify confused words.

The initial accuracy rate of speech recognition was 88% (6 errors of 50 vocabularies) for Construction Worker 1. This study thus modifies the grammar rules according to pronunciation and speaking behavior. For example, Taiwanese construction workers said "asphalt" as "li chin" in Chinese. Namely, the names used for the same materials in the grammar rules had to be edited to enhance speech recognition. The accuracy rate was increased to 98% (1 error in 50 words) after Construction Worker 1 tested the updated grammar rules. Other system components were also programmed while confirming the grammar rules.

Before applying the synchronous system at the construction site, the Opera web browser supporting the XHTML+Voice standard was applied to check all system components [32]. System errors were corrected as soon as they occurred. Consequently, this study ensured that the system components were

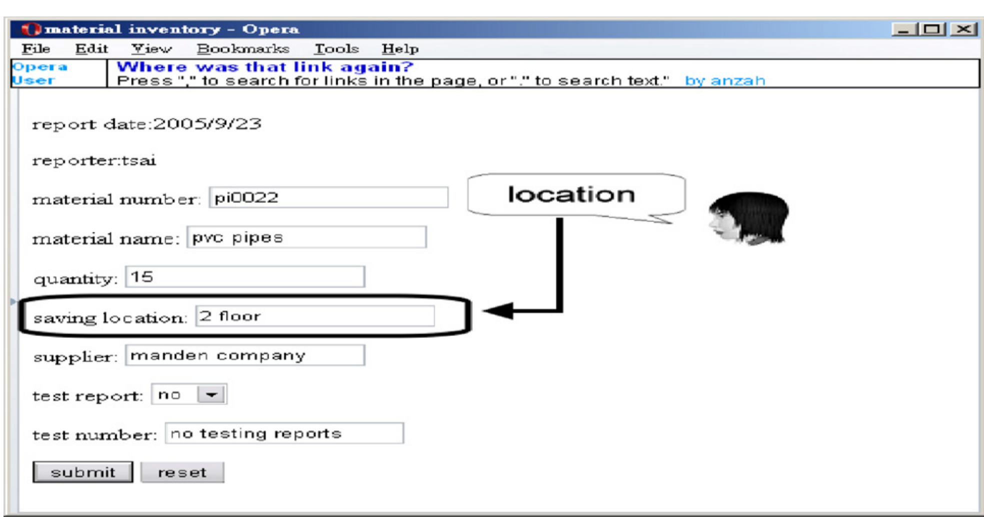


Fig. 7. Modifying an error via speech.

executed correctly. Fig. 8 (the material requirement report) shows that the delivered records were saved into the databases successfully. The construction managers immediately accessed the completed material reports through the Internet at the site office.

4.3.3. System operation

Construction Worker 1 applied the synchronous system at the construction site using the following client environment: a laptop fitted with an internal soundcard, a WLAN card, a Bluetooth adaptor, a Bluetooth headset integrated with a microphone and the Microsoft Windows XP operating system. Construction Worker 1 completed and delivered material reports via speech with the Bluetooth headset and WLANs. This study confirmed that the wireless devices and environments employed herein were in good condition.

However, background noise affected the accuracy of speech recognition. Construction workers not only felt uncomfortable but also had difficulty in performing auditory recognition while the noise level was over 90 dB [26]. For successful auditory and speech recognition, this study applied a high quality headset, and maintained the noise level of the system tests below 80 dB. Additionally, Construction Worker 1 had no experience in speech-enabled applications and, thus, was trained to understand the operation methods and human–machine communication before formal tests.

Based on operational methods, this study divided the application systems for on-site data collection into the asynchronous and synchronous systems. In the asynchronous system, Construction Worker 1 finished material reports through inputting data by hand and the keyboard (Fig. 2(A)). By contrast, in the synchronous system, Construction Worker 1 completed material reports via speech (Fig. 2(C)). During the system tests, besides communicating with the synchronous system, Construction Worker 1 also completed the required material reports using the asynchronous system in order to understand how these two systems differ.

The numbers of lead processes for the asynchronous and synchronous systems were different. The asynchronous system involved 9, 8 and 9 actual lead processes, while the synchronous system involved 3, 3 and 3 actual lead processes for material inventory, use and requirement records, respectively. For instance, in the asynchronous system, Table 1 and Fig. 3(A) indicate that construction workers executed 9 actual lead processes to complete a material inventory record, because 7 subprocesses of process 1 (excluding the switching subprocesses among different fields in a material record) and processes 2 and 3. Conversely, the number of actual lead processes in the synchronous system was 3, since the speech entry combined the individual subprocesses of manual data entry into one subprocess. If any erroneous data were found, then the operational lead processes and cycle time were changed.

Table 2 summarizes all measured results during the period of 14 working days for system tests. The obtained data included: 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). Productivity (prod), time efficiency (TE) and comparative work efficiency (CWE) were then calculated to determine the extent of efficiency improvement.

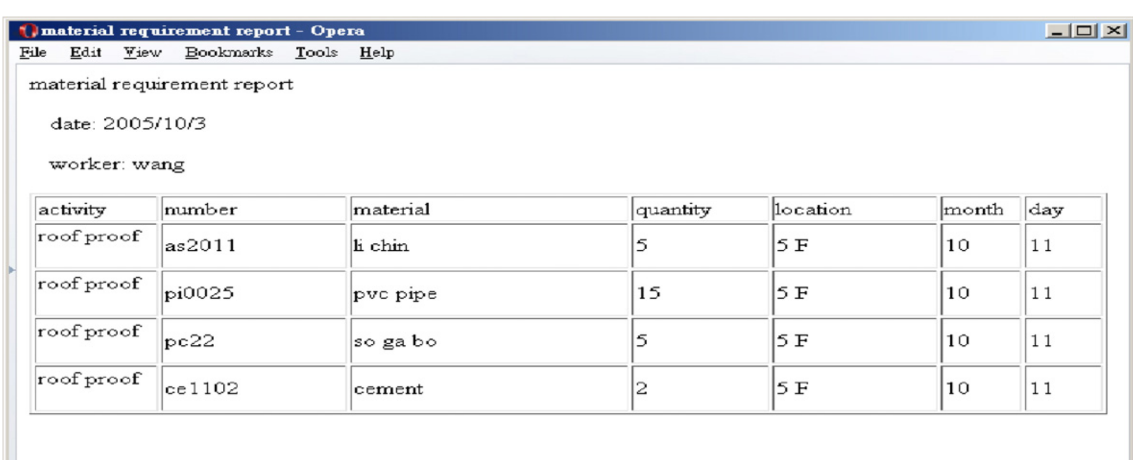
4.4. Performance evaluation

4.4.1. Operational measurements

Table 2 indicates that Construction Worker 1 spent 27,051 s and 23,596 s on completing 134 material records in the asynchronous and synchronous systems, respectively. Eq. (1) was used to determine productivity:

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

where records = the number of completed records, and TCT = the total cycle time. Thus, the productivity values of asynchronous and synchronous systems were 0.004954 and 0.005679. Clearly, the productivity was increased when Construction Worker 1 spent less total cycle time for the same material records.



material requirement report - Opera

File Edit View Bookmarks Tools Help

material requirement report

date: 2005/10/3

worker: wang

activity	number	material	quantity	location	month	day
roof proof	as2011	li chin	5	5 F	10	11
roof proof	pi0025	pvc pipe	15	5 F	10	11
roof proof	pc22	so ga bo	5	5 F	10	11
roof proof	ce1102	cement	2	5 F	10	11

Fig. 8. Material requirement report.

Table 2
Test results in asynchronous and synchronous systems

Record types					Asynchronous system							Synchronous system							TE (%)	CWE (%)
Day	inv[a]	use[b]	req[c]	Total	a-proc	returns	errs	o-proc	t-proc	TCT (s)	prod	a-proc	returns	errs	o-proc	t-proc	TCT (s)	prod		
1	5	7	0	12	101	3	0	3	104	2137	0.005615	36	0	1	1	37	1792	0.006696	16.14	64.42
2	2	5	2	9	76	2	0	2	78	1808	0.004978	27	0	0	0	27	1578	0.006696	16.14	65.38
3	0	5	1	6	49	2	0	2	51	1219	0.004922	18	0	0	0	18	1097	0.005469	10.01	64.71
4	3	6	5	14	120	3	0	3	123	2523	0.005549	42	0	1	1	43	2179	0.006425	13.63	65.04
5	8	5	2	15	130	4	1	5	135	3202	0.004683	45	0	2	2	47	2738	0.005478	14.52	65.19
6	0	6	1	7	57	1	0	1	58	1375	0.005091	21	0	0	0	21	1227	0.005705	10.76	63.79
7	0	7	3	10	83	1	0	1	84	1978	0.005056	30	0	0	0	30	1792	0.005580	9.40	64.29
8	4	3	0	7	60	3	0	3	63	1956	0.003579	21	0	1	1	22	1679	0.004169	14.16	65.08
9	6	6	0	12	102	4	1	5	107	2219	0.005408	36	0	3	3	39	1944	0.006173	12.39	63.55
10	2	4	2	8	68	2	0	2	70	1475	0.005424	24	0	1	1	25	1241	0.006446	15.86	64.29
11	4	6	1	11	93	1	0	1	94	2310	0.004762	33	0	1	1	34	2169	0.005071	6.10	63.83
12	5	4	0	9	77	3	1	4	81	2188	0.004113	27	0	1	1	28	1829	0.004921	16.41	65.43
13	0	7	0	7	56	1	0	1	57	1523	0.004596	21	0	0	0	21	1310	0.005344	13.99	63.16
14	0	6	1	7	57	1	0	1	58	1137	0.006157	21	0	0	0	21	1021	0.006856	10.20	63.79
Total				134	1129	31	3	34	1163	27,051	0.004954[d]	402	0	11	11	413	23,596	0.005679[e]	12.77[f]	64.49[g]

[a]Material inventory record; [b]material use record; [c]material requirement record; [d] $\frac{134}{27,051}$; [e] $\frac{134}{23,596}$; [f] $\left[\frac{(27,051-23,596)}{27,051}\right] \times 100\%$, and [g] $\left[\frac{(1163-413)}{1163}\right] \times 100\%$.

The total numbers of lead processes in the asynchronous and synchronous systems were 1163 (including 1129 actual lead processes, 3 erroneous data and 31 returns) and 413 (including 402 actual lead processes, 11 erroneous data and no returns). Various improvements were computed by Eqs. (2)–(4):

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

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

$$\text{improved operational lead processes} = \left\{\frac{[(\text{o-proc})^{AS} - (\text{o-proc})^{S}]}{(\text{o-prod})^{AS}}\right\} \times 100\% \quad (4)$$

where $(\text{prod})^{S}$ = the productivity in the synchronous system; $(\text{prod})^{AS}$ = the productivity in the asynchronous system; $(\text{a-proc})^{AS}$ = the number of actual lead processes in the asynchronous system; $(\text{a-proc})^{S}$ = the number of actual lead processes in the synchronous system; $(\text{o-proc})^{AS}$ = the number of operational lead processes in the asynchronous system, and $(\text{o-proc})^{S}$ = the number of operational lead processes in the synchronous system.

Consequently, the productivity was increased by 12.77% (Eq. (2)). The actual and operational (the sums of erroneous data and returns) lead processes decreased 64.39% (Eq. (3)) and 67.65% (Eq. (4)), respectively. The synchronous system required less cycle time and fewer total lead processes to complete material reports than the asynchronous system did. Although the synchronous system had more erroneous data, this study first focused on whether this system increased productivity and decreased total lead processes. Future research will attempt to improve the accuracy of speech recognition. The impacts (Fig. 9(A)) of operational measurements on the bottom line measurements (time efficiency, comparative working efficiency and completed reports) are explained below.

4.4.2. Time efficiency

The cycle time and time efficiency were the main indicators of improving on-site data collection procedures, because the information gained and the time saved on future work more than repaid the effort [33]. Time efficiency was identified by Eq. (5):

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

where $(\text{TCT})^{AS}$ = the total cycle time in the asynchronous system, and $(\text{TCT})^{S}$ = the total cycle time in the synchronous system. Additionally, decomposition of the combined impacts of operational measurements (Fig. 9(A)) shows that both productivity (Fig. 9(B)) and operational lead processes (Fig. 9(E)) directly affect time efficiency, excluding actual load processes (Fig. 9(C)).

Fig. 9(B) illustrates that Construction Worker 1 completed the same reports more efficiently, and was more productive, in the synchronous system than in the asynchronous system. In other words, the synchronous system required less operation time than the asynchronous system. The proc, TCT and TE columns of Table 2 show that all test results satisfied this condition. For instance, the productivities of asynchronous and synchronous systems were 0.005615 and 0.006696 in Day 1, accompanied by an increase in time efficiency of 16.14%. Moreover, the time efficiency was increased owing to the decreased operational lead processes (Fig. 9(E)). For example, the synchronous system had three fewer operational lead processes than the asynchronous system did on Day 12

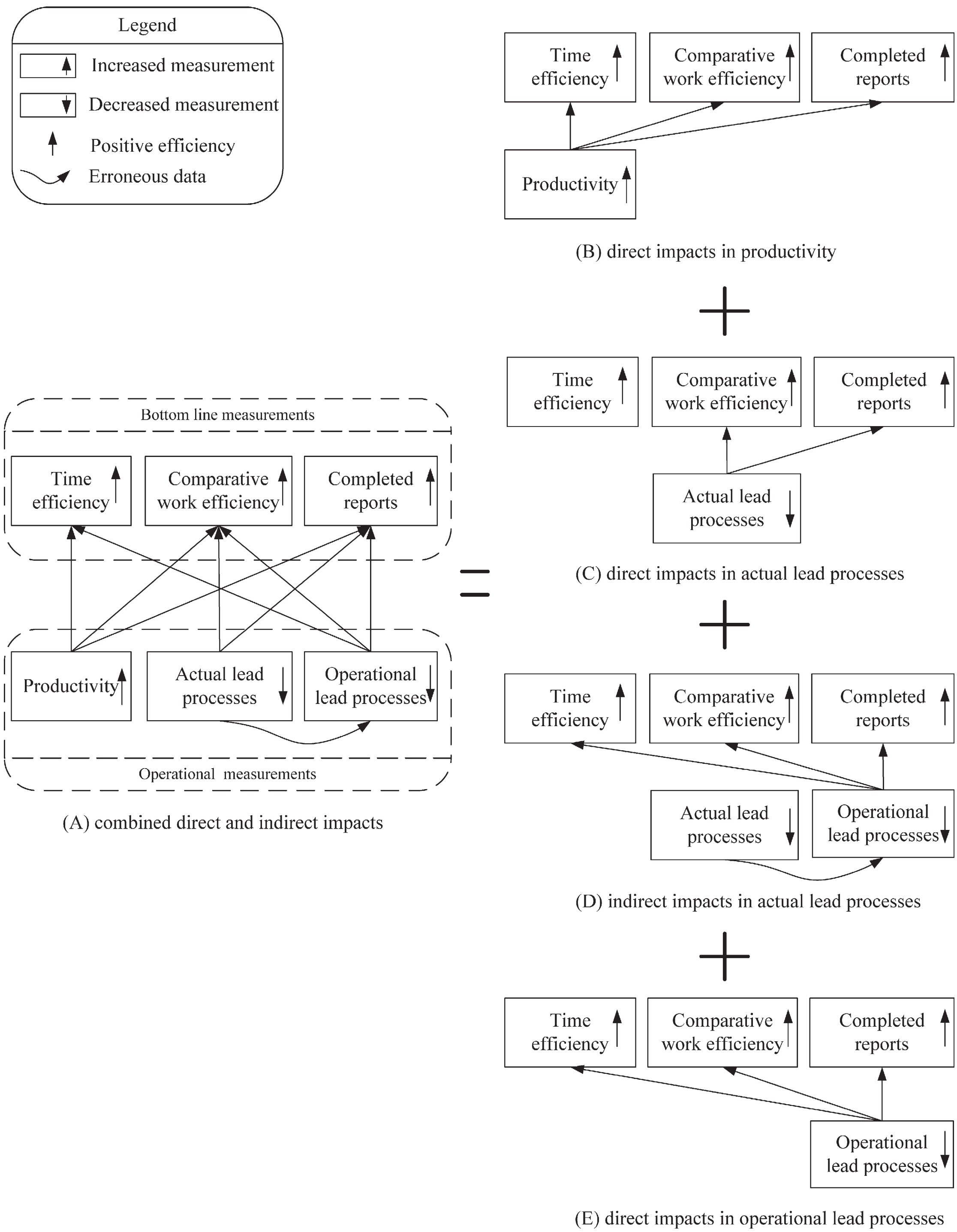


Fig. 9. Direct and indirect impacts in synchronous system (a modification from [12]).

(Table 2)). The time efficiency was 16.41% in the synchronous system.

Fig. 9(D) shows that the actual lead processes had an indirect impact, instead of a direct impact (Fig. 9(C)), on the time efficiency through the operational lead processes. Incorrect data entry and faulty speech recognition might have occurred when Construction Worker 1 produced the initial completed records in Process 1 (stage 3 of Fig. 4), and confirmed the errors in Process 2. The initial erroneous data thus affected the time efficiency. For example, the synchronous system in Days 6 and 8 had 0 and 1 errors, respectively. Construction Worker 1 spent more time on correcting erroneous data on Day 8 than on Day 6.

In summary, Table 2 reveals that the time efficiency ranged from 6.1% to 16.41%. After the system tests, the total time efficiency based on both the direct and indirect impacts increased 12.77% in the synchronous system. Fig. 10 depicts that the cumulative cycle time of the synchronous system was shorter than that of the asynchronous system when the number

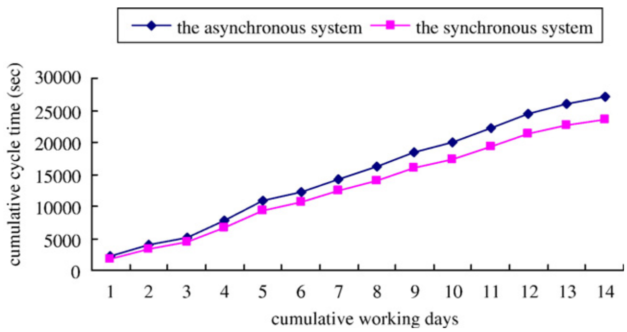


Fig. 10. Cumulative cycle time for 14 working days.

of working days was increased. The total cycle time saved through the synchronous system was 3455 s.

4.4.3. Comparative work efficiency

Automated data collection was accepted to be more efficient than manual data collection, because little work had been done in quantifying the efficiency increase [34]. Eq. (6) was used for calculating the comparative work efficiency:

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

where $(\text{t-proc})^{AS}$ = the total number of lead processes in the asynchronous system, and $(\text{t-proc})^{S}$ = the total number of lead processes in the synchronous system. Based on the impacted relationships, Fig. 9(B) shows that the comparative work efficiency also increased, while the productivity for activity completion increased. For instance, because Construction Worker 1 increased productivity in Day 2, the comparative work efficiency increased 65.38%.

Fig. 9(C–D) illustrate that the actual lead processes affected the comparative work efficiency directly and indirectly. For transferring the initial completed records quickly into the following processes, directly simplifying the executed subprocesses (e.g., avoiding separately filling in data) of the actual lead processes was a significant means of increasing the comparative work efficiency. For example, Construction Worker 1 had the same number of operational lead processes in the asynchronous and synchronous systems in Day 11. The respective numbers of actual lead processes in the asynchronous and synchronous systems were 93 and 33, leading to a difference in comparative work efficiency of 63.83%.

Although the initial completed records associated with erroneous data indirectly influenced the comparative work efficiency (Fig. 9(D)), unnecessary return was the other component of operational lead processes. Therefore, Fig. 9(E) shows that the comparative work efficiency for activity completion increased when the number of operational lead processes was reduced. For instance, besides eliminating 85 actual lead processes, the synchronous system also eliminated 3 operational lead processes in Day 5. The comparative work efficiency increased 65.19%.

Table 2 indicates that the comparative work efficiency ranged from 63.16% to 65.43%. When the proposed system synchronized the data entry for various fields and reduced unnecessary returns between working locations and application devices, the total improvement in comparative work efficiency reached 64.49%. Fig. 11 shows that the synchronous system required fewer total lead processes than the asynchronous system as the number of cumulative working days increased.

4.4.4. Completed reports

A computerized approach for collecting and processing site information can generate fast feedbacks on project statuses and problems [9]. Hence, whether Construction Worker 1 applied the synchronous system to complete material reports on schedule had to be determined. If Construction Worker 1 failed to complete the required reports by this system, then the improvement for on-site data collection would be useless; otherwise, this improvement would be useful.

Based on the above discussions, Fig. 9(B–E) show that such improvements were helpful for completing reports due to the increased productivity and decreased actual and operational lead processes. Furthermore, the total completed material records of asynchronous and synchronous systems were the same in the system tests period. Therefore, Construction Worker 1 successfully completed on-site data collection through the synchronous system.

4.5. Goal confirmation

This study integrated wireless and speech technologies to develop a synchronous system, which successfully achieved the cooperation between construction workers and application devices via direct communication. The improvements provided by a synchronous system over an asynchronous system are listed below.

- Data entry and confirmation: Although the required processes were the same for asynchronous and synchronous systems, the separated data entry still included various interdependent subprocesses. Construction workers could speak one sentence to report material details when speech technology was integrated with the synchronous system. Moreover, the proposed system automatically confirmed the recognized material data with construction workers.

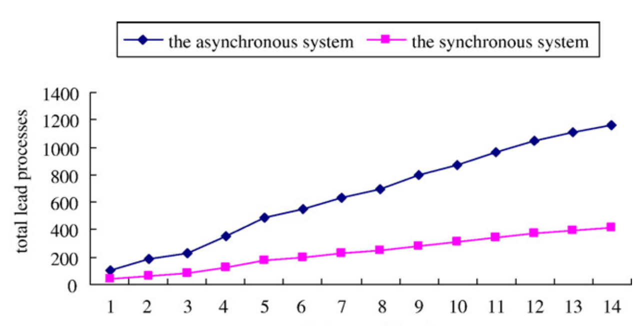


Fig. 11. Cumulative total lead processes for 14 working days.

Therefore, the above improvement not only simplified the data completion, but also speeded up other information flow processes.

- Information delivery and production: In contrast with the asynchronous system, construction workers communicated directly with the synchronous system via speech and Bluetooth technology. Construction workers did not have to return to the application device to deliver the obtained information. Meanwhile, the synchronous system analyzed the received information to complete material reports. Obviously, the synchronous system actively assisted construction workers to complete information production.
- Productivity: The reflected productivity of on-site data collection depended on the processes, subprocesses and cycle time. The system tests demonstrate that the synchronous system other than the asynchronous system required less cycle time and fewer actual and operational lead processes for completing on-site data collection. Consequently, the working productivity was clearly enhanced in this case study.

5. Conclusion

Based on a synchronization-based model proposed by a previous study, this study developed a synchronous system integrated with wireless and speech technologies for on-site data collection. This system was applied in a material management case study, in which construction workers communicated directly with application devices to achieve synchronous operations and simplify manual data entry. After the system tests, analytical results relating to efficiency improvement indicate that the proposed synchronous system increased productivity, time efficiency and comparative work efficiency due to the decreased lead processes and operation time.

The test procedures and results show that speech recognition is a significant factor for the cycle time and operational lead processes. Improving the accuracy of speech recognition raises the system performance. Additionally, construction workers still have various working requirements, such as progress control, equipment management and off-site data analysis. The framework of the proposed synchronous system would be a helpful reference for solving similar on-site information management problems. Consequently, future research plans include developing proper speech grammar rules to decrease erroneous speech recognition, and integrating the interdependent information flows through the synchronous system to increase improvement and activity productivity levels.

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